5G New Radio in Bullets

1st Edition

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5G New Radio

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These will be considered for future editions.

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The author would like to acknowledge his employer, Nokia UK Limited for providing the opportunities to gain valuable project experience. The author would like to thank his manager, Stuart Davis for supporting participation within projects which have promoted continuous learning and development. The author would also like to thank Juha Sarkioja and Poul Larsen for providing opportunities to work on global 5G activities within Nokia.

The author would like to acknowledge colleagues from within Nokia who have supported and encouraged the development of material for this book. These include Jyri Lamminmaki, Lorena Serna Gonzalez, Ian Horne and Poeti Boedhihartono. In addition, the author would like to thank colleagues from outside Nokia who have also supported the development of this book. These include Pinaki Roychowdhury, Mark Livas, Ammar Khalid and Paul Clarkson

The author would also like to offer special thanks to his parents who provided a perfect working environment during the weeks spent in Scotland. He would also like to thank them for their continuous support and encouragement

Edition 1, version 1

1 FUNDAMENTALS

1.1 INTRODUCTION

- 5G has been introduced within the release 15 version of the 3GPP specifications, whereas 4G was introduced within release 8
- 5G has been specified based upon the requirements of the following use cases:
  - enhanced Mobile Broadband (eMBB)
  - Ultra Reliable and Low Latency Communications (URLLC)
  - massive Machine Type Communications (mMTC)
- The Radio Access Network (RAN) belonging to 4G is known as Long Term Evolution (LTE), whereas the RAN belonging to 5G is known as New Radio (NR)
- NR has been standardised to allow tight interworking with LTE. Tight interworking supports the inter-connection of LTE and NR Base Stations. These Base Stations can then be used in combination to serve the population of User Equipment (UE). 5G network architectures based upon tight interworking between LTE and NR are known as Non-Standalone (NSA)
- Non-Standalone architectures allow a smooth and relatively simple evolution towards a complete end-to-end 5G System (5GS). Non-Standalone architectures allow re-use of existing LTE Base Stations and existing 4G Core Networks. In general, a software upgrade is sufficient to allow interworking with a set of NR Base Stations
- Standalone (SA) NR Base Stations provide connectivity to a 5G Core Network. The combination of NR Base Station and 5G Core Network is known as a 5G System (5GS). The benefits of 5G are maximised when using a 5G System
- NR Base Stations have a flexible architecture which supports a range of deployment options:
  - a 'classical' Base Station architecture can be adopted to keep the hardware within a single cabinet
  - alternatively, the Base Station can be split into a Centralised Unit (CU) and a Distributed Unit (DU). The CU accommodates the higher protocol stack layers, while the DU accommodates the lower protocol stack layers. A single CU can host a large number of DU (typically > 100), while each DU can host multiple cells (typically > 6)
  - in addition, the CU can be split into Control Plane (CP) and User Plane (UP) functions. This allows independent scaling of the CP and UP processing capabilities. It also allows the two functions to be deployed at different geographic locations. UP functions may be located in close proximity to the DU to help reduce user plane latency, while CP functions may be centralised to pool resources
  - all deployment options can use either passive or active antenna. Passive antenna are connected to radio modules using RF feeder cables whereas active antenna are connected to baseband processing hardware using high speed fibre
- Congestion within the lower operating bands, combined with a requirement for wider channel bandwidths has led to the specification of both low and high operating bands for 5G. Release 15 has adopted the use of Frequency Range 1 (450 MHz to 6 GHz) and Frequency Range 2 (24.25 GHz to 52.60 GHz). Frequency Range 1 supports channel bandwidths from 5 to 100 MHz, whereas Frequency Range 2 supports channel bandwidths from 50 to 400 MHz
- Frequency Range 1 includes operating bands which support Frequency Division Duplexing (FDD), Time Division Duplexing (TDD), Supplemental Downlink (SDL) and Supplemental Uplink (SUL), whereas Frequency Range 2 supports only TDD. 3GPP has specified mechanisms to allow dynamic changes to the uplink and downlink transmission pattern used by TDD
- The NR air-interface uses Cyclic Prefix OFDM (CP-OFDM) in both the uplink and downlink directions. In addition, Discrete Fourier Transform Spread OFDM (DFT-S-OFDM) can be used to help improve coverage in the uplink direction. Both waveforms can use QPSK, 16QAM, 64QAM and 256QAM. DFT-S-OFDM can also use $\pi/2$ BPSK in areas of weak coverage
- Subcarrier spacings of 15, 30 and 60 kHz are supported within Frequency Range 1, while subcarrier spacings of 60, 120 and 240 kHz are supported within Frequency Range 2. The 240 kHz subcarrier spacing is only used for the transmission of Synchronisation Signals and the Physical Broadcast Channel (PBCH). Smaller subcarrier spacings have longer symbol durations which allow support for larger cell ranges. Larger subcarrier spacings have shorter symbol durations which allow support for lower latencies
- Beamforming and MIMO are important for both the uplink and downlink of the NR air-interface. These can be combined within the context of massive MIMO (mMIMO). Beamforming is particularly important to improve the link budget when using Frequency Range 2. Multi-User MIMO (MU-MIMO) can be used to improve spectrum efficiency when UE have sufficient spatial separation
- Both 4G and 5G have been designed to support Packet Switched (PS) services. 4G supports the speech service using Voice over LTE (VoLTE), whereas 5G supports the speech service using Voice over NR (VoNR). 4G networks support Single Radio Voice Call Continuity (SRVCC) to allow inter-system handover towards the Circuit Switched (CS) domain belonging to either 3G or 2G. Release 15 does not support SRVCC for 5G but Packet Switched inter-system handovers from 5G to 4G are possible. SRVCC from 5G to 3G is specified within the release 16 version of the 3GPP specifications

1.2 USE CASES

★ 3GPP has adopted the set of use cases identified by the Radio Communications Sector of the International Telecommunications Union (ITU-R). These use cases are applicable to technologies being developed to support the requirements of International Mobile Telecommunications for 2020 (IMT2020) and beyond. The set of use cases are:

- o enhanced Mobile Broadband (eMBB)
- o Ultra Reliable and Low Latency Communications (URLLC)
- o massive Machine Type Communications (mMTC)

★ 3GPP is accounting for the requirements of these use cases when standardising 5G. Release 15 focuses upon the eMBB and URLLC categories, but additional capabilities for mMTC will be added in Release 16. The Narrow Band Internet of Things (NB-IoT) and LTE-Machine (LTE-M) technologies belonging to 4G provide a solution for mMTC within the timescales of release 15

★ Each use case category has its own set of requirements. For example, eMBB requires high connection throughputs and high network capacity, whereas URLLC requires low latency and high reliability for devices with both low and high mobility. The ITU-R has identified a general set of requirements and has assigned an importance to each requirement for each use case. These requirements and their importance are summarised in Figure 1

	Maximum Connection Throughput	Average Connection Throughput	Spectrum Efficiency	Area Traffic Capacity	Connection Density	Latency	Mobility	Network Energy Efficiency
eMBB	High Importance	High Importance	High Importance	High Importance	Medium Importance	Medium Importance	High Importance	High Importance
URLLC	Low Importance	Low Importance	Low Importance	Low Importance	Low Importance	High Importance	High Importance	Low Importance
mMTC	Low Importance	Low Importance	Low Importance	Low Importance	High Importance	Low Importance	Low Importance	Medium Importance

Figure 1 – Importance of various requirements for each Use Case

★ Requirements also vary within a specific use case category. For example, deploying eMBB across a rural area requires a focus upon coverage, whereas deploying eMBB across an urban area requires a focus upon capacity

★ Each use case category includes many individual applications. Examples of these applications are shown in Figure 2

★ Existing applications are included, e.g. voice services, video streaming, internet browsing, social media and instant messenger applications. Many emerging applications are also included, e.g. automatic vehicles, remote control, home automation, smart city applications, wearables, monitors and sensors

★ Many applications require components from multiple use case categories. For example, virtual reality requires low latency to provide responsiveness and high mobile broadband throughputs for the rapid transfer of content

★ 3GPP is ensuring that 5G has sufficient flexibility and capability to address the diverse set of requirements belonging to this broad range of applications

★ ITU-R References: Recommendation ITU-R M.2083-0

★ 3GPP References: TR 22.861, TR 22.862, TR 22.863

Figure 2 – Examples of applications associated with each Use Case category

1.2.1 Enhanced Mobile Broadband (eMBB)

- enhanced Mobile Broadband (eMBB) represents an evolution of the Mobile Broadband services offered by 4G
- eMBB applications generally involve humans accessing multi-media content, services and data
- eMBB aims to improve the end-user experience for existing applications and support the introduction of new applications
- 3GPP TR 22.863 identifies the main use case families as:
  - high data rate scenarios at offices, shopping centres, urban streets and residential locations. This use case family includes the broadcast of audio and video, e.g. 4K ultra high definition video. Deployments at residential locations should be capable of competing with fixed broadband services
  - high density scenarios to support the transfer of high data volumes per unit area, e.g. at offices and other hotspot locations including shopping centres, urban streets, stadiums and public transport
  - coverage scenarios including local area coverage within offices and educational establishments, as well as wide area coverage using mobility to provide seamless connectivity
  - high user mobility in fast moving vehicles with services that are supported using either on-board network equipment or an external fixed Base Station
  - devices with highly variable data rates, such as smart phones which often transfer small but frequent packets but can also transfer larger packets and data volumes. Smart phones may also act as a gateway for wearable sensors
  - fixed-mobile convergence to allow the combination of fixed and mobile broadband services. Devices should be able to use both fixed and mobile broadband connections either simultaneously to increase aggregate throughput, or individually
  - Femtocell deployments at office, residential and urban locations to provide a 5G air-interface with a fixed broadband backhaul

1.2.2 Massive Machine Type Communications (mMTC)

- massive Machine Type Communication (mMTC) is characterised by a very large number of connected devices which typically transmit low volumes of non-delay sensitive data
- mMTC devices are generally required to be low cost and have a long battery life
- 3GPP TR 22.861 identifies the main categories of application as:
  - Internet of Things (IoT) with a large number of devices transferring small volumes of non-time critical data
  - Smart Wearables (personal area network) using low complexity devices with a long battery life
  - Sensor Networks used to monitor a wide range of metrics, e.g. traffic, weather, parking spaces
- Many existing IoT devices do not use a cellular network, e.g. devices using WiFi to connect to the internet via a wireless router. These devices are typically short range, have little or no mobility and rely upon the availability of a wireless router. Bluetooth Low Energy (BLE) and ZigBee are other alternative wireless technologies used to connect IoT devices to each other and to the internet
- Within the context of 5G, the main focus is upon 'cellular IoT' devices which use 5G as the access network. Cellular IoT devices benefit from the ubiquitous wide area coverage provided by a mobile operator. These devices may support applications which involve mobility and they do not depend upon the availability of a wireless router
- The Smart Wearables category includes activity tracking devices, personal sensors, augmented reality headsets, smart watches, smart ear buds, smart glasses and identity wristbands for admission into theme parks. Most of these applications require mobility and benefit from the wide area coverage provided by cellular networks
- Sensor Networks may form part of the Smart City ecosystem. Sensors can be used to monitor traffic conditions and car parking occupancy. These metrics can be used as inputs to generate recommendations for drivers. Sensors can also be used to monitor environmental metrics such as air quality and weather conditions. Weather conditions can be used as an input for automatic street lighting or variable speed limits. Sensors used for security applications can detect movement or apply facial recognition
- IoT devices may not connect directly to the mobile network. For example, a smart watch may connect to a smart phone, and the smart phone connects to the mobile network, i.e. the smart phone acts as a relay device for the smart watch

1.2.3 Ultra Reliable and Low Latency Communications (URLLC)

★ Applications associated with Ultra Reliable and Low Latency Communications (URLLC) tend to have only moderate throughput requirements but require very high reliability and very low latency

★ 3GPP TR 22.862 identifies the main use case families as:

- o Higher Reliability and Lower Latency applications: this family of applications requires low latency but does not require very low latency. For example, the remote control of vehicles by a human operator has a latency requirement which is determined by the human reaction speed. It is not necessary for the system to have a reaction speed which is significantly faster than the human operator. Another example within this category is factory and process automation. Closed loop control systems within a factory involve a controller periodically sending commands to one or more devices which must respond with feedback within a specific time window. Both the commands and the feedback must be transferred with very high reliability
- o Higher Reliability, Higher Availability and Lower Latency applications: this family of applications is similar to the previous category but includes an additional requirement for high availability, i.e. system downtime must be very low. Industrial control applications can belong to this category. These applications may normally achieve high reliability and high availability by using cable connections rather than wireless connections. However, cable connections may not always be an attractive solution. The remote control of drones can fit into this family of applications. High availability is important to ensure that the drone is always under the control of the human operator. The latency requirement is dictated by the reaction speed of the human operator so does not need to be especially low
- o Very Low Latency: this family of applications includes the concept of the 'Tactile Internet'. The Tactile Internet supports a remote extension to the human body. For example, it allows a surgeon to remotely operate on a patient using a mechanical arm which reacts as though it was the surgeon's own arm. The surgeon receives both visual and tactile feedback from the remote device, e.g. when the surgeon presses against something with the remote arm then tactile feedback is provided so the surgeon can feel that he or she is pressing against something. The latency requirement for tactile control is more stringent than the latency requirement for human operated remote control vehicles
- o Higher Accuracy Positioning: this family of applications involves the measurement of location and the subsequent signalling of that location information. It is applicable to autonomous vehicles which exchange location information with each other to avoid collisions. Information must be transferred reliably and with low latency. The maximum permitted latency depends upon the speed of the vehicle and the accuracy requirement. Throughput requirements for this category tend to be low
- o Higher Availability; this family of applications refers to scenarios where there is a requirement for improved network availability. This could be applicable to scenarios where the normal mobile network is unavailable due to congestion or outage. It could also be applicable to scenarios where the normal mobile network does not have coverage. An example solution is to use satellite connectively as a back-up to the normal mobile network. Latency requirements are not particularly low but the secondary connection must be reliable and have high availability
- o Mission Critical Services: this family of applications requires prioritisation over normal network traffic. This prioritisation is required to ensure that mission critical services have high availability with short connection setup times. These services also require reliable data transfer with low latency. Prioritisation becomes especially important during periods of network congestion. Communications for the emergency services is an example of a mission critical service

1.2.4 Vehicle to Everything (V2X)

★ Vehicle to Everything (V2X) includes the following components which are illustrated in Figure 3:

- o Vehicle to Vehicle (V2V)
- o Vehicle to Network (V2N)
- o Vehicle to Infrastructure (V2I)
- o Vehicle to Pedestrian (V2P)

★ There are both cellular and non-cellular solutions for V2X communication. The IEEE 802.11 (WiFi) standard has been modified to create 802.11p specifically for the purposes of V2X applications. This represents a non-cellular solution for V2X. WiFi typically operates using unlicensed spectrum whereas 802.11p operates in licensed spectrum to help improve performance. 4G has been enhanced to include support for V2X communications within the release 14 version of the 3GPP specifications. This represents an example of a cellular solution for V2X. 5G provides another solution for cellular V2X

★ V2V involves the transfer of data directly between vehicles. This represents a variant of device-to-device (D2D) communication which uses the sidelink rather than the uplink or downlink. The V2V application imposes specific requirements upon the sidelink, e.g. support for reliable and low latency communication at high speeds

★ V2V communication is supported both inside and outside normal cellular coverage, i.e. it is not necessary for the vehicles to be within the coverage of the network. UE must schedule their own transmissions when operating outside the coverage of the network. In this case, UE are able to transmit and receive data while in RRC Idle mode because there is no Base Station for the RRC Connection setup procedure

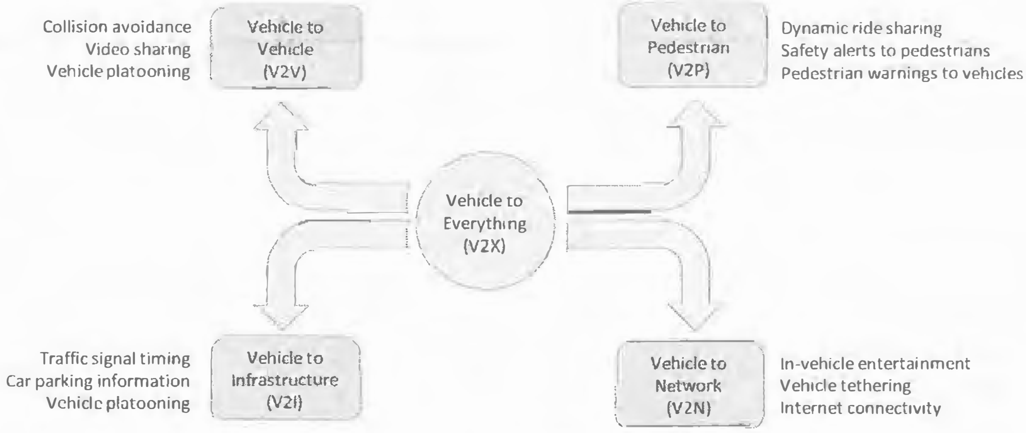


Figure 3 – Components belonging to Vehicle to Everything (V2X)

★ Collision avoidance is a key example of an application for V2V communication. Collision avoidance applications exchange location information between vehicles. This can supplement information provided by sensors which determine the proximity of nearby vehicles and obstacles. Video sharing is another example of an application for V2V communication. A car driving behind a truck can have limited visibility of the road ahead so can benefit from having a video feed displaying the view in front of the truck

★ V2I involves the transfer of data between vehicles and Road Side Units (RSU). RSU are application servers positioned along the road with built-in Base Station functionality (or built-in UE functionality) so they can communicate directly with passing vehicles. They form part of the highway infrastructure and can be either standalone or can have connectivity into a larger network

★ The transfer of traffic signal timing information is an example of V2I. In this case, the RSU is aware of the timing used by nearby traffic signals. This timing is provided to vehicles approaching the signals so they are able to react appropriately. The transfer of car parking information is another example of V2I. In this case, the RSU has information regarding the status of local car parking facilities. This information is provided to vehicles to help them find a parking space

★ V2N involves the transfer of data between vehicles and the mobile network, e.g. providing connectivity to the internet. Vehicles may connect to the mobile network to collect weather reports or to provide information regarding local attractions. Screens and input devices within the vehicle can be used to provide end-users with internet connectivity and in-vehicle entertainment. In-vehicle entertainment allows end-users to stream audio or video, play games, access social media or browse the internet

★ Vehicle tethering is an example of V2N. In this case, the vehicle acts as a relay for end-users within the vehicle. The vehicle is likely to have a better link budget than the end-users within the vehicle, e.g. antenna which are larger and outside the vehicle. The vehicle may also have more antenna and a higher transmit power capability. The vehicle takes advantage of these factors to connect to the network and relay data transfer for end-users within the vehicle. The end-users are able to transmit with a reduced power and thus help to conserve their battery life

★ V2P involves the transfer of data between vehicles and pedestrians. Similar to V2V applications, V2P represents a variant of device-to-device (D2D) communication which uses the sidelink rather than the uplink or downlink. The vehicle communicates directly with a device, e.g. smartphone belonging to a pedestrian

★ Dynamic ride sharing is an example of V2P. This application allows pedestrians to advertise their interest in sharing a vehicle to reach a specific destination. It also allows vehicles to advertise their willingness to collect pedestrians and take them to their desired destination. Dynamic ride sharing could be used by taxi companies, or could be used by private vehicles

★ Vehicle platooning is an important application for V2X which can use a combination of V2V and V2I. Vehicle platooning involves a group of vehicles connected to one another and effectively moving like a train. Vehicles share speed, direction and braking/accelerating intentions. This allows them to travel with a reduced distance between vehicles and also allows them to operate with improved fuel efficiency. The vehicle which creates the platoon becomes responsible for managing the platoon. This vehicle uses V2I for communication with Road Side Units (RSU). The information received from an RSU is subsequently shared with all platoon members using V2V communication

★ The 5G Automotive Association (5GAA) has been created to help connect the telecom industry with vehicle manufacturers. This association aims to support the development of end-to-end solutions for future mobility and transportation services. 5GAA is a Market Representation Partner (MRP) within 3GPP

★ 3GPP References: TR 22.886, TS 22.185, TS 22.186

1.3 REQUIREMENTS

★ The Radio Communications Sector of the International Telecommunications Union (ITU-R) has specified a set of requirements for IMT2020 technologies within report ITU-R M.2410-0. These requirements will be used when evaluating candidate technologies, e.g. the 5G solution specified by 3GPP. The set of requirements is presented in Table 1

		Applicable Use Case	Uplink	Downlink
Peak Data Rate		eMBB	10 Gbps	20 Gbps
Peak Spectral Efficiency		eMBB	15 bps/Hz	30 bps/Hz
User Experienced Data Rate		eMBB	50 Mbps	100 Mbps
User Spectral Efficiency (5th percentile)	Indoor Hotspot	eMBB	0.210 bps/Hz	0.300 bps/Hz
	Dense Urban	eMBB	0.150 bps/Hz	0.225 bps/Hz
	Rural	eMBB	0.045 bps/Hz	0.120 bps/Hz
Average Spectral Efficiency per TRP	Indoor Hotspot	eMBB	6.75 bps/Hz	9.00 bps/Hz
	Dense Urban	eMBB	5.40 bps/Hz	7.80 bps/Hz
	Rural	eMBB	1.60 bps/Hz	3.30 bps/Hz
Area Traffic Capacity	Indoor Hotspot	eMBB	-	10 Mbps/m^2
User Plane Latency		eMBB	4 ms	4 ms
		URLLC	1 ms	1 ms
Control Plane Latency		eMBB & URLLC	20 ms	
Connection Density		mMTC	1 000 000 devices / km^2	
Energy Efficiency		eMBB	High Sleep Ratio & Long Sleep Duration while Inactive	
Reliability		URLLC	$1 - 10^{-5}$	$1 - 10^{-5}$
Mobility	10 km/hr Indoor Hotspot	eMBB	1.50 bps/Hz	-
	30 km/hr Dense Urban	eMBB	1.12 bps/Hz	-
	120 km/hr Rural	eMBB	0.80 bps/Hz	-
	500 km/hr Rural	eMBB	0.45 bps/Hz	-
Mobility Interruption Time		eMBB & URLLC	0 ms	

Table 1 – Minimum Requirements for IMT2020 Radio Interface (specified by ITU-R)

★ The Peak Data Rate requirement is a largely theoretical figure because it represents the peak throughput which could be achieved by a single user in ideal radio conditions, i.e. assuming the air-interface does not cause any bit errors. It is most likely achievable using the higher operating bands because the target values require a large quantity of spectrum. Considering the Peak Spectral Efficiency values in the next row of the table, the quantity of spectrum required to achieve the Peak Data Rates is $20 \times 10^9 / 30 = 667$ MHz

★ Spectral Efficiency is a measure of throughput per unit of bandwidth (measured in bps/Hz). Spectral Efficiency improvements are primarily achieved using multiple antenna transmission schemes, e.g. 8×8 MIMO. In the case of TDD, Spectral Efficiency calculations must account for the uplink/downlink factor, i.e. the ratio between the uplink and downlink time slots on the shared carrier

★ The Peak Spectral Efficiency requirement is also largely theoretical because it assumes ideal radio conditions. The Peak Spectral Efficiency corresponds to the Peak Data Rate divided by the channel bandwidth. The ITU-R requirement for IMT2020 Peak Spectral Efficiency is equal to the 3GPP requirement for LTE Advanced Peak Spectral Efficiency. Both cases assume 8 spatial multiplexing streams in the downlink and 4 spatial multiplexing streams in the uplink

★ The User Experienced Data Rate represents the throughput which can be achieved by 95 % of the users within a dense urban coverage area. The large difference between the Peak Data Rate requirement and the User Experienced Data Rate requirement reflects the difference between ideal peak performance and the more realistic performance which can be achieved by 95 % of users. It is expected that the User Experienced Data Rate will be higher when users are served by small cell and indoor solutions

★ The User Spectral Efficiency represents the Spectral Efficiency which can be achieved by 95 % of users within a specific type of coverage area (indoor hotspot, dense urban or rural). This requirement accounts for the frequency re-use factor. If the network is deployed using a frequency re-use of 1 then there is no impact but if the frequency re-use factor is greater than 1 then the channel bandwidth is multiplied by the frequency re-use factor before calculating the Spectral Efficiency. In the case of TDD, the channel bandwidth is also scaled by the uplink/downlink factor

★ The Average Spectral Efficiency per Transmission / Reception Point (TRP) represents the average Spectral Efficiency per unit of hardware. This metric also accounts for the frequency re-use pattern and the TDD uplink/downlink factor. The requirements are significantly greater than the User Spectral Efficiency primarily because they are averages rather than 5 percentiles

- ★ The Area Traffic Capacity is the total traffic throughput per m^2. This metric depends upon the site density, i.e. higher site densities are likely to generate higher area traffic capacity (assuming intercell interference does not dominate). The requirement for Area Traffic Capacity is only specified for the downlink of the indoor hotspot scenario

- ★ User Plane Latency represents the contribution of the radio network towards the one-way delay associated with transferring an application packet. It is defined as the delay between a packet entering layer 2/3 at the transmit side and leaving layer 2/3 at the receive side. The requirement assumes that the UE is already RRC Connected and is ready to transfer data. It also assumes a small packet size, e.g. a payload which includes only an IP header. Separate requirements are specified for the eMBB and URLLC use cases

- ★ Control Plane Latency represents the delay associated with making the transition from a battery efficient state to the start of continuous data transfer. The battery efficient state could be RRC Idle mode. Separate requirements are specified for the eMBB and URLLC use cases. The ITU-R states that proposed technologies should target values less than the specified requirement of 20 ms, e.g. 10 ms could be targeted. The equivalent requirement for IMT-Advanced (4G) was 100 ms

- ★ Connection Density represents the maximum number of UE per unit area which allows those UE to fulfil a specific Quality of Service (QoS). The Connection Density requirement is applicable to the mMTC use case. The QoS requirement is defined as the ability to successfully transfer 99 % of packets with a maximum of 10 s delay. The requirement assumes a Poisson packet arrival process for each UE with a minimum average packet arrival rate of 1 message per day per UE (an average packet arrival rate of 1 message per 2 hours per UE is also suggested). Packets are assumed to have a size of 32 bytes. Specific inter-site distances and system bandwidths are also specified for this requirement, i.e. either a 500 m inter-site distance with a 10 MHz system bandwidth, or a 1732 m inter-site distance with a 50 MHz system bandwidth

- ★ Energy Efficiency has been included as a general requirement but without a specific target. The requirement is applicable to both the device and the network. It is noted that Energy Efficiency in the active state is reflected by the Average Spectral Efficiency, while Energy Efficiency in the inactive state is reflected by the sleep ratio. It is stated that proposed technologies should support a high sleep ratio with a long sleep duration

- ★ Reliability corresponds to the ability to transmit a specific quantity of traffic within a specific time duration with a high probability of success. This requirement is applicable to the URLLC use case so the time duration (latency) is relatively short and the reliability requirement is high. The success probability must be $1 - 10^{-5} = 99.999$ % when transferring 32 bytes of data within a 1 ms time duration. The packet must be successfully transferred from the top of layer 2/3 at the transmit side to the top of layer 2/3 at the receive side. In addition, it is specified that the requirement must be achieved at the edge of urban macro coverage

- ★ Mobility corresponds to the ability to maintain a specific normalised traffic channel data rate while moving at a specific speed. The normalised traffic channel data rate is similar to spectral efficiency and has units of bps/Hz. It is calculated by dividing the data rate by the traffic channel bandwidth rather than the complete channel bandwidth. The ITU-R has specified a set of uplink requirements for a range of environment types and speeds

- ★ Mobility Interruption Time represents the duration that a UE is unable to transfer any user plane packets when completing a handover. This requirement is applicable to both the eMBB and URLLC use cases. A requirement of 0 ms is specified so data transfer must be continuous during mobility procedures

- ★ 3GPP has generated its own set of requirements which either achieve or exceed the requirements specified by the ITU-R. These requirements are defined within 3GPP TR 38.913

- ★ 3GPP has specified a User Plane Latency requirement of 0.5 ms for both the uplink and downlink of the URLLC use case. 3GPP has also specified a 10 ms Control Plane Latency. 3GPP TR 38.913 includes notes to help accommodate scenarios involving satellite links, e.g. it is stated that User Plane Latency can be as high as 600 ms for geostationary orbits, as high as 180 ms for medium earth orbits and as high as 50 ms for low earth orbits

- ★ 3GPP also specifies a maximum uplink latency of 10 s for the transfer of infrequent small packets when the UE starts from its most battery efficient state. The UE must achieve this requirement with a 164 dB coupling loss. The coupling loss is measured between the UE antenna connector and the Base Station antenna connector

- ★ Table 2 presents throughput requirements which 3GPP has specified for a set of relatively high coupling losses. These requirements are relatively low due to the high coupling loss

Coupling Loss	Uplink	Downlink
164 dB	160 bps	160 bps
143 dB	30 kbps	1 Mbps
140 dB	60 kbps	2 Mbps

Table 2 – 3GPP requirements for Throughputs as a function of Coupling Loss

- ★ 3GPP also specifies a UE battery life requirement for the mMTC use case. The UE battery life is specified to be at least 10 years when assuming a stored energy capacity of 5 Watt Hours and a UE which transfers 200 bytes per day in the uplink and 20 bytes per day in the downlink while having a coupling loss of 164 dB

- ★ ITU-R References: ITU-R M.2410-0, ITU-R M.2412-0

- ★ 3GPP References: TR 38.913, TS 22.261

1.4 NETWORK ARCHITECTURE

★ The 5G System (5GS) includes the 5G Core Network (CN), the 5G Access Network (AN) and the User Equipment (UE). Figure 4 illustrates these components belonging to the 5G System. The 5G Core Network provides connectivity to the internet and to application servers. The 5G Access Network can be a 3GPP Next Generation Radio Access Network (NG RAN), or a non-3GPP Access Network

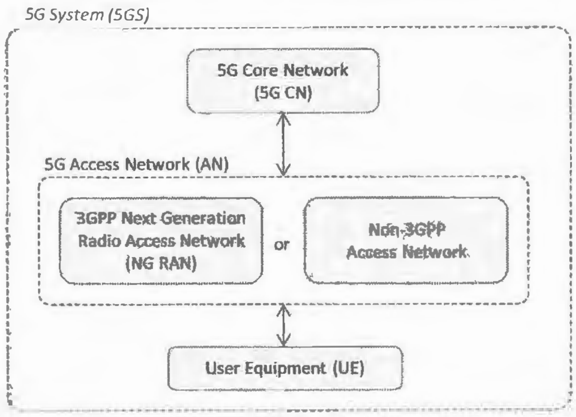


Figure 4 – 5G System (5GS)

★ A 3GPP Next Generation Radio Access Network (NG RAN) can be based upon any of the following options:

- o Standalone New Radio (NR) Base Station
- o Standalone Long Term Evolution (LTE) Base Station upgraded to allow connection to the 5G Core Network
- o Non-Standalone Base Station using NR as the anchor and LTE as an extension
- o Non-Standalone Base Station using LTE as the anchor and NR as an extension

These Base Station architectures are described in section 1.5. A New Radio (NR) Base Station is known as a gNode B, whereas an LTE Base Station which has been upgraded to allow connectivity with the 5G Core Network is known as an enhanced eNode B or a Next Generation eNode B

★ An example of a non-3GPP Access Network is a Wireless Local Area Network (WLAN) based upon WiFi. Non-3GPP Access Networks use a Non-3GPP Interworking Function (N3IWF) to allow connectivity with the 5G Core Network. The N3IWF supports 3GPP interfaces towards the 5G Core Network and non-3GPP interfaces towards the non-3GPP Access Network

★ 3GPP has specified both 'Reference Point' and 'Service based' architectures for the 5G System (5GS)

★ The 'Reference Point' architecture is based upon a set of Network Elements (NE) which use point-to-point interfaces to inter-connect those Network Elements. Signalling procedures are specified for each point-to-point interface. This type of architecture is illustrated in Figure 5. The 'Reference Point' architecture can lead to repetition within the specifications if the same signalling procedure is used across multiple interfaces

Figure 5 – Concept of Reference Point system architecture

★ The 'Service based' architecture replaces the set of Network Elements with a set of Network Functions (NF). Each Network Function can provide services to other Network Functions, i.e. each Network Function is a service provider. This type of architecture is illustrated in Figure 6. The point-to-point interfaces are replaced by a common bus which inter-connects all Network Functions. Services are specified for the Network Function providing them, rather than for each pair of providing and consuming Network Functions

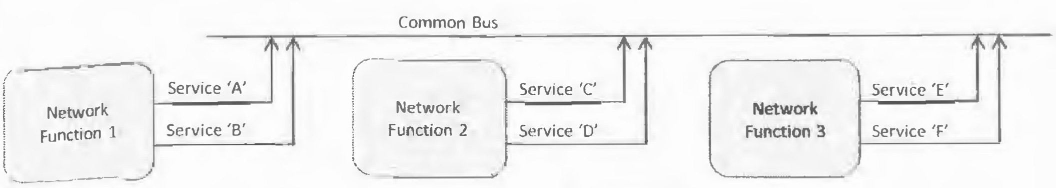


Figure 6 – Concept of Service based system architecture

★ An important characteristic of the 5G system architecture is the separation of user plane and control plane functions. This differs from the original 4G system architecture. For example, the Packet Gateway belonging to the original 4G Evolved Packet Core (EPC) provides both control plane and user plane functions, e.g. it provides the control plane function of IP address allocation, and it provides the user plane function of packet forwarding. The 5G system architecture includes the Session Management Function (SMF) for IP address allocation, and the User Plane Function (UPF) for packet forwarding, i.e. control plane and user plane functions are separated

★ User plane and control plane separation allows independent scaling of the two functions. For example, operators can add more user plane capability without having to add more control plane capability. It also allows different deployment strategies to be adopted for the user plane and control plane. For example, user plane functions could be distributed while control plane functions could be centralised. Distributing the user plane functions helps to keep them located geographically close to the access network and so helps to minimise latency

★ The release 14 version of the 3GPP specifications includes support for an enhanced version of the 4G EPC which allows user plane and control plane separation. This enhanced version of the 4G EPC is defined within 3GPP TS 23.214

★ 3GPP References: TS 23.501

1.4.1 REFERENCE POINT SYSTEM ARCHITECTURE

★ The 5G System Reference Point architecture is illustrated in Figure 7. This architecture specifies a set of Network Elements and a set of point-to-point interfaces which inter-connect those Network Elements. The functionality associated with each Network Element is described in section 1.4.3

★ Figure 7 illustrates the separation of user plane and control plane functions. Uplink user plane data is transferred from the UE to the 5G Access Network. It is then transferred through one or more User Plane Functions (UPF) before being forwarded to an external data network, e.g. the internet or a private corporate network. Downlink user plane data follows the same path but in the opposite direction

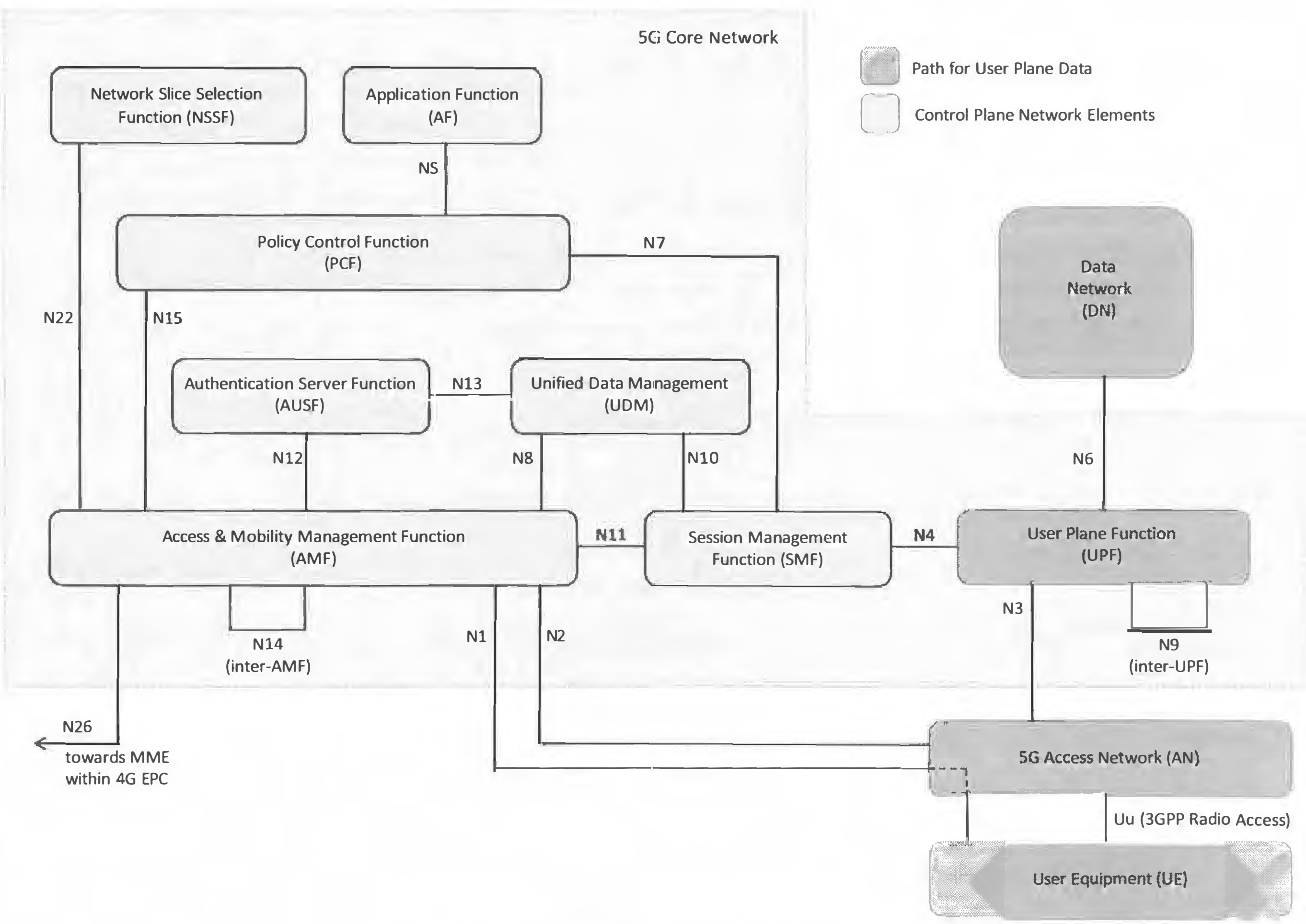


Figure 7 – 5G System Reference Point Architecture

- There are exceptions to the separation of user plane and control plane functions. For example, user plane data belonging to the Short Message Service (SMS) can be transferred using Non-Access Stratum (NAS) signalling between the UE and Access and Mobility Management Function (AMF). The SMS Function (SMSF) is not shown in Figure 7 but it can be connected to the AMF using an N20 interface
- The point-to-point interfaces connecting the Network Elements are labelled as N1, N2, N3, etc. These interfaces are known as Reference Points within 3GPP TS 23.501, e.g. N3 is the Reference Point between the 5G Access Network and the User Plane Function (UPF). N1 is the Reference Point between the UE and the Access and Mobility Management Function (AMF). This Reference Point is typically shown as a direct logical connection between the UE and AMF. Figure 7 illustrates the connection passing through the 5G Access Network to highlight that all signalling between the UE and AMF is transferred through the Access Network
- The N9 Reference Point is used to inter-connect User Plane Functions (UPF). A first UPF can be deployed to provide connectivity to the 5G Access Network while a second UPF can be deployed to provide connectivity to the external data network. The N9 Reference Point defines the connection between the two UPF. Similarly, the N14 Reference Point defines the connection between two AMF
- The N26 Reference Point can be used to connect an AMF within the 5G Core Network, with a Mobility Management Entity (MME) within the 4G Evolved Packet Core (EPC). This Reference Point is used for inter-working between 4G and 5G, e.g. inter-system handovers
- When using a 3GPP Next Generation Radio Access Network (NG RAN), user plane data and control plane signalling are transferred between the UE and NG RAN using the Uu air-interface

1.4.2 SERVICE BASED SYSTEM ARCHITECTURE

- The 5G System Service Based architecture is illustrated in Figure 8. This architecture specifies a set of Network Functions (NF) and a common bus which inter-connects those Network Functions. The Service Based architecture is applicable to the control plane section of the 5G Core Network. The Reference Point architecture remains for the user plane section of the 5G Core Network. The functionality associated with each Network Function is described in section 1.4.3

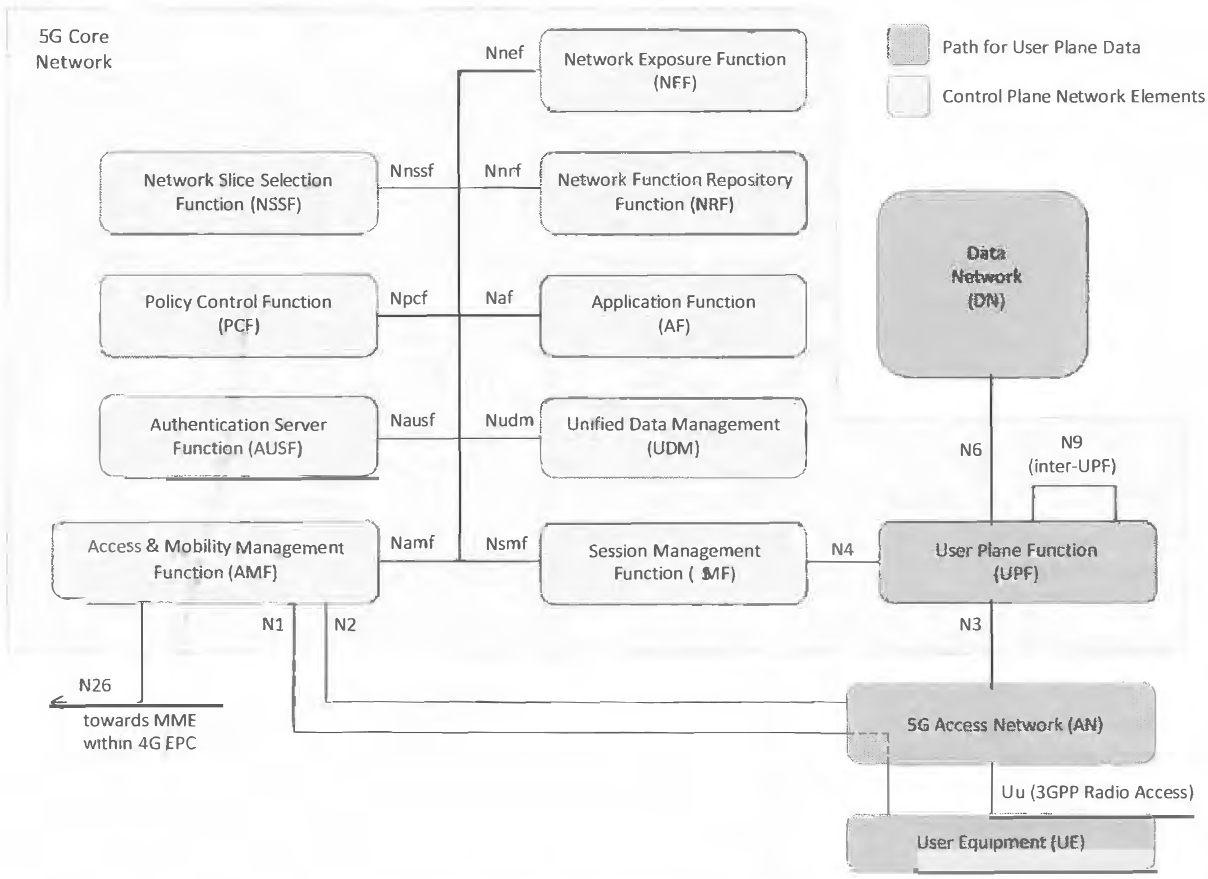


Figure 8 – 5G System Service Based Architecture

★ The Network Function Repository Function (NRF) plays a central role within the Service Based architecture. Network Functions register the services they offer with the NRF. They then use the NRF as a database to discover the services offered by other Network Functions. The following three mechanisms are used:

- o service registration: allows a Network Function to register with the NRF and inform the NRF which services are offered
- o service discovery: allows a Network Function to discover other Network Functions and the services they offer
- o service authorization: ensures that a Network Function is authorized to use the services provided by other Network Functions

★ The Service Based interfaces connecting each Network Function to the common bus are labelled as N_{amf}, N_{smf}, N_{pcf}, etc. Services are provided and consumed using these interfaces

★ Network Functions signal to each other using Hypertext Transfer Protocol version 2 (HTTP/2) specified by the IETF within RFC7540. 3GPP TS 29.500 describes the use of HTTP/2 within the context of the Service Based architecture. The HTTP/2 protocol defines 'methods' for signalling between Network Functions. Example HTTP/2 methods include:

- o POST: can be used to request a service from a Network Function
- o GET: can be used to retrieve data from a Network Function
- o PUT: can be used to create new data at a Network Function
- o PATCH: can be used to update existing data at a Network Function
- o DELETE: can be used to delete data at a Network Function

★ As an example of the services offered by a Network Function, Table 3 presents the services offered by the Access and Mobility Management Function (AMF). These services are specified within 3GPP TS 29.518

Service Name	Service Operations	Example Consumers
Namf_Communication	UEContextTransfer	Peer AMF
	RegistrationStatusUpdate	Peer AMF
	CreateUEContext	Peer AMF
	ReleaseUEContext	Peer AMF
	N1MessageNotify	AMF, LMF, PCF
	N2InfoNotify	LMF, AMF
	N1N2MessageSubscribe	PCF
	N1N2MessageUnsubscribe	PCF
	N1N2MessageTransfer	SMF, SMSF, LMF, PCF
	N1N2TransferFailureNotification	SMF, SMSF, LMF
	NonUeN2MessageTransfer	LMF, CBCF, PWS-IWF
	NonUeN2InfoSubscribe	CBCF, PWS-IWF
	NonUeN2InfoUnsubscribe	CBCF, PWS-IWF
	NonUeN2InfoNotify	LMF, CBCF, PWS-IWF
	EBIAssignment	SMF
	AMFStatusChangeSubscribe	SMF, PCF, NEF, SMSF, UDM
	AMFStatusChangeUnsubscribe	SMF, PCF, NEF, SMSF, UDM
	AMFStatusChangeNotify	SMF, PCF, NEF, SMSF, UDM
Namf_MT	EnableUEReachability	SMSF
	ProvideDomainSelectionInfo	UDM
Namf_EventExposure	Subscribe	NEF, SMF. PCF, UDM
	Unsubscribe	NEF, SMF. PCF, UDM
	Notify	NEF, SMF. PCF, UDM
Namf_Location	ProvidePositioningInfo	GMLC
	EventNotify	GMLC
	ProvideLocationInfo	UDM

Table 3 – Services provided by the Access & Mobility Management Function (AMF)

★ The AMF provides connectivity towards the Access Network so the AMF provides the *Namf_Communication* service to allow signalling towards the Base Station and the UE. The *N1N2MessageTransfer* operation can be used to request the AMF to forward a message to the Base Station or to the UE. For example, the Short Message Service Function (SMSF) can use this service operation to forward an SMS over Non-Access Stratum (NAS) signalling towards the UE. This is initiated by the SMSF using an HTTP POST method to send an *N1N2MessageTransfer* message to the AMF. This message encapsulates the SMS to be forwarded to the UE

- If a UE is in Idle Mode then the *Namf_MT* service can be used to request the AMF to page the UE and consequently bring the UE into Connected Mode. For example, the SMSF can use the *EnableUEReachability* operation in advance of using the *N1N2MessageTransfer* operation if sending an SMS to a UE which is in Idle Mode
- The *Namf_EventExposure* service allows Network Functions to subscribe to notifications of specific events. For example, the Unified Data Management (UDM) can use the *Subscribe* operation to request the AMF to provide notifications regarding the location of the UE. Similarly, the AMF can provide notifications regarding the registration state, connectivity state or reachability of a UE
- The *Namf_Location* service allows Network Functions to initiate positioning requests. A Gateway Mobile Location Centre (GMLC) can use the *ProvidePositioningInfo* operation to initiate a request for the GPS coordinates of a UE
- Table 4 provides a list of the 3GPP specifications which describe the services offered by the main Network Functions

AMF	SMF	UDM	UDR	PCF	AUSF	NRF	NSSF	NEF
TS 29.518	TS 29.502 TS 29.508	TS 29.503	TS 29.504	TS 29.507 TS 29.512 TS 29.514	TS 29.509	TS 29.510	TS 29.531	TS 29.522

Table 4 – 3GPP specifications which describe the services offered by Network Functions

- The Service Based architecture represents a move towards a cloud implementation of the Core Network. Legacy Core Networks have been deployed using separate hardware for each Network Element. Newer Core Networks have been deployed using virtualised Network Elements to allow multiple Network Elements to operate using a shared hardware platform. A virtualised solution can provide fault tolerance by allowing the software to switch between hardware platforms in case of a failure. A cloud implementation is expected to increase flexibility, agility, efficiency and scalability relative to previous solutions. Flexibility is particularly important for 5G due to the wide range of target applications. Agility allows new services to be introduced with minimal effort and a short time-to-market
- The 5G Core Network is also designed to support connectionless services, i.e. services which allow data transfer without a connection being established across the 5G network. Connectionless communication is a requirement for massive Machine Type Communication (mMTC) to support the very high density of devices
- 3GPP References: TS 23.501, TS 23.502, TS 29.500

1.4.3 NETWORK FUNCTIONS

1.4.3.1 ACCESS & MOBILITY MANAGEMENT FUNCTION (AMF)

- The Access and Mobility Management Function (AMF) is a control plane function within the 5G Core Network. The primary responsibilities of the AMF include:
  - Registration Management
  - Reachability Management
  - Connection Management
  - Mobility Management
- Registration Management allows a UE to register and deregister with the 5G System. A UE must complete the registration procedure to receive authorisation to use 5G services. Registration moves the UE from the RM-Deregistered state to the RM-Registered state. Registration Management is described in section 1.9. Registration creates a UE Context within the network. A UE Context is a set of parameters which identify and characterise the UE. Some of the parameters belonging to a UE Context are presented in Figure 9. The AMF interacts with other Network Functions during the registration procedure. For example, the AMF forwards the Permanent Equipment Identifier (PEI) to the SMF, UDM and PCF
- Connection Management is used to establish and release the control plane signalling connection between the UE and the AMF, i.e. across the N1 interface. Establishing an N1 signalling connection moves the UE from CM-Idle to CM-Connected. Connection Management is described in section 1.10. The N1 signalling connection allows Non Access Stratum (NAS) messages to be exchanged between the UE and AMF. The NAS signalling protocol is specified by 3GPP within TS 24.501. The AMF is the termination point within the Core Network for the integrity protection and ciphering applied to NAS messages. The termination point for NAS signalling procedures can be either the AMF or the SMF:
  - the Registration, Authentication, Service Request and Identity Request procedures are examples of NAS signalling procedures managed by the AMF. Messages belonging to these procedures are exchanged between the UE and AMF
  - the PDU Session Establishment, Modification and Release procedures are examples of NAS signalling procedures managed by the SMF. The AMF acts as a transparent router for these procedures and forwards messages between the UE and SMF

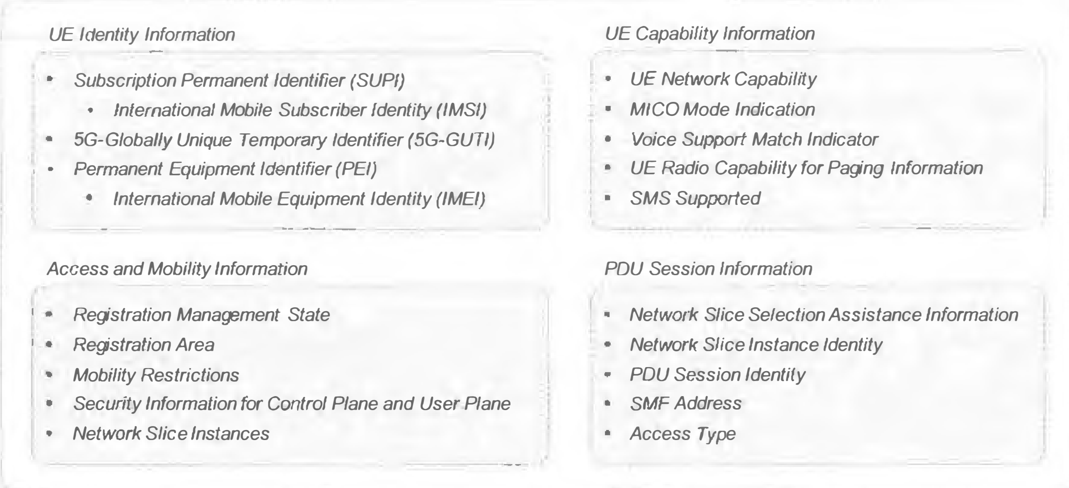


Figure 9 – Example content of UE Context stored by AMF

★ Reachability Management is used to ensure that a UE is always reachable, i.e. it is possible to page the UE when there is a requirement to establish a mobile terminated connection. Paging a UE which is in the CM-Idle state triggers the UE to initiate the NAS Service Request procedure and subsequently establish an N1 signalling connection before moving into the CM-Connected state. The AMF supports Reachability Management by storing location information as part of the UE context. The UE context includes the registration area (a Tracking Area, or a list of Tracking Areas) within which the UE is registered. The UE context can also include more specific information regarding the UE location, i.e. recommended cells and nodes for paging

★ UE which are configured to use Mobile Initiated Connection Only (MICO) are categorised as being unreachable. These UE cannot be paged and are only able to establish mobile originated connections from the CM-Idle state. The MICO mode of operation is described in section 1.17.

★ Mobility Management is used to maintain knowledge of the UE's location within the network. The UE is required to complete periodic registration updates after it has completed initial registration. These periodic updates act as keep-alives to verify that the UE remains on the system, and has not moved out of coverage or become unavailable due to any other reason, e.g. the battery has drained. The UE is also required to complete updates due to mobility. These updates are triggered if the UE moves outside the current registration area, i.e. outside the Tracking Area or list of Tracking Areas within which the UE is currently registered

★ The AMF is also responsible for handling Next Generation Application Protocol (NGAP) signalling which is transferred between the AMF and a Next Generation RAN node, i.e. between an AMF and a Base Station. NGAP is specified within 3GPP TS 38.413 and is equivalent to S1AP which is used in 4G networks (between the MME and Base Station). Categories of NGAP signalling procedures include:

- o PDU Session Management
- o UE Context Management
- o UE Mobility Management
- o Paging Procedures
- o Transport of NAS Messages
- o Interface Management
- o Configuration Transfer
- o Warning Message Transmission

★ PDU Session Management procedures are used to setup, modify and release resources at the Base Station and UE. The SMF is responsible for PDU Session Management so these procedures are completed after the AMF has been instructed by the SMF

★ UE Mobility Management procedures are used to support handover procedures. Xn based handover procedures use the NGAP Path Switch signalling procedure (the Xn inter-connects a pair of 5G BTS similar to the X2 interface used by 4G). N2 based handover procedures use the NGAP Handover Required, Handover Request, Handover Command and Handover Notify signalling procedures

★ NGAP is used to transfer NAS messages between the BTS and AMF, while a Signalling Radio Bearer (SRB) is used to transfer NAS messages between the UE and BTS. The combination of these hops provides the end-to-end transfer of NAS messages across the N1 interface between the UE and AMF. The combination of NAS and NGAP signalling is illustrated in Figure 10. This figure also illustrates a subset of NAS messages being transferred to and from the SMF

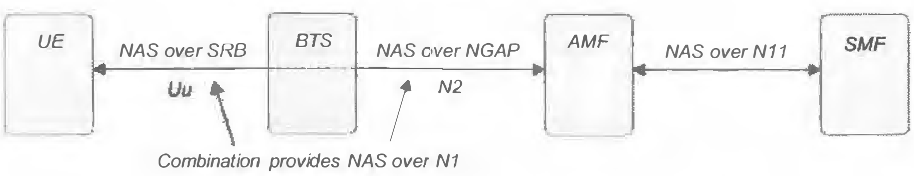


Figure 10 – Summary of NAS and NGAP Signalling Paths

* Interface Management procedures are used to setup the NG connection between the Base Station and AMF. Both the N1 and N2 interfaces use the NG connection between the Base Station and AMF. Interface Management procedures also allow both RAN and AMF configuration updates to be provided. For example, the RAN configuration update allows the Base Station to inform the AMF of any changes to the supported PLMN or Tracking Areas
* Configuration Transfer procedures allow the Base Station and AMF to exchange information related to Self Optimising Networks (SON). For example, these procedures can be used to support Automatic Neighbour Relations (ANR). The end-to-end transfer of information could be between a pair of Base Stations but the information has to be sent via the AMF if an Xn interface does not exist between the Base Stations
* The AMF is responsible for allocating a 5G Globally Unique Temporary Identifier (5G-GUTI), which is a concatenation of the Globally Unique AMF Identifier (GUAMI) and the 5G Temporary Mobile Subscription Identifier (5G-TMSI). The 5G-GUTI provides greater privacy than the IMSI because it is a temporary identity which the AMF can re-assign at any time. The 5G-GUTI is described in section 18.4. 3GPP has specified mapping rules between the 5G-GUTI and the 4G-GUTI. This includes a mapping between the AMF identity and the MME identity. The 5G-TMSI is mapped onto the 4G M-TMSI
* The AMF is responsible for selecting an appropriate Authentication Server Function (AUSF) during the registration procedure. The AUSF allows the UE to authenticate itself with the 5G Core Network, i.e. verify that the subscriber is genuine and authorised to access the network. The AMF may be configured to use a specific AUSF or the AMF may use the Network Function Repository Function (NRF) to discover suitable AUSF within the 5G Core Network
* The AMF is responsible for selecting an appropriate Unified Data Management (UDM) function during the registration procedure. The UDM manages the user's subscription information. The AMF may be configured to use a specific UDM or the AMF may use the Network Function Repository Function (NRF) to discover a UDM which manages the user's subscription
* The AMF is responsible for selecting an appropriate Policy Control Function (PCF) for the UE during the registration procedure. The PCF provides the AMF with an 'Access and Mobility Policy' for the UE. This may include a specification of allowed or forbidden Tracking Areas. The AMF may be configured to use a specific PCF or the AMF may use the Network Function Repository Function (NRF) to discover a PCF which can provide the relevant UE information
* The AMF is responsible for selecting an appropriate Session Management Function (SMF) during PDU Session establishment. The AMF can apply a range of criteria during the selection procedure:
    - Data Network Name (DNN): A DNN is the 5G equivalent of a 4G Access Point Name (APN). It refers to the data network to which the PDU Session provides connectivity. For example, there may be a DNN for connectivity towards the public internet. A specific SMF may be configured to support a specific set of DNN
    - Subscription information: the AMF retrieves subscription information from the Unified Data Management (UDM) function during the Registration procedure. This can include information regarding the set of subscribed DNN
    - Single Network Slice Selection Assistance Information (S-NSSAI): An S-NSSAI identifies a Network Slice. It comprises a Slice/Service Type (SST) and a Slice Differentiator (SD). The SST defines the expected network behaviour, e.g. value 1 refers to enhanced Mobile Broadband (eMBB), and value 2 refers to Ultra Reliable Low Latency Communication (URLLC). The SD allows differentiation of services belonging to the same SST. Network Slicing is described in section 1.15
* The AMF provides support for the Short Message Service (SMS). Mobile terminated SMS are received from the SMS Function (SMSF) and are packaged within a NAS message before being transferred to the UE. A Signalling Radio Bearer (SRB) is used to transfer the NAS message across the air-interface. The AMF receives mobile originated SMS within uplink NAS messages and forwards them to the SMSF. The SMSF is an optional Network Function
* 3GPP References: TS 23.501, TS 23,502, TS 24.501, TS 38.413

1.4.3.2 SESSION MANAGEMENT FUNCTION (SMF)

* The Session Management Function (SMF) is a control plane function within the 5G Core Network. The primary responsibilities of the SMF include:
    - PDU Session Management
    - IP Address Allocation
    - GTP-U Tunnel Management
    - Downlink Notification Management
* PDU Session Management includes the setup, modification and release of PDU Sessions. A PDU Session is the 5G equivalent of an EPS Bearer in 4G. It represents a connection between the UE and the exit of a User Plane Function (UPF) towards a specific Data Network (DN). The exit is identified by its Data Network Name (DNN). Figure 11 illustrates the concept of a PDU session and the DNN providing connectivity to a specific Data Network

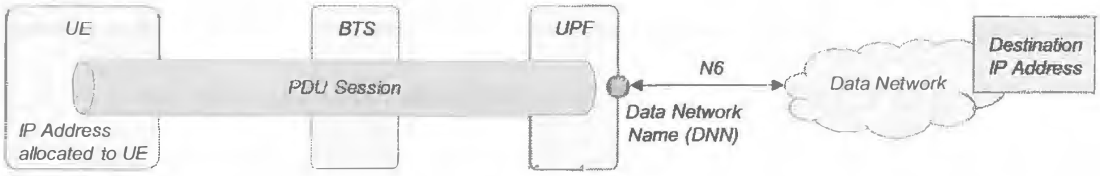


Figure 11 – Concept of a PDU Session

- PDU Session Management requires the SMF to complete signalling procedures towards the UE, Base Station and User Plane Function (UPF). The SMF can signal directly with the UPF but requires the AMF to support signalling towards the UE and Base Station. The SMF uses Non Access Stratum (NAS) signalling messages to communicate with the UE. Both the Base Station and AMF act as transparent routers for these messages which are relayed between the SMF and UE. The UE can initiate the setup of a PDU Session by sending a NAS: *PDU Session Establishment Request*. Assuming a successful setup, the SMF responds with a NAS: *PDU Session Establishment Accept* message. Signalling towards the Base Station requires the AMF to transfer messages using the Next Generation Application Protocol (NGAP). The AMF and Base Station are responsible for managing NGAP signalling procedures but content is relayed to and from the SMF when those procedures relate to Session Management

- IP Address Allocation is dependent upon the type of PDU Session. A PDU Session can be setup to transfer either IPv4, IPv6, Ethernet or Unstructured data types. The UE can request a specific data type within the NAS: *PDU Session Establishment Request* message. The allocated data type is confirmed within the NAS: *PDU Session Establishment Accept* message. IP Address allocation is applicable to PDU Sessions which transfer IPv4 or IPv6 packets. The IP Address defines the network layer source address for uplink packets and destination address for downlink packets. PDU Session data types are described further in section 1.13. The 3GPP specifications also allow the UE to request the use of Dynamic Host Configuration Protocol (DHCP) to obtain an IP Address. In this case, the SMF does not allocate an address and instead, the UE uses the connectivity provided by the PDU Session to obtain an IP Address from a DHCP server

- GTP-U Tunnel Management refers to the management of the user plane GTP-U tunnel between the Base Station and UPF. GTP-U tunnels are used to transfer user plane data between the Base Station and UPF. A GTP-U tunnel operates by adding a set of IP/UDP/GTP-U headers to the user plane data packets. The IP layer is used to route the packets between the Base Station and UPF. The UDP layer is used to provide connectionless data transfer and to specify the port number for the GTP-U layer. The GTP-U layer specifies the Tunnel Endpoint Identifier (TEID) which links the user plane packet to a specific PDU Session. The general concept of a GTP-U tunnel is illustrated in Figure 12. The UPF allocates a Tunnel Endpoint Identifier (TEID) for uplink data transfer. The Base Station addresses all uplink data belonging to the relevant PDU Session towards that TEID. The TEID is signalled from the UPF to the Base Station via the SMF and AMF. Similarly, the Base Station allocates a TEID for downlink data transfer. This TEID is signalled to the UPF via the AMF and SMF

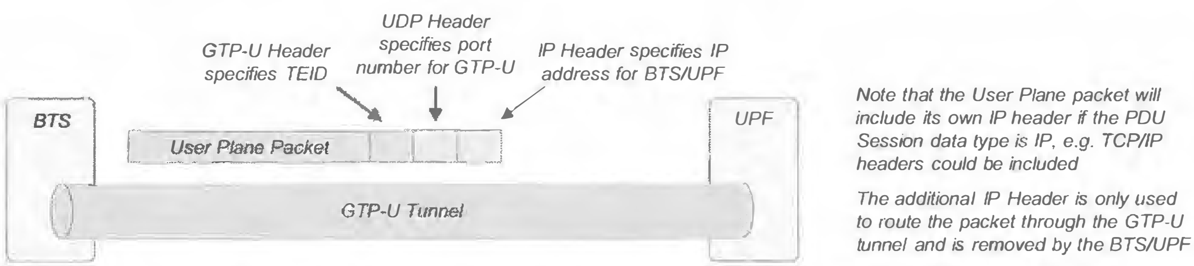


Figure 12 – Concept of a GTP-U Tunnel between the Base Station and User Plane Function (UPF)

- Downlink Notification Management refers to the initiation of the paging procedure. A UE needs to be paged if downlink data arrives at the UPF after the UE has been released to RRC Idle mode (CM-IDLE state). The UPF recognises that the UE does not have a GTP-U tunnel towards the Base Station. This triggers the UPF to inform the SMF that downlink data has arrived for the UE. The SMF subsequently informs the AMF from where the Network Triggered Service Request procedure is initiated, i.e. the UE is paged. This triggers the UE to establish an RRC Connection and send a NAS: *Service Request* message to the SMF

- The SMF is responsible for selecting an appropriate UPF during the setup of a PDU Session. The selection algorithm can account for UPF load, geographic location, Network Slicing, supported features and PDU Session Type (IPv4, IPv6, Ethernet, Unstructured). Load information can help the SMF to balance network load across multiple UPF. The geographic location can be important for low latency applications which require a short transport connection to the Data Network. It may be necessary to account for Network Slicing if different UPF are configured to support different Slice/Service Types (SST), e.g. one UPF may be configured to support enhanced Mobile Broadband (eMBB), while another UPF may be configured to support Ultra Reliable Low Latency Communication (URLLC)

- The SMF is responsible for selecting an appropriate Policy Control Function (PCF) during the setup of a PDU Session, i.e. it selects the PCF to provide the policy for a specific PDU Session (the AMF selects the PCF during a UE registration procedure to obtain the 'Access and Mobility Policy', e.g. set of forbidden Tracking Areas). The PCF associated with a PDU Session provides the policy for the Quality of Service (QoS), e.g. the authorised 5QI, Allocation and Retention Policy (ARP) and Session Aggregate Maximum Bit Rate (Session-AMBR). The selection algorithm can account for the PCF already selected by the AMF, the Data Network Name (DNN) used by the PDU Session, or information configured within the SMF, e.g. an SMF may be configured to use a specific PCF

- The SMF retrieves subscription information from the Unified Data Management (UDM) function during the setup of a PDU Session. The information retrieved can include authorised PDU type (IPv4, IPv6, Ethernet, Unstructured), default 5QI, default Allocation and Retention Priority (ARP), Session-Aggregate Maximum Bit Rate (Session-AMBR) and authorised Session and Service Continuity (SSC). SSC refers to the preservation of connectivity and IP address allocation throughout the lifetime of a PDU Session, e.g. ensuring that service connectivity is maintained when changing the UPF which provides the Data Network connection

- The SMF provides support for interfacing with the network charging system. This could be either an Online Charging System (OCS) or an Offline Charging System (OFCS). An Online Charging System involves the authorisation of data transfer before it is transferred, e.g. for a prepaid mobile broadband subscription. An Offline Charging System allows data to be transferred and billed at a later time. Data utilisation measurements are completed by the UPF. The SMF is able to configure those measurements and also collect the resultant reports from the UPF. The SMF then provides the reports to the charging system

1.4.3.3 USER PLANE FUNCTION (UPF)

- The User Plane Function (UPF) is responsible for routing and forwarding user plane packets between the Base Station and the external Data Network

- Uplink packets arriving from the Base Station use a GTP-U tunnel to reach the UPF. The UPF has to remove the packet headers belonging to the GTP-U tunnel before forwarding the packets into the external Data Network. The UPF may provide connectivity towards multiple Data Networks so the UPF has to ensure that packets are forwarded towards the correct network. Each GTP-U tunnel belongs to a specific PDU Session and each PDU Session is setup towards a specific Data Network Name (DNN). The DNN identifies the external network to which user plane packets should be forwarded. Thus, the UPF has to keep a record of the mapping between GTP-U tunnel, PDU Session and DNN

- Downlink packets arriving from the external Data Network must be mapped onto specific QoS Flows belonging to specific PDU Sessions before forwarding towards the appropriate Base Station. A QoS Flow corresponds to a stream of packets which have equal QoS. A PDU Session can have multiple QoS Flows. Section 1.14 describes the concept of QoS Flows in greater detail. The UPF uses a set of Service Data Flow (SDF) Templates to map each downlink packet onto a specific QoS Flow. SDF Templates provide a set of rules for this mapping process. For example, the following parameter combination {source IP address 'X'; destination IP address 'Y'; source port number 'J'; destination port number 'K'} should be mapped onto QoS Flow 'A' belonging to PDU Session 1. The concept of mapping packets onto QoS Flows using SDF Templates is illustrated in Figure 13

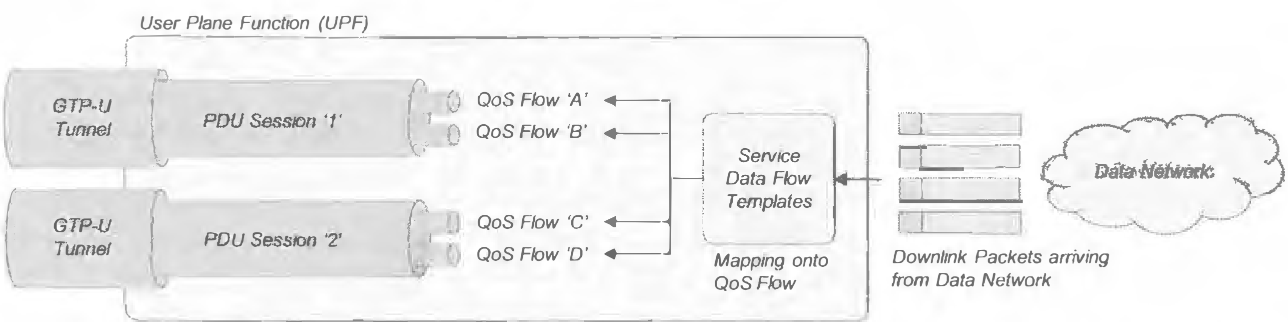


Figure 13 – Concept of mapping downlink data packets onto QoS Flows at the User Plane Function (UPF)

- After identifying the appropriate QoS Flow, the UPF forwards the packets across the GTP-U Tunnel belonging to the parent PDU Session. There is one GTP-U Tunnel per PDU Session rather than one GTP-U Tunnel per QoS Flow. The UPF 'marks' the GTP-U header to indicate the QoS Flow associated with each packet, i.e. the QoS Flow Identity (QFI) is included within the GTP-U header

- The UPF receives the set of SDF Templates from the Session Management Function (SMF) during the setup of the PDU Session. The SMF generates them from information provided by the Policy Control Function (PCF)

- The UPF also verifies that the SDAP layer within the 5G BTS is applying the correct mapping between uplink data packets and QoS Flow, i.e. the UPF inspects the uplink packets to confirm that the correct mapping has been applied according to the set of SDF Templates

- The UPF can prioritise the packets being transferred across the transport network by 'marking' them within the IP header belonging to the GTP-U tunnel, i.e. the outer IP header added by the UPF rather than the inner IP header which belongs to the end-user application (assuming a PDU Session has been setup to transfer IP packets). The Differentiated Services Code Point (DSCP) field within the IP header can be used for this purpose

- The UPF is responsible for notifying the SMF when downlink data arrives for a UE which is in the CM-IDLE state, i.e. the UE needs to be paged before the data can be forwarded across the N3 interface towards the Base Station. The downlink data is buffered by the UPF while waiting for the UE to establish its connection and move into the CM-CONNECTED state

★ The UPF is responsible for enforcing the Session Aggregate Maximum Bit Rate (Session-AMBR) which defines the maximum permitted bit rate summed across all non-GBR QoS Flows belonging to a specific PDU Session. The UPF receives the Session-AMBR from the SMF during the setup of the PDU Session. The SMF obtains it from the Policy Control Function (PCF)

★ The UPF is responsible for tracking the volume of data transferred by each PDU Session and reporting this information to the SMF. The SMF provides these reports to the charging system for billing purposes

★ The UPF acts as an anchor point for mobility procedures which do not involve a change of UPF. In general, the majority of Xn based handovers and N2 based handovers will not require the UPF to be changed. In these cases, the data path is simply switched from the source Base Station to the target Base Station

★ Multiple UPF can be used to support 'multi-homed' PDU Sessions. A multi-homed PDU Session is one which has more than a single anchor UPF providing Data Network connectivity. For example, a PDU Session can have a single 'branching point' UPF providing connectivity towards the Base Station, combined with two 'anchor' UPF providing a pair of interfaces towards the external Data Network. This type of architecture is shown in Figure 14. Multi-homed connections can be used to provide redundancy and increase system reliability

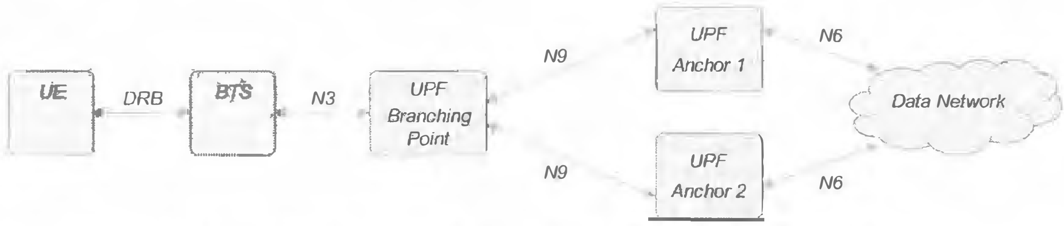


Figure 14 – Multi-homed PDU Session using multiple User Plane Functions (UPF)

1.4.3.4 AUTHENTICATION SERVER FUNCTION (AUSF)

★ The Authentication Server Function (AUSF) is a control plane function within the 5G Core Network. Its primary function is to support both subscriber and network authentication, i.e. the network verifies that the UE is a genuine authorised subscriber, while the UE verifies that the network is genuine

★ The AMF can call upon the AUSF to support authentication during the UE Registration procedure. Similarly, the AMF can call upon the AUSF to support authentication during any other procedure which involves establishing a signalling connection with the UE, e.g. the Service Request procedure

★ The Authentication procedure is completed between the UE and the AUSF. However, the AUSF cannot communicate directly with the UE. The AMF is used to relay information between the UE and AUSF. The AMF uses Non Access Stratum (NAS) signalling towards the UE. Authentication is categorised as a Mobility Management NAS procedure

★ The 5G System supports the following authentication methods:

  o EAP-AKA', which is a revised version of EAP-AKA. EAP is an acronym for 'Extensible Authentication Protocol', whereas AKA is an acronym for 'Authentication and Key Agreement'. EAP-AKA' is specified within IETF RFC 5448

  o 5G AKA, which is a revised version of EPS AKA, and is specified within 3GPP TS 33.401

★ In addition to authenticating the UE, these procedures generate keys for subsequent security procedures

★ The AUSF uses the Unified Data Management (UDM) function during the authentication procedure (subscription information is managed by the UDM). The AUSF may be configured to use a specific UDM, or it may use the Network Function Repository Function (NRF) to discover an appropriate UDM

1.4.3.5 UNIFIED DATA MANAGEMENT (UDM)

★ The Unified Data Management (UDM) is a control plane function within the 5G Core Network. It is similar to the Home Subscriber Server (HSS) within the 4G Evolved Packet Core (EPC)

★ The UDM manages subscriber data and may also store subscriber data. The subscriber data can be stored locally within a UDM, or it can be stored within a Unified Data Repository (UDR). The latter solution allows multiple UDM to access the subscriber data from a central storage location

- The Subscription Permanent Identifier (SUPI) is managed by the UDM. 3GPP devices use their International Mobile Subscriber Identity (IMSI) as the SUPI. Non-3GPP devices can use their Network Access Identifier (NAI) as the SUPI
- The UDM interacts with the AUSF during the authentication procedure. The AUSF provides the UDM with either the SUPI or the Subscription Concealed Identifier (SUCI). The SUCI is a privacy preserving identifier which contains the SUPI. If the UDM receives a SUCI then it extracts the SUPI before proceeding. The UDM uses the SUPI to select an authentication method based upon the end-user's subscription profile. The UDM then generates an authentication vector and sends this vector to the AUSF
- The UDM interacts with the AMF during the Registration procedure. The UDM stores (or uses a UDR to store) the AMF identity for the UE which is completing the Registration procedure. Storing the AMF identity allows the UDM to support UE Reachability procedures. The UDM provides the AMF with Access and Mobility subscription data and also subscription data to support the selection of an SMF
- The UDM interacts with the SMF during the PDU Session Establishment procedure. The UDM stores (or uses a UDR to store) the PDU Session Identity, the SUPI, the SMF Identity, the SMF Address and the Data Network Name (DNN). The UDM provides the SMF with subscription information which can include authorised PDU type (IPv4, IPv6, Ethernet, Unstructured), default 5QI, default Allocation and Retention Priority (ARP), Session-Aggregate Maximum Bit Rate (Session-AMBR) and authorised Session and Service Continuity (SSC)
- The UDM can provide updates to the AMF and SMF if subscriber data is changed. The AMF can be updated if the Access and Mobility subscription data is changed, whereas the SMF can be updated if the Session Management subscription data is changed
- The UDM is required when sending SMS over Non Access Stratum (NAS) signalling messages. The SMS Function (SMSF) selects and registers with a UDM during the UE registration procedure. The UDM stores (or uses a UDR to store) the SMSF identity for the UE which is completing the Registration procedure. The UDM provides the SMSF with relevant subscription information. The SMS Gateway Mobile Switching Center (SMS-GMSC) contacts the UDM when sending a mobile terminating SMS. The UDM provides the SMS-GMSC with the identity of the relevant SMSF to which the SMS can be forwarded

1.4.3.6 UNIFIED DATA REPOSITORY (UDR)

- The Unified Data Repository (UDR) is used to store data belonging to the Unified Data Management (UDM) Network Function, Policy Control Function (PCF) and Network Exposure Function (NEF), i.e. the UDR is able to store:
  - subscription data which can be retrieved by a UDM
  - policy data which can be retrieved by a PCF
  - structured data which can be retrieved and exposed by an NEF
- Structured data refers to data which has a known and organised format. Within the context of the NEF, it refers to records of events which have occurred. For example, the AMF may detect a loss of connectivity towards a specific UE. This event can be stored by the UDR and subsequently retrieved and exposed (made available) to other Network Functions by the NEF
- Figure 15 illustrates the general connection of a UDR to an NEF, PCF and UDM. Other Network Functions use a UDSF rather than a UDR to store their data

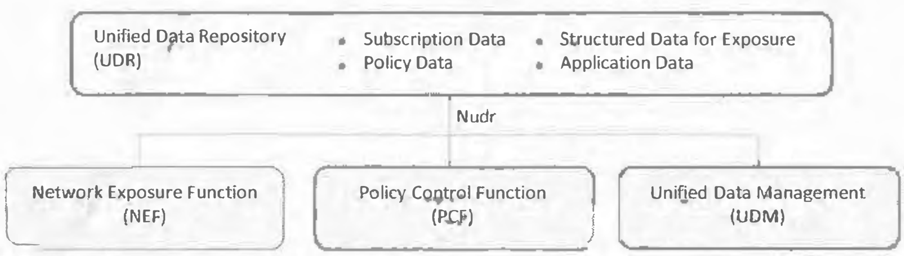


Figure 15 – Unified Data Repository (UDR) connected to NEF, PCF and UDM

- A UDR can be implemented to be dedicated to a specific Network Function rather than shared by the UDM, PCF and NEF. For example, a UDM implementation may include a UDR which only serves that UDM. Similarly, a PCF implementation may include a UDR which only serves that PCF

1.4.3.7 UNSTRUCTURED DATA STORAGE FUNCTION (UDSF)

★ The Unstructured Data Storage Function (UDSF) is used to store data belonging to other Network Functions. For example, an AMF may use a UDSF to store the UE contexts that are being managed at that point in time. Network Functions may have their own UDSF or they may share a common UDSF. Figure 16 illustrates the general connection of a UDSF to another Network Function

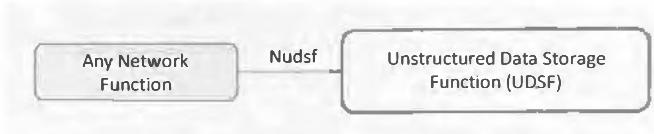


Figure 16 – Unstructured Data Storage Function (UDSF) connected to other Network Functions

★ Storing data within a UDSF at a central location helps to allow Network Functions to operate in a 'stateless' manner. Stateless operation means that Network Functions do not rely upon making transitions between states. Instead, every transaction is treated as a new transaction. If a network includes multiple instances of a specific Network Function, then stateless operation allows one instance of the Network Function to take over from another without needing to transfer any information regarding the current 'state'

★ Figure 17 illustrates an example of stateless operation when an AMF experiences outage. This example assumes a first AMF which is managing UE 'a' and 'b', and a second AMF which is managing UE 'c'. Both AMF share a common UDSF so both have access to all UE context data. If AMF 1 experiences outage then AMF 2 can immediately access the data for UE 'a' and 'b'. This prevents UE context data being lost when AMF 1 experiences outage and allows a relatively seamless continuation of services

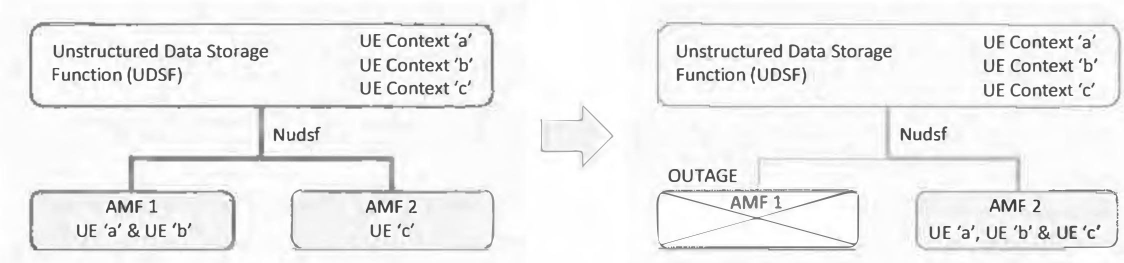


Figure 17 – Example of 'Stateless' behaviour during AMF outage

1.4.3.8 POLICY CONTROL FUNCTION (PCF)

★ The Policy Control Function (PCF) is a control plane function within the 5G Core Network. It is responsible for providing polices associated with mobility management and policies associated with session management. Mobility management policies can impact UE mobility in both RRC Idle and RRC Connected modes. Session Management polices impact the Quality of Service (QoS) offered by a PDU Session. Session Management polices also offer a mechanism to manage subscriber spending limits

★ The general pattern of interaction between the AMF, UDM and PCF is illustrated in Figure 18. The AMF obtains subscription information from the UDM. The UDM may store this information locally, or may need to retrieve it from a UDR. The AMF subsequently provides this subscription information to the PCF. The PCF stores the subscription information, either locally or using a UDR. The PCF may then decide to modify the subscribed policy information according to operator policies. For example, the subscribed policy from the UDM may not include any access restrictions. The operator policy configured within the PCF may specify that the UE is not permitted to access a specific TAC during business hours. In that case, the PCF would modify the subscribed policy during business hours and would provide the modified policy to the AMF

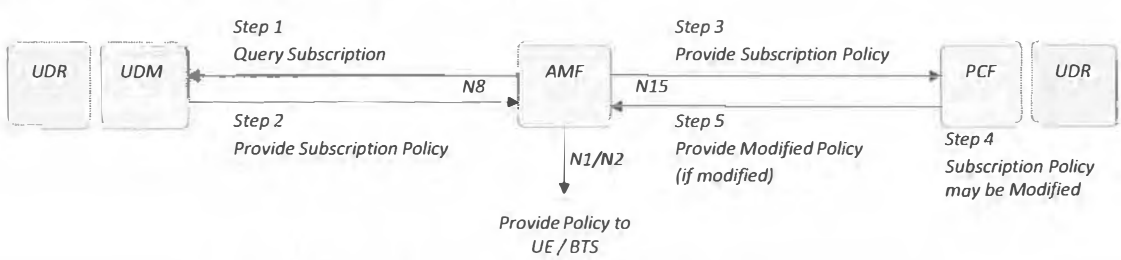


Figure 18 – General pattern of interaction between AMF, UDM and PCF

★ The general pattern illustrated in Figure 18 is applicable to the 'Access and Mobility Policy' which the AMF retrieves from the UDM during the UE Registration procedure. The 'Access and Mobility Policy' allows the definition of service area restrictions. The UE is responsible for applying restrictions in the CM-IDLE/RRC Idle, and CM-CONNECTED/RRC Inactive states. In this case, the network provides the UE with the relevant service area restrictions, e.g. a list of forbidden Tracking Areas. Service area restrictions can be signalled to the UE using a NAS: *Registration Accept* message. The network is responsible for applying restrictions when the UE is in the CM-CONNECTED/RRC Connected state. In this case, the network can apply Handover Restriction Lists to prevent specific mobility paths

★ The general pattern illustrated in Figure 18 is also applicable to the 'RAT/Frequency Selection Priority' (RFSP). The RFSP is an index which is provided to the Base Station and is then used to select specific Radio Resource Management (RRM) strategies. For example, the RFSP can be used to determine the set of cell reselection priorities provided to a UE. Alternatively, it may be used to move RRC Connected mode UE to a specific network layer. Similar to the 'Access and Mobility Policy', the AMF retrieves the subscribed RFSP from the UDM during the UE registration procedure. It is subsequently provided to the PCF where it can be modified according to an operator policy (RFSP is equivalent to the 'Subscriber Profile Identity' (SPID) used by 4G networks)

★ The PCF can define an Access Network Discovery and Selection policy. The UE uses this policy for selecting non-3GPP access networks, e.g. a Wireless Local Area Network (WLAN) based upon WiFi. The non-3GPP access network can be used to offload traffic from the 3GPP access network. The UE can be provided with a WLAN Selection Policy (WLANSP) which specifies the conditions under which the UE should search for a WLAN and the set of selection criteria, e.g. the maximum WLAN load and a list of Service Set Identifiers (SSID)

★ The PCF can define a UE Route Selection Policy (URSP) which provides the UE with rules for routing outgoing traffic. The rules can indicate that traffic should be routed to an existing PDU Session, or that a new PDU Session should be established, or that traffic should be offloaded to a non-3GPP access network. The URSP includes a set of traffic descriptors which allow the UE to recognise a specific type of traffic, e.g. destination IP address, destination port number and higher layer protocol identity. The URSP also includes a set of route selection descriptors to indicate where the traffic should be routed, e.g. a specific Data Network Name (DNN)

★ The PCF can receive information regarding the load of a Network Slice from a Network Data Analytics Function (NWDAF). The NWDAF is an optional Network Function which can collect Network Slice load statistics without having knowledge of specific subscribers. The PCF can use the load information when generating its policies

★ An Application Function (AF) may contact the PCF to request a time window for background data traffic. For example, if a large number of UE require a software update then the download of that software can be treated as background data traffic. The request includes the quantity of data to be transferred and the expected quantity of UE. The PCF can respond with a recommended time window, a corresponding charging rate and a maximum bit rate

★ The PCF interacts with the SMF during the establishment of a PDU Session. The SMF retrieves QoS parameters from the Unified Data Management (UDM) Network Function. These parameters include the default 5QI, the default Allocation and Retention Priority (ARP) and the subscribed Session Aggregate Maximum Bit Rate (Session-AMBR). The SMF subsequently provides this information to the PCF. The PCF applies its policy making decisions and generates an authorised 5QI, ARP and Session-AMBR. These authorised parameters are then returned to the SMF. The SMF forwards the parameters to the relevant Network Functions for enforcement, e.g. they are forwarded to the User Plane Function (UPF)

★ The PCF provides the SMF with Service Data Flow (SDF) Templates. The SMF forwards the SDF Templates to the User Plane Function (UPF) which uses them to map downlink packets arriving from the external Data Network onto specific QoS Flows belonging to specific PDU Sessions

★ The PCF provides the SMF with charging rules. These rules can be based upon data volume, time, or specific events. Charging rules can also indicate that charging should not be applied. The PCF helps to enforce subscriber spending limits using information provided by the Online Charging System (OCS). The OCS is connected to the PCF using the N28 Reference Point when using the Reference Point system architecture. The OCS tracks the current subscriber spending and provides spending limit reports to the PCF

★ The PCF can provide traffic steering rules to the SMF. The SMF forwards these rules to the User Plane Function (UPF) where they are used to select an appropriate N6 interface towards the external Data Network. For example, traffic steering can be used to direct traffic belonging to a specific PDU Session through a Parental Control path to help ensure that any content being accessed is appropriate

1.4.3.9 NETWORK SLICE SELECTION FUNCTION (NSSF)

★ The Network Slice Selection Function (NSSF) is a control plane function within the 5G Core Network. The NSSF is connected to the Access and Mobility Management Function (AMF) using the N22 Reference Point. The AMF can request the NSSF to complete Network Slice selection during the UE Registration procedure. The principles of Network Slicing are described in section 1.15

★ A single Network Slice is identified by its Single Network Slice Selection Assistance Information (S-NSSAI). A set of one or more Network Slices is identified by its Network Slice Selection Assistance Information (NSSAI)

- The AMF can provide the NSSF with the following information:
  - Requested NSSAI (generated by the UE from the Allowed and/or Configured NSSAI)
  - the mapping from Requested NSSAI for the serving PLMN to Configured NSSAI for the Home PLMN
  - Subscribed S-NSSAI, with an indication of any default S-NSSAI
  - identity of the UE's Home PLMN
  - identity of the UE's current Tracking Area
- The NSSF uses the information provided by the AMF to:
  - verify that the UE is subscribed to each of the S-NSSAI belonging to the Requested NSSAI
  - select one or more network slices to serve the UE and generate the Allowed NSSAI
  - identify a set of candidate AMF which can be used to serve the UE
- If the NSSF determines that the current serving AMF is unable to support the selected NSSAI then an AMF relocation is initiated, i.e. the NAS: *Registration Request* is re-routed to a new AMF
- The NSSF may also select the Network Function Repository Function (NRF) which can be used to select other Network Functions within the selected Network Slice

1.4.3.10 APPLICATION FUNCTION (AF)

- The Application Function (AF) is a control plane function within the 5G Core Network. The Application Function acts as an application server providing support for specific services. For example, there could be an Application Function for a video streaming service
- Application Functions with direct access to the 5G Core Network are connected to the PCF using the N5 Reference Point. If an Application Function does not have direct access to the 5G Core Network then it can use the Network Exposure Function (NEF) to provide connectivity. 3rd party Application Functions may be untrusted and be required to use the NEF
- Application Functions are able to influence User Plane Function (UPF) selection and also traffic routing towards specific Data Networks. Application Functions send requests to the PCF. The PCF can translate those requests into policies for specific PDU Sessions. The policies are subsequently provided to the Session Management Function (SMF)
- An Application Function (AF) and User Plane Function (UPF) may be co-sited with a BTS when deploying Multi-Access Edge Computing (MEC). MEC provides the benefit of keeping the service content physically close to the access network. This reduces latency and also helps to reduce the requirement for transport bandwidth. The MEC Application Function interacts with the PCF to request that the SMF selects the MEC UPF for the appropriate PDU sessions, and also that those PDU Sessions are routed towards the local content server
- Application Functions are already used within the 4G network architecture when using an IP Multimedia Subsystem (IMS) to support Voice over LTE (VoLTE). In that case, the Proxy - Call Session Control Function (P-CSCF) acts as an Application Function for the voice service

1.4.3.11 NETWORK EXPOSURE FUNCTION (NEF)

- The Network Exposure Function (NEF) is a control plane function within the 5G Core Network
- The NEF is able to provide information regarding the capability of Network Functions within the 5G System to external Network Functions, i.e. it is able to expose certain network capabilities. For example, the NEF is able to expose the network monitoring capability. This allows external Network Functions to subscribe to the reporting of specific events
- Network Functions within the 5G System are able to report specific events to the NEF. The NEF can then provide reports of those events to other Network Functions. Example events include:
  - loss of connectivity for a specific UE - reported by the AMF
  - location information for a specific UE - reported by the AMF
  - a change in the relationship between Subscription Permanent Identifier (SUPI) and Permanent Equipment Identifier (PEI), i.e. an end-user moves a USIM from one device to another - reported by the UDM
  - roaming status for a specific UE - reported by the UDM

★ Figure 19 illustrates the signalling used by a Network Function when subscribing to a specific event. The Network Function sends a subscribe request to the NEF. The NEF then has to subscribe to receive reports from the relevant Network Function. In this example, it is assumed that the UDM is providing the reports. Once the subscription procedure is complete, the UDM will start to send reports to the NEF which can then be forwarded towards the Network Functions which have subscribed

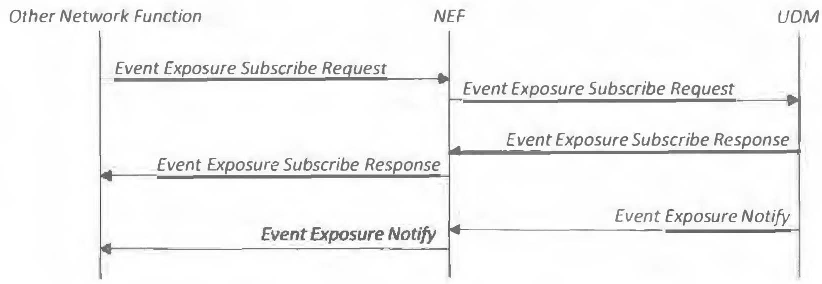


Figure 19 – Event exposure signalling using the NEF

★ The NEF supports event exposure towards Network Functions within the 5G System and also towards Network Functions located outside the 5G System, i.e. external Network Functions. For example, an external application could collect statistics regarding the location of devices. The NEF is responsible for masking network and user sensitive information when reporting to external Network Functions, e.g. UE identifiers are likely to be masked to protect privacy

★ The NEF is also able to expose the network provisioning capability. This allows external Network Functions to identify the information which can be provisioned for UE belonging to the 5G System. The NEF forwards any provisioning information onto the UDM where it is stored as part of the UE profile. The type of information which can be provisioned is the expected UE behaviour in terms of its movement and communication characteristics. The information can be accessed by other Network Functions within the 5G system to help configure mobility management or session management parameters

★ The NEF is also able to expose the policy/charging capability of the network. This allows external Network Functions to influence the QoS and charging policy for specific UE. For example, the priority and charging rate for a specific UE can be influenced

★ The NEF stores its data using a Unified Data Repository (UDR). The data is stored as structured data using a defined format

1.4.3.12 NETWORK FUNCTION REPOSITORY FUNCTION (NRF)

★ The Network Function Repository Function (NRF) is a control plane function within the 5G Core Network

★ The NRF allows Network Functions to register their services and then allows other Network Functions to discover those services, i.e. the general pattern is Network Function Service Registration followed by Network Function Service Discovery. These general procedures are illustrated in Figure 20

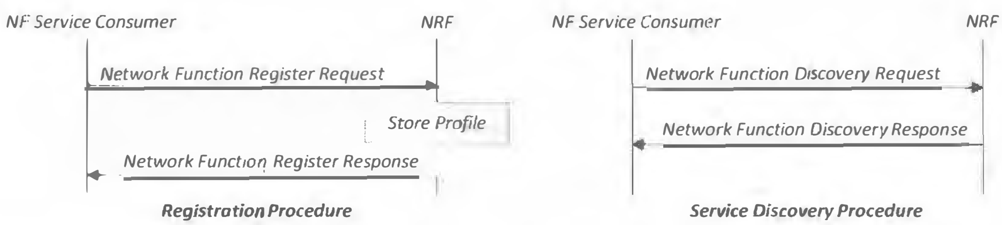


Figure 20 – Network Function Service Registration and Discovery procedures

★ Network Functions are expected to complete the Service Registration procedure when they first become active in the network. Network Functions provide a list of their services in addition to their Network Function type and contact details, i.e. an IP address or Fully Qualified Domain Name (FQDN)

★ Network Functions attempting the Service Discovery procedure provide the NRF with the name of the service being sought and the target Network Function type. The NRF is responsible for authorising requests. Some Network Functions may be configured such that they can only be discovered by other Network Functions belonging to the same Network Slice

★ 3GPP References: TS 23.501, TS 23,502

1.5 BASE STATION ARCHITECTURES

1.5.1 STANDALONE BASE STATION

★ A 5G Base Station is known as a gNode B (next 'generation' Node B). This is in contrast to a 4G Base Station which is known as an eNode B ('evolved' Node B), and a 3G base station which is known as a Node B

★ Figure 21 illustrates two Standalone (SA) Base Station architectures. These are known as 'option 2' and 'option 5'. This naming originates from the 3GPP study of 5G radio access technologies documented within 3GPP Technical Report 38.801. Both architectures have Base Stations which connect to the 5G Core Network

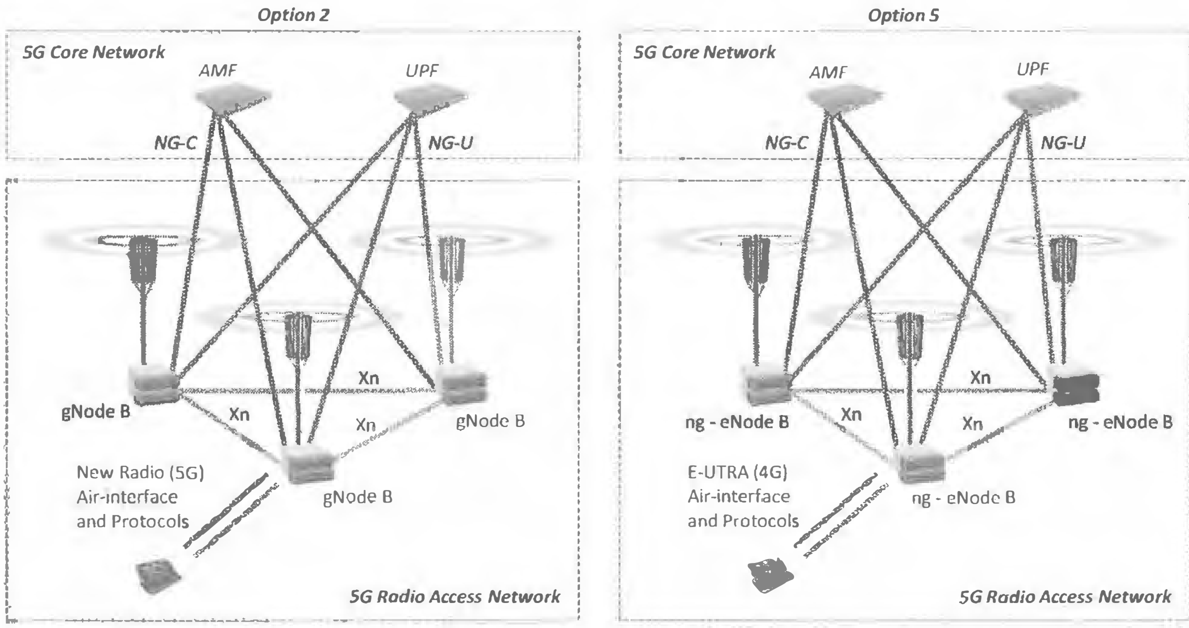


Figure 21 – Standalone Base Station Architectures

★ The 'option 2' architecture is based upon a gNode B connected to the 5G Core Network. The gNode B uses the New Radio (NR) air-interface and signalling protocols towards the end-user device. The gNode B connects to an Access and Mobility Management Function (AMF) for control plane signalling with the 5G Core Network. The gNode B connects to a User Plane Function (UPF) for the transfer of application data. The gNode B are inter-connected using the Xn interface

★ The gNode B can be connected to one or more AMF. The gNode B selects an initial AMF for each UE. Connectivity towards the AMF is based upon the Next Generation - Control Plane (NG-C) interface. This interface uses the Next Generation Application Protocol (NGAP) to transfer signalling messages between the gNode B and the AMF. NGAP messages are specified within 3GPP TS 38.413 and are transferred using SCTP over IP. The UE and AMF signal to one another using Non-Access Stratum (NAS) signalling messages. NGAP is used to transfer these messages between the gNode B and AMF. Some specific types of application data can be transferred using NAS signalling messages, e.g. content belonging to the Short Message Service (SMS). The NG-C interface corresponds to the N2 Reference Point

★ The gNode B can be connected to one or more UPF. The Session Management Function (SMF) selects a UPF for each PDU Session. Connectivity towards the UPF is based upon the Next Generation - User Plane (NG-U) interface. This interface uses the GPRS Tunnelling Protocol – User Plane (GTP-U) to transfer application data belonging to PDU Sessions. There is a single GTP-U tunnel for each PDU Session. User plane packets are transferred using GTP-U over UDP over IP. The NG-U interface corresponds to the N3 Reference Point

★ The 'option 5' architecture is based upon a next generation eNode B (ng-eNode B) connected to the 5G Core Network, i.e. an upgraded 4G Base Station is connected to the 5G Core Network. The ng-eNode B uses the E-UTRA (4G) air-interface and signalling protocols towards the end-user device. The ng-eNode B connects to the 5G Core Network using the NG-C and NG-U interfaces, i.e. the ng-eNode B is capable of supporting 5G core network signalling procedures and is also capable of transferring application data to and from a User Plane Function (UPF)

★ 3GPP References: TS 38.300, TR 38.801

1.5.2 NON-STANDALONE BASE STATION

★ Non-Standalone (NSA) Base Stations use Multi-RAT Dual Connectivity (MR-DC) to provide user plane throughput across both the 4G and 5G air-interfaces. This requires an eNode B and gNode B to operate together. The eNode B and gNode B can be connected using non-ideal backhaul, i.e. a realistic transport connection. The eNode B and gNode B have their own independent packet schedulers for allocating resources to the UE

★ Legacy 4G UE can continue to use the eNode B in the normal way, while newer UE with a 4G/5G capability can take advantage of the Multi-RAT Dual Connectivity. Non-Standalone Base Stations can be used to provide an evolution path from 4G to 5G. Figure 22 illustrates two configurations for Non-Standalone Base Stations when using the 4G Core Network. These configurations can be deployed prior to introducing the 5G Core Network

★ The configurations shown in Figure 22 are known as 'option 3' and 'option 3a' within the context of the 3GPP RAN architecture evaluation process (3GPP TR 38.801). In both cases, the 4G eNode B provides control plane connectivity towards the Core Network and acts as the Master Node (MN). The 5G gNode B has control plane connectivity across the X2 interface and acts as the Secondary Node (SN). These configurations require the gNode B to support the X2 interface rather than the Xn interface

★ Option 3 has the drawback of tunnelling all user plane data through the legacy eNode B. It is likely that the eNode B hardware has been dimensioned to support the air-interface throughputs offered by 4G. The hardware may not be capable of supporting the higher throughputs offered by 5G. The PDCP layer within the eNode B (Master Node) dynamically splits the downlink data between the eNode B and gNode B. The data allocated to the gNode B is forwarded across the X2 interface

★ Option 3a resolves the drawback associated with option 3 by providing user plane connectivity between the S-GW and gNode B. The eNode B remains the Master Node and is able to control the selection of the downlink data path from the S-GW, i.e. the eNode B can provide the MME with the IP address of the gNode B for some EPS Bearers, while it can provide the MME with its own IP address for other EPS Bearers (the MME forwards the destination IP address to the S-GW, so the S-GW can forward downlink data towards the appropriate Base Station). For example, an EPS Bearer transferring speech may be directed towards the eNode B, whereas an EPS Bearer transferring data may be directed towards the gNode B

★ Option 3a has the drawback of not supporting the transfer of application data across the X2 interface. The coverage provided by the gNode B may be smaller than the coverage provided by the eNode B (the gNode B may be using a higher operating band with higher air-interface attenuation). A UE may move out of the coverage of the gNode B making it necessary to switch all data transfer to the eNode B. This can be done using a Path Switch procedure initiated by the eNode B (the eNode B instructs the MME to request the S-GW to switch its downlink data path from the gNode B IP address to the eNode B IP address). However, the Path Switch procedure is relatively slow and is not a dynamic solution

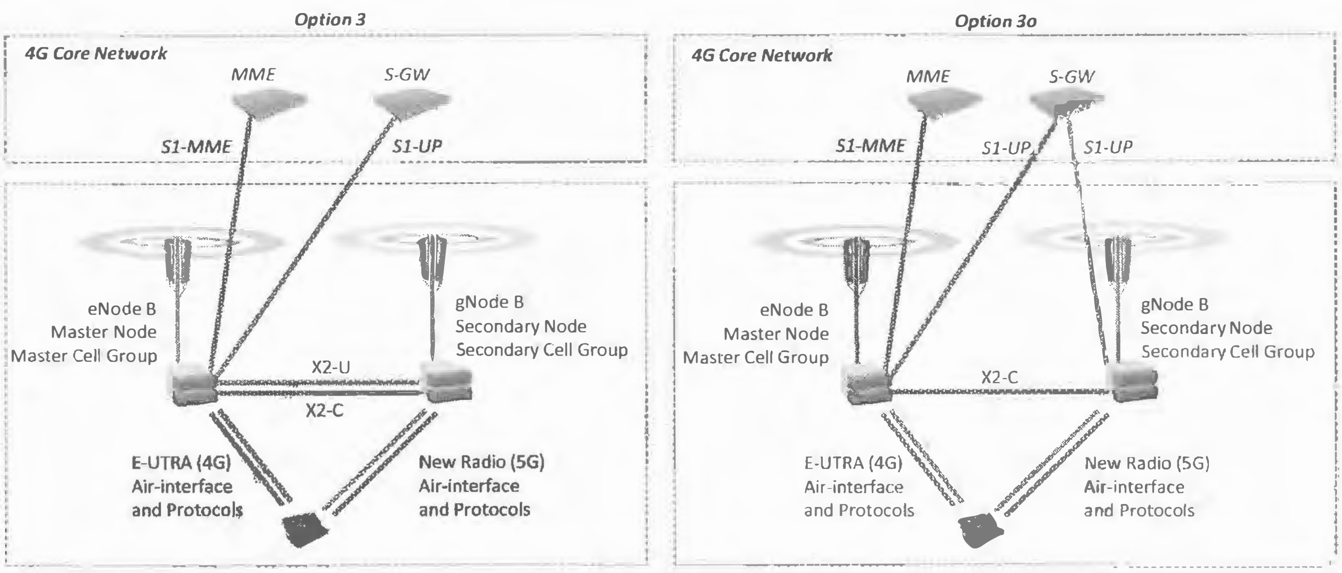


Figure 22 – Non-Standalone Base Station Architectures using the 4G Core Network (Options 3 and 3a)

★ A third Non-Standalone Base Station architecture has been developed to overcome the drawbacks associated with Options 3 and 3a. This architecture is illustrated in Figure 23 and is known as 'Option 3x'. In this case, the user plane paths are full meshed between the eNode B, gNode B and S-GW. The eNode B remains the Master Node and is able to control the selection of the downlink data path from the S-GW, i.e. the eNode B can provide the MME with the IP address of the gNode B for some EPS Bearers, while it can provide the MME with its own IP address for other EPS Bearers. If coverage from the gNode B becomes weak then the gNode B can dynamically forward data across the X2 interface towards the eNode B

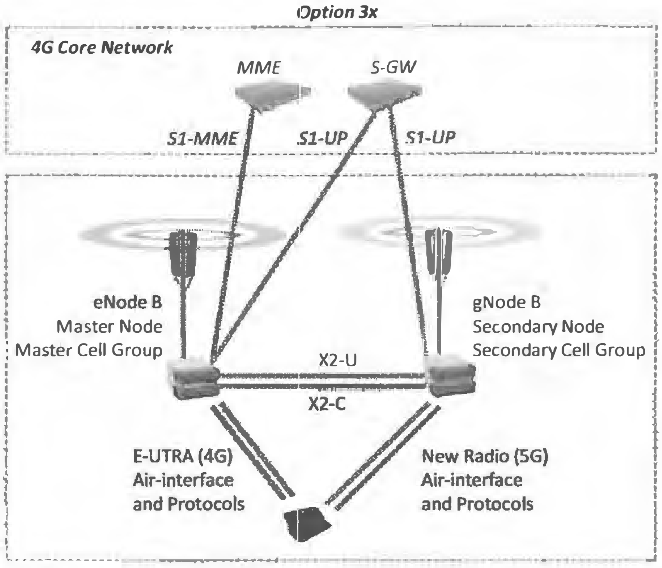


Figure 23 – Non-Standalone Base Station Architecture with 4G Core Network (Option 3x)

★ The deployment options illustrated in Figure 22 and Figure 23 are known as E-UTRA – New Radio Dual Connectivity (EN-DC), where E-UTRA refers to the 4G air-interface and New Radio refers to the 5G air-interface. This naming convention orders the air-interface technologies according to Master Node followed by Secondary Node, i.e. E-UTRA is the Master Node so is named first

★ UE which support EN-DC are required to be capable of receiving downlink data simultaneously across the 4G and 5G air-interfaces. The release 15 version of the 3GPP specifications defines EN-DC band combinations which include up to 5 different operating bands (current EN-DC band combinations always include 1 × 5G band but can include up to 4 × 4G bands). The band combinations can include a mix of FDD and TDD operating bands. Band combinations are described in section 1.19.3.

★ In general, UE which support EN-DC are required to be capable of transmitting uplink data simultaneously across the 4G and 5G air-interfaces. 3GPP allows some exceptions due to potential issues with inter-modulation products. A UE with 2 transmitters can generate inter-modulation products which fall within the UE's receive bandwidth, i.e. the UE can desensitise itself by generating interference (inter-modulation products) within its own downlink receiver

★ Figure 24 illustrates an example when using operating band 1 for 4G and operating band 77 for 5G. 2nd order inter-modulation products are generated according to ($f_2 - f_1$). This leads to inter-modulation products within the range 1320 to 2280 MHz, i.e. across the downlink of operating band 1. The inter-modulation products will not always coincide with the downlink of operating band 1 but will depend upon the specific allocations within each band. For example, if a UE is allocated a 20 MHz 4G channel {1920 to 1940 MHz} and a 50 MHz 5G channel {3300 to 3350 MHz}, then the 2nd order inter-modulation products will fall within the range 1360 to 1430 MHz. In this case, the UE will not desensitise itself

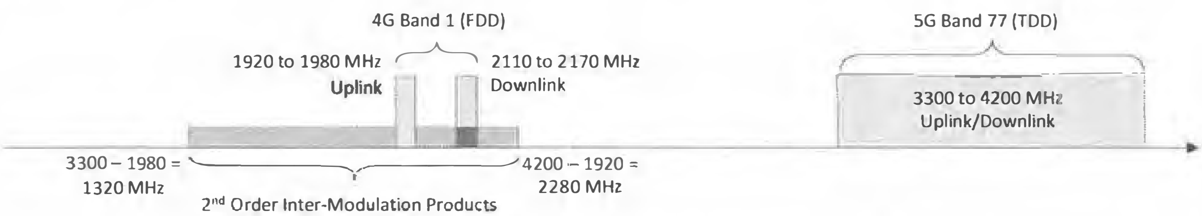


Figure 24 – Example of 2nd order Inter-Modulation Products desensitising UE receiver

★ 3GPP TS 38.101-3 specifies which band combinations allow single uplink transmission. The UE vendor can decide whether or not to support multiple simultaneous uplink transmission for these band combinations. In some cases, the desensitisation may be tolerable and the UE vendor may decide to support multiple uplink transmission. 3GPP TS 38.306 specifies the '*singleUL-Transmission*' information element which allows the UE to signal its capability for specific operating band combinations

★ The eNode B is the Master Node so the majority of RRC signalling procedures terminate at the eNode B rather than the gNode B. Signalling Radio Bearer 0 (SRB0), SRB1 and SRB2 terminate at the eNode B. This means that the 4G RRC signalling protocol specified in 3GPP TS 36.331 is applicable. SRB1 and SRB2 can be configured as 'split' SRB. This allows RRC messages to be transmitted and received by both the eNode B and gNode B

★ SRB3 can be setup at the request of the 5G Secondary Node. SRB3 terminates at the Secondary Node (gNode B) and so the 5G RRC signalling protocol specified in 3GPP TS 38.331 is applicable. SRB3 is used for signalling procedures which are time sensitive with respect to the gNode B, e.g. mobility procedures. SRB3 supports a limited number of signalling messages, i.e. *RRC Reconfiguration*, *RRC Reconfiguration Complete* and *Measurement Report* messages. Section 1.12 describes the set of SRB in greater detail

★ Figure 25 illustrates the 3 types of user plane bearer which can be supported by an EN-DC Base Station. These are Master Cell Group (MCG) Bearer, Secondary Cell Group (SCG) Bearer and Split Bearer

★ An MCG Bearer uses the RLC, MAC and Physical layers within the Master Node, i.e. it uses the 4G implementation of these layers and the 4G air-interface. The PDCP layer is located within the Master Node if the S1 connection is between the S-GW and the eNode B. This represents a special case because the PDCP layer can be configured to operate in either a 4G or 5G mode. Some services may benefit from using the 4G mode while other services may benefit from using the 5G mode

 o the 4G version of the PDCP layer (3GPP TS 36.323) supports a minimum Sequence Number (SN) length of 7 bits. The 5G version of the PDCP layer (3GPP TS 38.323) supports a minimum Sequence Number length of 12 bits. The sequence number is included within the PDCP header information

 o the speech service can benefit from the shorter Sequence Number length because it helps to minimise the overhead generated by the PDCP layer. Thus, user plane bearers transferring speech content may be allocated an MCG bearer using the 4G PDCP layer. These bearers would then be kept on the 4G network and use only the 4G air-interface

 o the data service typically uses larger packets so the percentage overhead generated by the PDCP layer is smaller. This means that larger Sequence Number sizes can be used without having a significant impact. In addition, it is necessary to allocate an increased number of bits to the Sequence Number when using high throughput applications. This provides a larger set of Sequence Numbers and helps to avoid issues associated with Sequence Number ambiguity

 ● user plane bearers transferring data content may be allocated an MCG bearer using the 5G PDCP layer. This could be applicable to an end-user located outside of 5G coverage, i.e. the MCG bearer uses only the 4G air-interface. If the end-user subsequently moves into 5G coverage then the MCG bearer using the 5G PDCP layer can then be switched to a Split bearer without having to reconfigure the PDCP layer

★ A SCG Bearer uses the RLC, MAC and Physical layers within the Secondary Node, i.e. it uses the 5G implementation of these layers and the 5G air-interface. SCG Bearers always use the 5G version of the PDCP layer irrespective of Master/Secondary Node

★ A Split Bearer uses the RLC, MAC and Physical layers within both the Master and Secondary Nodes, i.e. both 4G and 5G air-interfaces can be used. Split Bearers always use the 5G version of the PDCP layer irrespective of the node providing the S1 connection towards the S-GW. This is known as a 'unified' solution because the location of the S1 connection is transparent to the UE and both Split Bearers appear to be the same from the perspective of the UE

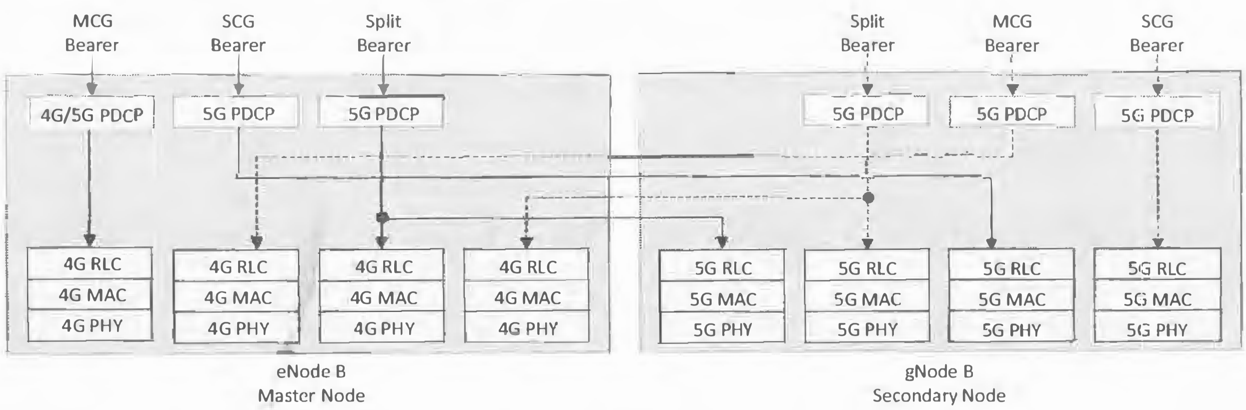


Figure 25 – Master Cell Group (MCG), Secondary Cell Group (SCG) and Split Bearers for EN-DC configurations

★ The Master Cell Group (MCG) is the group of serving cells belonging to the Master Node, i.e. the Master Node can use Carrier Aggregation in combination with Multi-RAT Dual Connectivity (MR-DC). Similarly, the Secondary Cell Group (SCG) is the group of serving cells belonging to the Secondary Node. The use of multiple serving cells at the Master and Secondary Nodes will depend upon the set of supported band combinations

★ Figure 26 illustrates two Non-Standalone Base Station configurations using the 5G Core Network. These configurations are known as 'option 4' and 'option 4a' within the context of the 3GPP RAN architecture evaluation process (3GPP TR 38.801). In both cases, the 5G gNode B provides control plane connectivity towards the Core Network and acts as the Master Node (MN). The Next Generation eNode B (ng-eNode B) has control plane connectivity across the Xn interface and acts as the Secondary Node (SN). These configurations require the ng-eNode B to support the Xn interface rather than the X2 interface. In the case of 'option 4a', the ng-eNode B also has to support the NG-U interface towards the User Plane Function (UPF). Neither option requires the ng-eNode B to connect to the Access and Mobility Management Function (AMF)

★ The deployment options illustrated in Figure 26 are known as New Radio - E-UTRA Dual Connectivity (NE-DC), where New Radio refers to the 5G air-interface and E-UTRA refers to the 4G air-interface

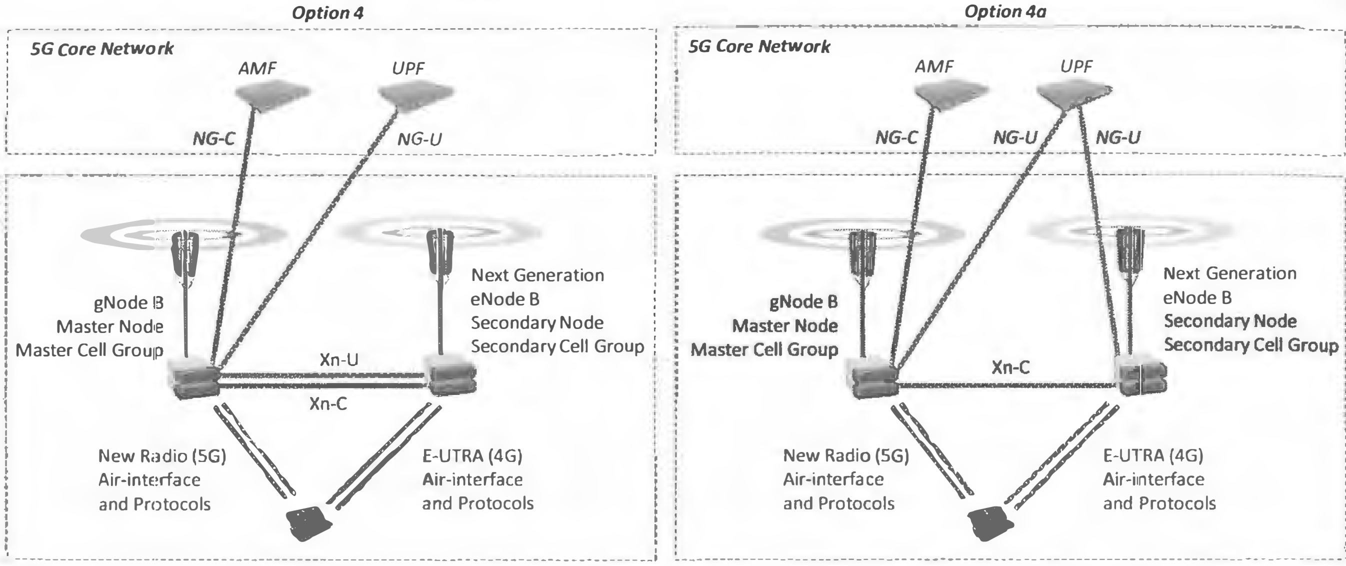


Figure 26 – Non- Standalone Base Station Architectures using the 5G Core Network (Options 4 and 4a)

★ Figure 27 illustrates the 3 types of user plane bearer which can be supported by an NE-DC Base Station. These are similar to those supported by an EN-DC Base Station but with some important differences

- o all user plane bearers connected to the 5G Core Network use the Service Data Adaptation Protocol (SDAP) layer. This layer is located above the PDCP layer and is used to map QoS Flows onto Data Radio Bearers (DRB). The SDAP layer is not present when user plane bearers are connected to the 4G Core Network
- o all user plane bearer types use the 5G version of the PDCP layer. This is in contrast to the EN-DC configurations which are able to use either the 4G or 5G version of the PDCP layer for MCG Bearers hosted by the Master Node. Using the 5G PDCP layer for all user plane bearers simplifies the architecture and the UE implementation

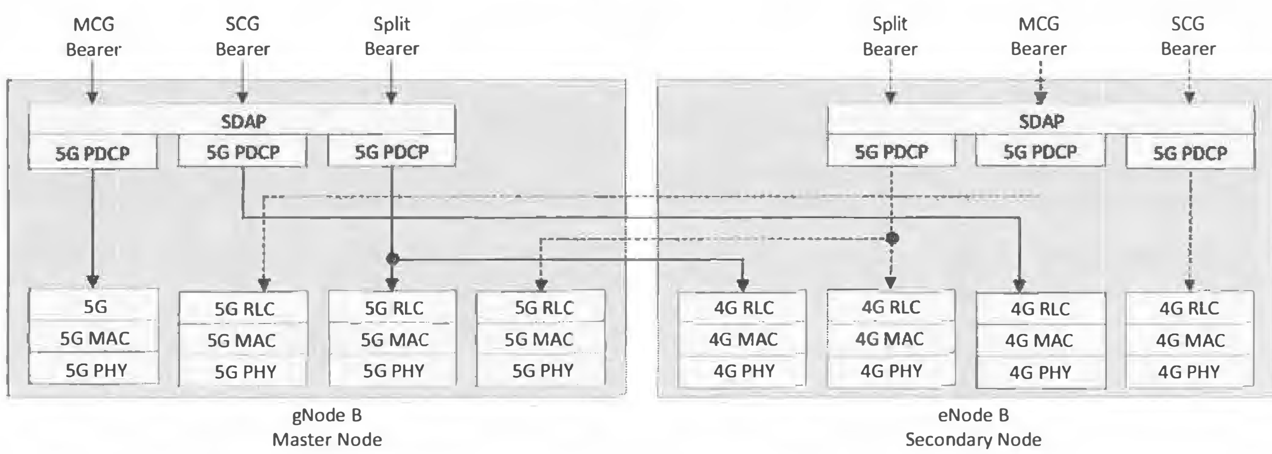


Figure 27 – Master Cell Group (MCG), Secondary Cell Group (SCG) and Split Bearers for NE-DC

★ Figure 28 illustrates two further configurations for Non-Standalone Base Stations using the 5G Core Network. These configurations are known as 'option 7' and 'option 7a'. In both cases, the Next Generation eNode B (ng-eNode B) provides control plane connectivity towards the Core Network and acts as the Master Node (MN). The gNode B has control plane connectivity across the Xn interface and acts as the Secondary Node (SN). These configurations require the ng-eNode B to support the NG-C, NG-U and Xn interfaces

★ The deployment options illustrated in Figure 28 are another variant of E-UTRA – New Radio Dual Connectivity (EN-DC), where E-UTRA refers to the 4G air-interface and New Radio refers to the 5G air-interface. They are similar to options 3 and 3a but the 4G Core Network is changed to the 5G Core Network and the X2 interfaces become Xn interfaces

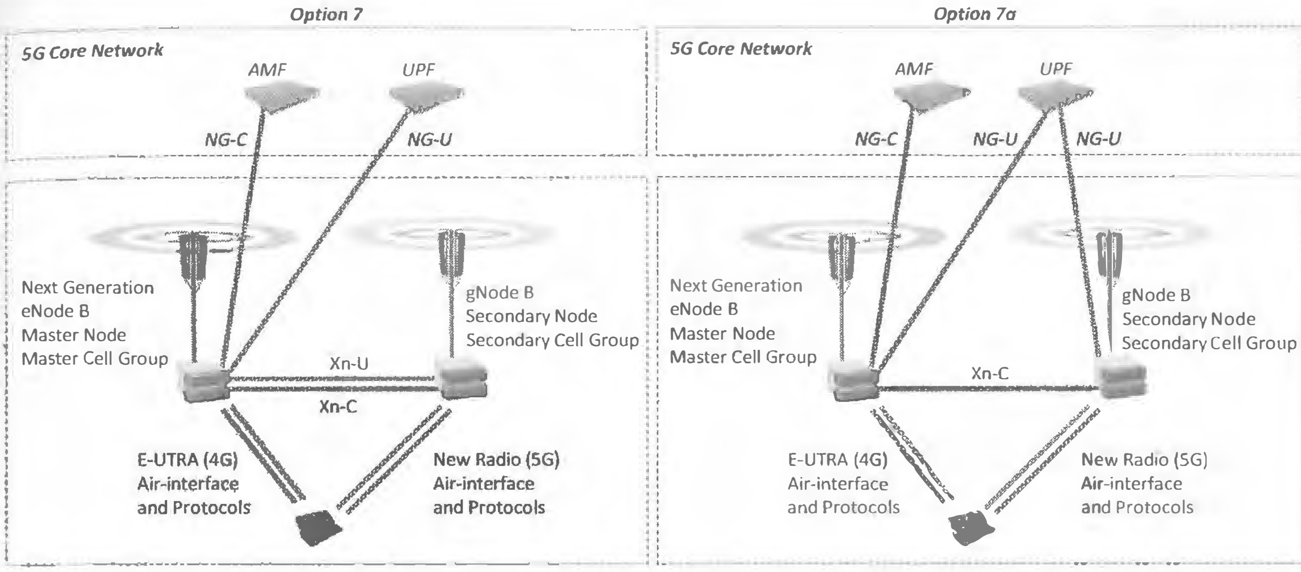


Figure 28 – Non- Standalone Base Station Architectures using the 5G Core Network (Options 7 and 7a)

★ 3GPP References: TR 38.801, TS 37.340

1.5.3 CU-DU SPLIT BASE STATION

★ The Centralised Unit (CU) – Distributed Unit (DU) Split Base Station architecture allows the gNode B to be deployed using two physically separated units. These two units are connected using an open interface standardised by 3GPP, i.e. it should be possible to use a CU provided by one network vendor and a set of DU provided by another network vendor

★ The CU provides support for the higher layers of the protocol stack. There is a single CU for each gNode B. The Centralised Units belonging to multiple gNode B can be implemented using a shared hardware platform. Cloud computing and Network Function Virtualisation (NFV) can provide benefits when deploying the population of CU

★ The DU provides support for the lower layers of the protocol stack. There can be multiple DU connected to each CU. For example, there could be more than 100 DU connected to a specific CU. The DU includes both baseband processing and RF functions

★ The general structure of a CU/DU Split base station architecture is illustrated in Figure 29. The CU supports the SDAP, RRC and PDCP protocol stack layers, whereas the DU supports the RLC, MAC and Physical layers. The SDAP layer will not be present if the CU is connected to a 4G Core Network

★ Each DU is able to support one or more cells, while each cell is able to support one or more beams. This leads to a range of mobility scenarios, i.e. UE mobility can be intra-gNode B, intra-DU, intra-cell, inter-beam, or intra-gNode B, intra-DU, inter-cell, or intra-gNode B, inter-DU, or inter-gNode B

★ The PDCP layer is able to provide data recovery for inter-DU handovers, i.e. the PDCP layer supports re-transmissions for specific scenarios. This is necessary to achieve lossless handovers when the source DU has buffered packets which are lost when the source DU is released as part of the handover procedure. There is no interface between DU for data forwarding

★ The Distributed Unit is responsible for allocating the C-RNTI to a UE during the Random Access procedure. This results from the Random Access procedure being managed by the MAC layer, and the MAC layer being located within the Distributed Unit. The Distributed Unit forwards the allocated C-RNTI to the Centralised Unit after receiving MSG3, i.e. both the allocated C-RNTI and MSG3 are forwarded together. This is done using the Initial UL RRC Message Transfer procedure illustrated in Figure 30. If a UE is completing the RRC Connection Setup procedure to make the transition from RRC Idle mode to RRC Connected mode then MSG3 will be the *RRC Setup Request* message

★ The Distributed Unit also allocates the C-RNTI during an incoming Handover procedure. In this case, the Distributed Unit allocates the C-RNTI during the Handover Preparation phase. The Centralised Unit receives the incoming Handover Request and subsequently initiates the UE Context Setup Request procedure with the Distributed Unit. The Distributed Unit includes the C-RNTI within the *UE Context Setup Response* message. This procedure is also illustrated in Figure 30

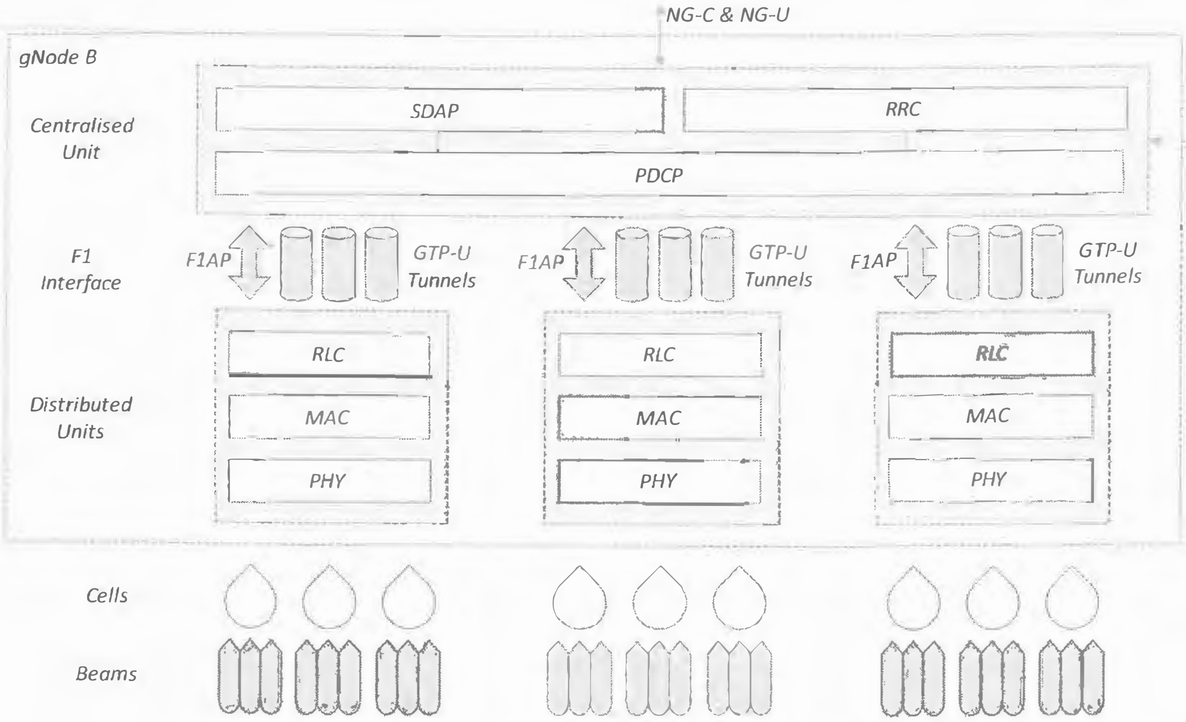


Figure 29 – Centralised Unit (CU) / Distributed Unit (DU) Split Base Station Architecture

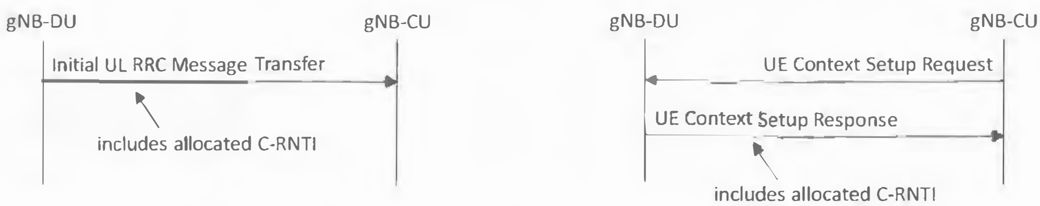


Figure 30 – DU Allocation of the C-RNTI during the Initial UL RRC Message Transfer and UE Context Setup procedures

- The F1 interface connects the CU to each DU. Both control plane signalling and user plane data are transferred across the F1 interface. Control plane signalling is based upon the F1 Application Protocol (F1AP) specified within 3GPP TS 38.473. F1AP uses SCTP over IP and supports Interface Management, UE Context Management and RRC Message Transfer procedures
  - examples of Interface Management procedures include the F1 Setup, gNB-DU Configuration Update and gNB-CU Configuration Update procedures. A DU initiates the F1 Setup procedure by sending an F1AP: *F1 Setup Request* message to the CU
  - examples of UE Context Management procedures include the UE Context Setup, UE Context Modification and UE Context Release procedures. The UE Context Setup procedure is always initiated by the CU, whereas the Modification and Release procedures can be initiated by either the CU or DU
  - examples of RRC Message Transfer procedures include the Initial UL RRC Message Transfer, DL RRC Message Transfer and UL RRC Message Transfer procedures. These procedures are used to transfer RRC messages in the form of PDCP PDU between the CU and DU
- User plane data is transferred across the F1 interface using GTP-U over UDP over IP. A GTP-U tunnel is setup across the F1 interface for each Data Radio Bearer (DRB). Each tunnel is identified using the combination of {source Tunnel Endpoint Identifier (TEID), destination TEID, source IP address, destination IP address}
- The NR User Plane Protocol specified within 3GPP TS 38.425 is used to control the transfer of downlink user plane data towards the DU. Figure 31 illustrates PDU Type 0 which is sent from the CU to a DU, and PDU Type 1which is sent from a DU to the CU
- The CU uses PDU Type 0 to add a sequence number to each downlink data packet. The DU uses this sequence number to detect lost packets. The CU can also use PDU Type 0 to provide various discard instructions. If the DU reports Radio Link outage then the CU may attempt re-transmission from the PDCP layer using a second DU. If the second DU reports successful delivery of the PDCP PDU, the CU instructs the original DU to discard the successfully delivered packets to avoid unnecessary transmission

Downlink User Data (PDU Type 0)

PDU Type = 0	Spare	DL Discard Blocks	DL Flush	Report Polling
Spare	Report Delivered	User Data Exist.	Assist Info. Report Poll	ReTx Flag
NR-U Sequence Number				
DL Discard NR PDCP PDU SN				
DL Discard Number of Blocks				
DL Discard NR PDCP PDU SN Start (first block)				
Discarded Block Size (first block)				
...	...			
DL Discard NR PDCP PDU SN Start (last block)				
Discarded Block Size (last block)				
DL Report NR PDCP PDU SN				

Downlink Data Delivery Status (PDU Type 1)

PDU Type = 1	Highest Tx NR PDCP SN Ind.	Highest Delivered NR PDCP SN Ind.	Final Frame Ind.	Lost Packet Report
Spare	Data Rate Ind.	Highest ReTx NR PDCP SN Ind.	Highest Deliv. ReTx NR PDCP SN Ind.	Cause Report
Desired Buffer Size for the Data Radio Bearer				
Desired Data Rate				
Number of Lost NR-U Sequence Number Ranges Reported				
Start of Lost NR-U Sequence Number Range				
End of Lost NR-U Sequence Number Range				
Highest Successful Delivered NR PDCP Sequence Number				
Highest Transmitted NR PDCP Sequence Number				
Cause Value				
Highest Successful Delivered Retx NR PDCP Sequence Number				
Highest Retransmitted NR PDCP Sequence Number				

Figure 31 – PDU Types 0 and 1 belonging to the NR User Plane Protocol

★ The DU uses PDU Type 1 to report any lost packets and also to control the rate at which downlink data is sent by the CU, i.e. it provides a mechanism for flow control to avoid the buffers within the DU becoming too full. The DU signals the sequence number of the highest successfully delivered PDCP PDU, the desired buffer level and the desired data rate. The desired data rate is specified as the number of bytes which the DU would like to receive within a 1 second time interval. The CU uses these information elements to determine the quantity of data to forward towards the DU

★ The DU can also use PDU Type 1 to indicate 'Radio Link Outage' or 'Radio Link Resume'. This status information is signalled using the 'Cause Value' field. The CU stops forwarding data for the UE if the DU reports Radio Link Outage. The CU can start forwarding data for the UE if the DU reports Radio Link Resume

★ The CU/DU split illustrated in Figure 29 is known as a 'Higher Layer' split because the protocol stack is divided between the PDCP and RLC layers. This solution has been standardised for the release 15 version of the 3GPP specifications. Keeping the RLC and MAC layers within the DU provides reduced latency for both RLC and MAC re-transmissions, i.e. Automatic Repeat Request (ARQ) and Hybrid Automatic Request (HARQ) re-transmissions

★ 3GPP also discussed the possibility of a 'Lower Layer' split and generated TR 38.816. A 'Lower Layer' split could divide the protocol stack between the MAC and Physical layers, or it could divide the protocol stack between the upper and lower parts of the Physical layer. 3GPP concluded not to progress the specification of a 'Lower Layer' split but noted that organisations outside of 3GPP may do so. For example, the xRAN initiative may provide a solution for a 'Lower Layer' split

★ Network equipment vendors already offer solutions which include both 'Upper Layer' and 'Lower Layer' splits. This leads to Base Station architectures which are divided into 3 functional units. Figure 32 illustrates an example based upon a Lower Layer split which distributes the Physical layer across 2 functional units. The Lower Layer split divides the DU into a Radio Access Unit (RAU) and a Radio Unit (RU). The Radio Unit is typically an Active Antenna with baseband processing capability

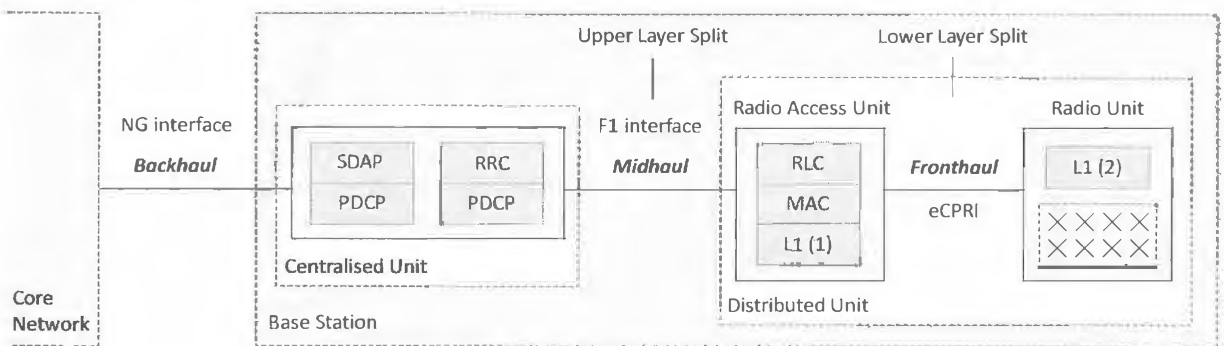


Figure 32 – Base Station architecture using both Upper Layer and Lower Layer splits

- Within the context of Figure 32, the transport network which connects the Base Station to the Core Network is known as the Backhaul, while the connection between the CU and DU is known as the Midhaul and the connection between the Radio Access Unit and Radio Unit is known as the Fronthaul. The Fronthaul has more demanding transport requirements in terms of bandwidth and latency when compared to the Midhaul and Backhaul
- The Fronthaul is not an interface standardised by 3GPP. Instead, it is typical to use the Common Public Radio Interface (CPRI) or enhanced CPRI (eCPRI) specifications for the Fronthaul. CPRI and eCPRI have been developed by a consortium of companies and are intended to complement the work of 3GPP. Within the context of CPRI and eCPRI, the Radio Access Unit is known as the Radio Equipment Control (REC) and the Radio Unit is known as the Radio Equipment (RE).
- 3GPP References: TS 38.401, TS 38.470, TS 38.471, TS 38.472, TS 38.473, TS 38.474, TS 38.425

1.5.4 CP-UP SEPARATION

- Section 1.4 described Control Plane (CP) User Plane (UP) separation for the 5G Core Network. The same principle can be applied to the Centralised Unit (CU) belonging to the Base Station. CP-UP separation allows independent scaling of the Base Station hardware. For example, the UP capability can be increased to support higher throughputs without having to increase the CP capability. CP-UP separation also provides benefits in terms of geographic location flexibility. The CP capability may be centralised using a cloud based platform, whereas the UP capability may be distributed to minimise latency towards the Distributed Unit (DU)
- Figure 33 illustrates CP-UP separation for the CU. The CP includes the RRC and PDCP protocol stack layers and is responsible for RRC signalling. The UP includes the SDAP and PDCP layers and is responsible for handling application data. The CP and UP sections of the CU are connected using the E1 interface. The E1 interface is only used for control plane signalling and does not transfer user plane data. 3GPP TS 38.463 specifies the E1 Application Protocol (E1AP) for the purposes of signalling across the E1 interface
- The UP section of the CU is responsible for allocating GTP Tunnel Endpoint Identifiers (TEID) for the uplink of the F1-U interface. It is also responsible for allocating GTP TEID for the downlink of the NG-U interface. A GTP tunnel is configured for each Data Radio Bearer (DRB) on the F1-U interface, and for each PDU Session on the NG-U interface

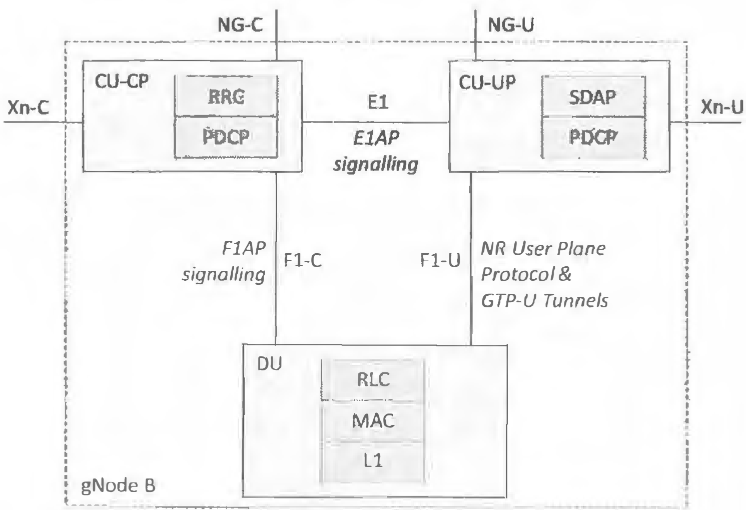


Figure 33 – Base Station architecture using Control Plane – User Plane Separation

- A Base Station using CP-UP separation can include a single CU-CP, multiple CU-UP and multiple DU. The interconnection of multiple CU-UP and DU is illustrated in Figure 34. 3GPP specifies that a Base Station can include multiple CU-CP for the purposes of resiliency, i.e. a single CU-CP is active at any point in time. A specific DU can be connected to multiple CU-UP under the control of the same CU-CP. Similarly, a specific CU-UP can be connected to multiple DU under the control of the same CU-CP
- The connection of multiple CU-UP to a single DU means that each cell can have a choice of CU-UP. A first CU-UP could be deployed at a centralised location to take advantage of cloud technology. This CU-UP could be used for eMBB applications. A second CU-UP could be deployed at the Base Station location to help minimise user plane latency. This CU-UP could be used for URLLC applications. The selection of appropriate CU-UP can form part of a Network Slicing implementation
- The CP-UP separation architecture can introduce drawbacks associated with control plane latency, i.e. the CU-CP will have to signal to the CU-UP across a transport network if the two functional units are physically separated. The CP-UP separation architecture can also increase network complexity due to the introduction of additional units and interfaces

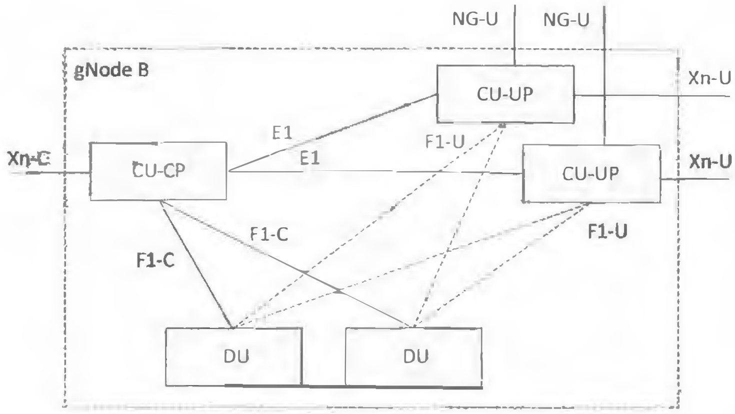


Figure 34 – Control Plane – User Plane Separation with multiple User Plane Centralised Units

1.5.5 ANTENNA ARCHITECTURES

★ Legacy technologies have predominantly used Base Station architectures which include a Base Station cabinet connected to one or more passive antenna. Feeder cables are used to connect the Base Station cabinet to the passive antenna

★ A Mast Head Amplifier (MHA), also known as a Tower Mounted Amplifier (TMA) may be connected between the Base Station cabinet and the passive antenna. MHA are used to improve the Signal to Noise Ratio (SNR) of the uplink transmission received by the Base Station cabinet. They achieve this by using a Low Noise Amplifier to boost the wanted signal strength before it is degraded by the noise figures of the feeder cable and Base Station, i.e. the negative impacts of the feeder cable and Base Station become relatively small because the wanted signal becomes stronger. The benefit of an MHA is maximised if it has high gain, a low noise figure and is located as close as possible to the passive antenna

★ MHA improve the uplink link budget but typically introduce a small loss in the downlink direction. This makes them suitable for scenarios where coverage is uplink limited. Within an uplink link budget, MHA are often assumed to compensate for the losses generated by the feeder cable, e.g. a feeder loss of 2 dB would be set to 0 dB if an MHA is configured. A more precise calculation can be completed using Friis' noise figure equation. The requirement for an MHA can be avoided if the base station cabinet, or the RF parts of the base station cabinet are positioned physically close to the passive antenna. This reduces the requirement for feeder cable and so helps to remove its negative impact. Remote Radio Heads (RRH) are an example of positioning the RF parts of the Base Station physically close to the passive antenna

★ Within the context of 5G, it is assumed that this legacy Base Station architecture may be used for operating bands belonging to Frequency Range 1 (450 MHz to 6 GHz). 3GPP TS 38.104 specifies Base Station Type 1-C, illustrated in Figure 35 to cater for this architecture. The '1' refers to Frequency Range 1, whereas the 'C' refers to 'conducted' requirements. Conducted requirements are those which can be measured by connecting a probe to the Base Station cabinet or antenna subsystem. Examples include Base Station output power, Adjacent Channel Leakage Ratio (ACLR), unwanted emissions, spurious emissions, receiver sensitivity, Adjacent Channel Selectivity (ACS) and receiver blocking. Figure 35 illustrates that these 'conducted' requirements can be measured at either Port A or Port B depending upon whether or not the antenna subsystem includes any external hardware, e.g. an MHA

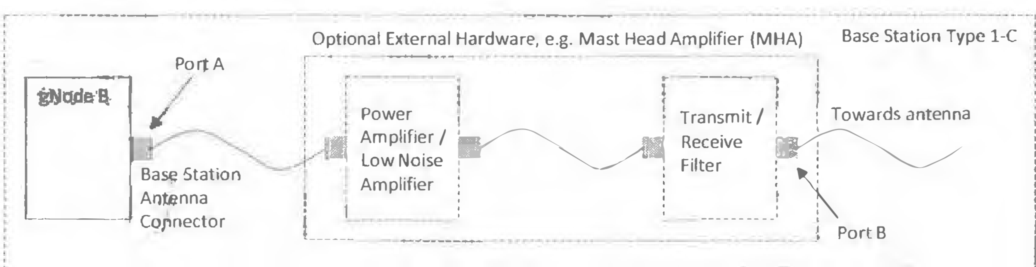


Figure 35 – Base Station architecture Type 1-C

★ The introduction of active antennas has changed the architecture of both the Base Station and the antenna. Active antennas move the transceivers from the Base Station into the antenna. Figure 36 illustrates the general architecture when using a legacy passive antenna (only the transmit path is shown whereas in reality there would also be a receive path). The transceiver includes the Digital to Analogue (D/A) converter, the local oscillator used to mix the signal from baseband to RF, and the power amplifier. The analogue RF signal is transmitted towards the passive antenna using RF feeder cable

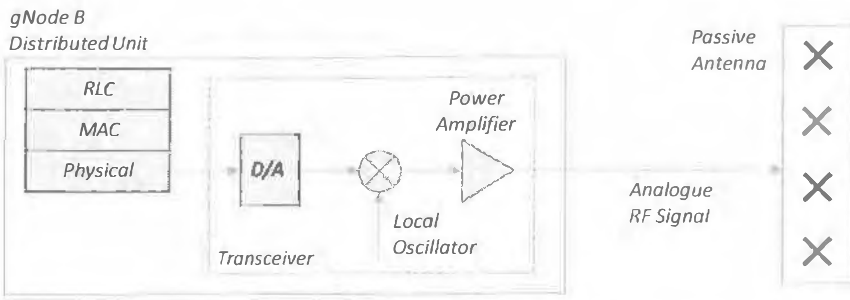


Figure 36 – Passive antenna architecture

- Figure 37 illustrates the architecture when using an active antenna. The transceiver functionality is moved from the Base Station into the antenna. In general, active antennas have a larger number of lower power transceivers relative to a Base Station connected to a passive antenna. For example, a Base Station connected to a passive antenna may have 2 × 20 W transceivers per cell when configured to use 2×2 MIMO. An example active antenna may have {2 × 16} × 5 W transceivers per cell. This corresponds to an active antenna with 32 transceivers. It is common to discuss active antenna with 4, 8, 16, 32, 64 and 128 transceivers. Increasing the number of transceivers increases the cost, weight and power consumption of the antenna but also increases the beamforming capability which can translate into improved coverage and increased capacity

- The architecture illustrated in Figure 37 assumes that Physical layer processing is completed within the Distributed Unit before forwarding the baseband signal to the active antenna. Advanced active antenna may also support some of the Physical layer processing, i.e. some parts of the baseband processing can be moved from the Base Station to the antenna. This could include the application of the beamforming weights when using digital beamforming. It can also include the Inverse Fast Fourier Transform (IFFT) and Fast Fourier Transform (FFT) used to generate the downlink signal and receive the uplink signal respectively

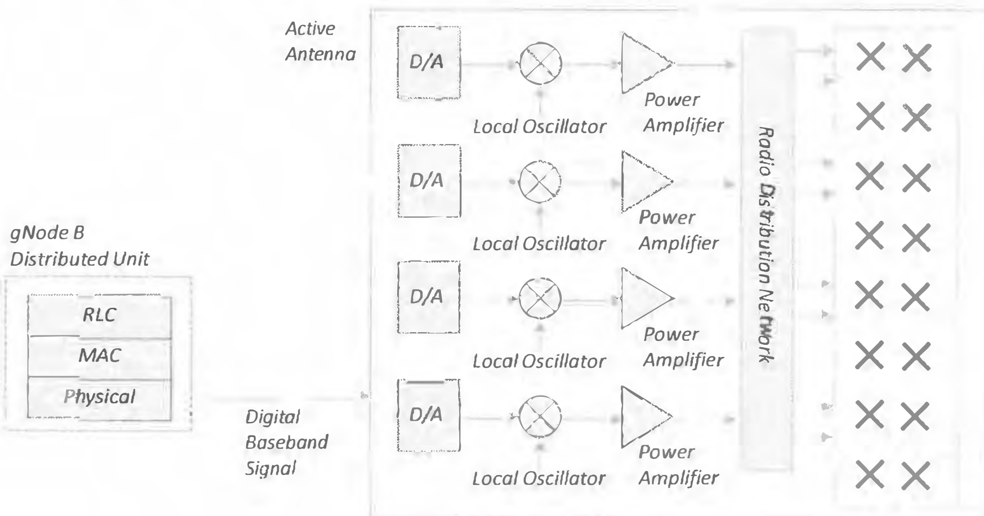


Figure 37 – Active antenna architecture

- An active antenna typically has more antenna elements than it has transceivers. This means that each transceiver is connected to multiple antenna elements. The example illustrated in Figure 37 has 4 transceivers and 2 columns of cross polar antenna elements. Each transceiver could be connected to a single column of antenna elements and this would provide basic horizontal beamforming. Horizontal beamforming performance would be improved if the number of transceivers and the number of columns of cross polar antenna elements were increased. Combined horizontal and vertical beamforming can be achieved if each column of antenna elements is divided in subsets and a transceiver is allocated to each subset. In this case, transceivers are stacked both horizontally and vertically. Figure 38 illustrates examples of the allocation of transceivers to antenna elements to achieve horizontal and combined horizontal/vertical beamforming. Section 1.21 describes beamforming in greater detail

- Within the context of 5G, it is assumed that active antenna may be used for operating bands belonging to both Frequency Range 1 (450 MHz to 6 GHz) and Frequency Range 2 (24.25 GHz to 52.60 GHz). 3GPP TS 38.104 specifies Base Station Types 1-O and 2-O, illustrated in Figure 39 to cater for active antenna. The numerical values '1' and '2' refer to the Frequency Range, whereas the 'O' refers to Over the Air (OTA) requirements. Over the Air requirements (also known as radiated requirements) are those which are measured by placing a probe at the Radiated Interface Boundary (RIB)

- Conducted measurements are not normally possible when using active antenna because all RF components are integrated into the antenna and the connectors provide a baseband signal rather than an RF signal. The position of the Radiated Interface Boundary (RIB) depends upon the wavelength and the dimensions of the antenna. The far field starts at a distance given by $2D^2/\lambda$ meters, when the antenna dimensions are significantly greater than the wavelength, where D is the largest dimension of the antenna and λ is the wavelength

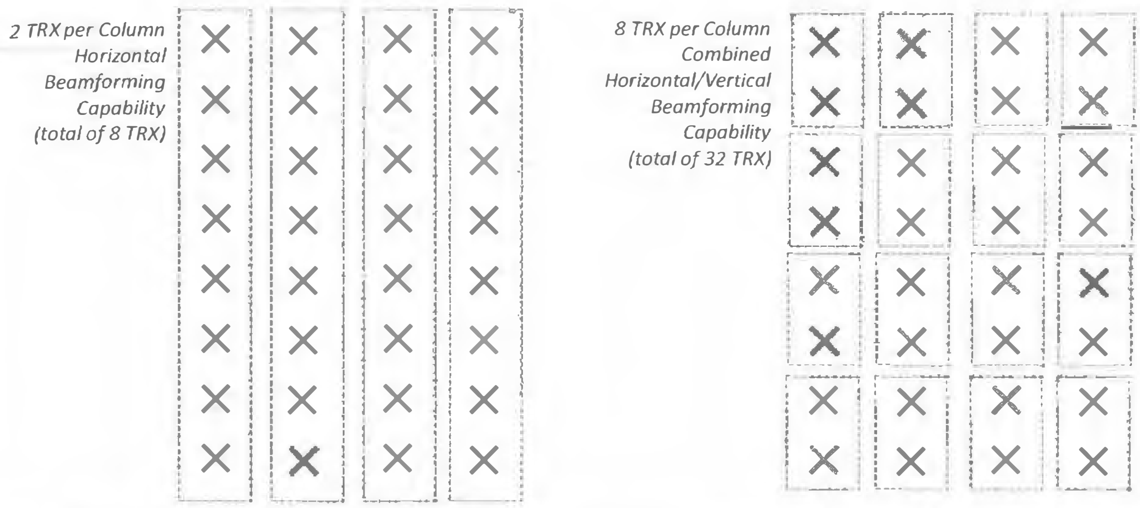


Figure 38 – Example association between antenna elements and transceivers for horizontal and 3-dimensional beamforming

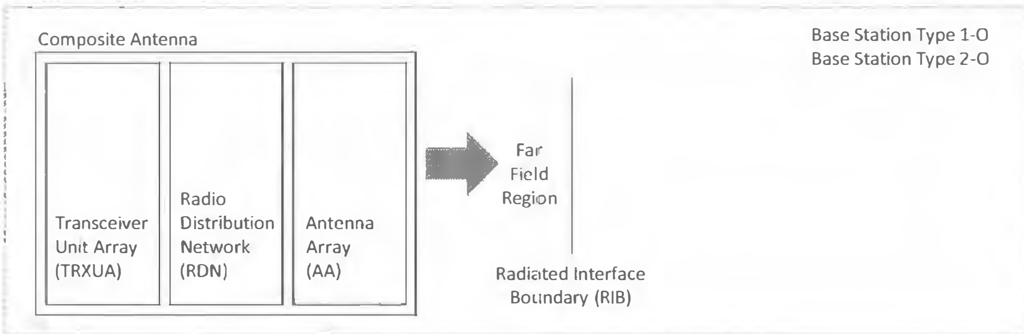


Figure 39 – Base Station architecture Types 1-O and 2-O

★ The set of radiated requirements is similar to the set of conducted requirements, i.e. they include Base Station output power, Adjacent Channel Leakage Ratio (ACLR), unwanted emissions, spurious emissions, receiver sensitivity, Adjacent Channel Selectivity (ACS) and receiver blocking

★ Within the context of 5G, 3GPP specifies that an active antenna for Base Station Type 1-O must have at least 8 transceivers. There is no equivalent requirement for Base Station Type 2-O

★ In the case of Frequency Range 1 (450 MHz to 6 GHz), 3GPP has also specified requirements for Base Station Type 1-H. The numerical value '1' refers to the Frequency Range, whereas the 'H' refers to Hybrid requirements. Hybrid means that some requirements are specified using conducted measurements, while other requirements are specified using radiated measurements

★ Base Station Type 1-H is applicable to Base Stations equipped with active antenna which have a set of connectors between the transceivers and antenna elements. These connectors can be used for conducted measurements. Figure 40 illustrates the architecture of Base Station Type 1-H

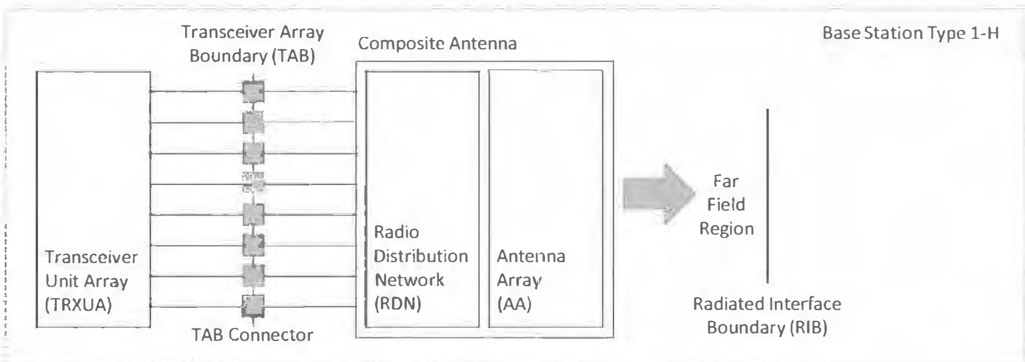


Figure 40 – Base Station architecture Type 1-H

★ 3GPP References: TR 37.843, TS 38.104

1.5.6 BASE STATION CLASSES

- 3GPP TS 38.104 specifies 3 Base Station Classes: Wide Area, Medium Range and Local Area. These classes correspond to macro, micro and pico deployment scenarios. Base Station Classes have been defined to ensure that certain RF characteristics are specified using limits which are suitable for the deployment scenario. For example, a 'Local Area Base Station' is specified to have a transmit power capability < 24 dBm, a 'Medium Range Base Station' is specified to have a transmit power capability < 38 dBm, while a 'Wide Area Base Station' does not have an upper transmit power limit
- Base Station Types 1-C and 1-H are categorised as Wide Area, Medium Range or Local Area according to their Minimum Coupling Loss (MCL). The MCL is the smallest practical link loss measured between the Base Station and the UE antenna connector. The measurement reference point at the Base Station depends upon the Base Station Type. In the case of Base Station Type 1-C, the measurement reference point is either port A or port B illustrated in Figure 35. In the case of Base Station Type 1-H, the measurement reference point is the TAB connector illustrated in Figure 40
- 3GPP uses the following MCL to categorise the Base Station Class:
    - Wide Area Base Station: an MCL of 70 dB based upon macro cell scenarios
    - Medium Range Base Station: an MCL of 53 dB based upon micro cell scenarios
    - Local Area Base Stations: an MCL of 45 dB based upon pico cell scenarios
- Base Station Types 1-O and 2-O do not have RF connectors at the Base Station so it is not possible to measure MCL. Instead, these Base Station Types are categorised as Wide Area, Medium Range or Local Area according to a minimum distance between the Base Station and UE
- 3GPP uses the following minimum distances to categorise the Base Station Class:
    - Wide Area Base Station: a minimum distance along the ground equal to 35 m based upon macro cell scenarios
    - Medium Range Base Station: a minimum distance along the ground equal to 5 m based upon micro cell scenarios
    - Local Area Base Stations: a minimum distance along the ground equal to 2 m based upon pico cell scenarios
- The distances used to categorise Base Station Types 1-O and 2-O can be derived from the MCL used to categorise Base Station Types 1-C and 1-H. For example, assuming free space path loss for a Medium Range Base Station, Path Loss (dB) = 38.25 + 20 LOG (distance (m)). Antenna gains of 0 dBi and a body loss of 1 dB can also be assumed. An MCL of 53 dB corresponds to a path loss of 52 dB after accounting for 0 dBi antenna gains and 1 dB body loss. Then, $10^{(52 - 38.25)/20} = 5$ m
- 3GPP References: TS 38.104

1.6 INTERFACES

1.6.1 Xn INTERFACE

★ The Xn interface connects one gNode B to another gNode B. The control plane of the Xn (Xn-C) allows signalling between neighbouring gNode B. The user plane of the Xn (Xn-U) allows the transfer of application data between neighbouring gNode B

★ The Xn interface is typically setup as part of the Automatic Neighbour Relation (ANR) procedure. UE based ANR relies upon a UE reporting the Physical Cell Identity (PCI) belonging to a cell of a neighbouring gNode B. The UE is requested to decode the Cell Global Identity (CGI) from the System Information if the PCI is not already known to the serving gNode B. The serving gNode B uses the CGI to retrieve the IP address of the neighbouring gNode B by sending a query to the AMF. The AMF forwards the query to the neighbouring gNode B to obtain its IP address before responding to the serving gNode B. The serving gNode B uses the IP address to establish an SCTP connection with the neighbouring gNode B. The Xn Setup procedure can be initiated once the SCTP connection has been established

★ Figure 41 illustrates the control plane and user plane protocol stacks belonging to the Xn interface. The control plane uses SCTP over IP, whereas the user plane uses GTP-U over UDP over IP

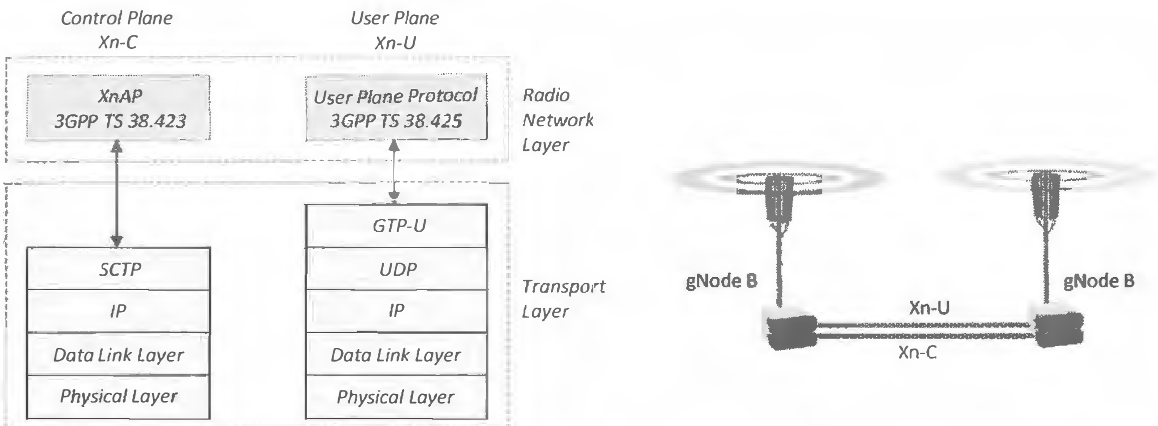


Figure 41 – Protocol stacks for Xn interface

★ Control plane signalling across the Xn interface is based upon the Xn Application Protocol (XnAP) specified within 3GPP TS 38.423. Signalling procedures are categorised as Global, Mobility or Dual Connectivity. Table 5 presents the procedures belonging to each of these categories

Global Procedures
Xn Setup
NG-RAN Node Configuration Update
Cell Activation
Reset
Error Indication
Xn Removal

Mobility Procedures
Handover Preparation
SN Status Transfer
Handover Cancel
Retrieve UE Context
RAN Paging
Data Forwarding Address Indication
UE Context Release

Dual Connectivity Procedures
S-NG-RAN Node Addition Preparation
S-NG-RAN Node Reconfiguration Completion
M-NG-RAN Node initiated S-NG-RAN Node Modification Preparation
S-NG-RAN Node initiated S-NG-RAN Node Modification
S-NG-RAN Node initiated S-NG-RAN Node Change
M-NG-RAN Node initiated S-NG-RAN Node Release
S-NG-RAN Node initiated S-NG-RAN Node Release
S-NG-RAN Node Counter Check
RRC Transfer
Notification Control Indication
Activity Notification
E-UTRA – NR Cell Resource Coordination

Table 5 – Xn Application Protocol (XnAP) Procedures

★ The Xn Setup procedure is used to create a logical Xn connection between the two gNode B. The Xn Setup procedure has prerequisites of a first gNode B knowing the IP address of a second gNode B, and the first gNode B using that IP address to establish an SCTP connection. The *Xn Setup Request / Xn Setup Response* handshake can be completed once the SCTP connection has been established. These messages allow the gNode B to exchange information regarding their cells, their AMF connectivity and their Tracking Areas. The Xn Setup procedure is typically completed after detecting a new neighbouring Base Station. It does not need to be repeated unless the Xn connection is deleted and requires re-establishment, e.g. after a site reset

★ The NG-RAN Node Configuration Update procedure allows a gNode B to maintain its configuration information over time, i.e. the information exchanged during the Xn Setup procedure can be updated if it changes. For example, it allows updates to be provided regarding the set of supported Tracking Areas. The procedure can also be used to support changes triggered by 'Energy Saving' functions. The gNode B may decide to deactivate one or more cells during periods of low traffic. This helps to conserve energy and also reduces the operating cost of the Base Station. A gNode B can inform its neighbours about cell deactivation using the NG-RAN Node Configuration Update procedure. Similarly, a gNode B may decide to re-activate one or more cells if traffic levels subsequently increase. Neighbours can be informed about re-activation using the NG-RAN Node Configuration Update procedure. The procedure uses the *NG-RAN Node Configuration Update / NG-RAN Node Configuration Update Acknowledge* handshake

★ The Cell Activation procedure is also applicable to 'Energy Saving' functions, i.e. the NG-RAN Node Configuration Update procedure allows a specific gNode B to signal its intentions for cell deactivation/activation (the procedure is initiated by the Base Station doing the deactivation/activation), whereas the Cell Activation Procedure allows a neighbouring gNode B to request that cell activation is initiated (the procedure is initiated by a neighbouring Base Station). The Cell Activation procedure uses the *Cell Activation Request / Cell Activation Response* handshake. The response message specifies the set of cells which have been re-activated so it is not necessary to use the NG-RAN Node Configuration Update procedure following a Cell Activation procedure

★ The Reset procedure can be used to initiate either a 'Full' or 'Partial' reset. A 'Full' reset triggers the target Base Station to delete all UE context information associated with the source Base Station. The target Base Station does not delete application level data which was provided during the Xn Setup or NG-RAN Node Configuration Update procedures, e.g. cell lists are not deleted. A 'Partial' reset triggers the target Base Station to delete information associated with specific UE contexts addressed using their XnAP identities. The target Base Station responds to the source Base Station using a *Reset Response* message

★ The Error Indication procedure is used to report errors which have been detected within an incoming XnAP message. This procedure is applicable if the errors cannot be reported using a failure message belonging to the procedure which has created the errors

★ The Xn Removal procedure is used to delete the signalling connection between the source and target Base Stations. The source Base Station initiates the procedure by sending the *Xn Removal Request* message, which the target Base Station acknowledges using an *Xn Removal Response* message. The source Base Station removes the transport network layer association between the pair of Base Stations after receiving the response message. The source Base Station can include an *Xn Removal Threshold* information element within the request message. The target Base Station can use this information element to decide whether or not to accept the request for Xn removal. If the target Base Station determines that the importance level of the Xn connection is greater than the value of the *Xn Removal Threshold* then it can respond using an *Xn Removal Failure* message to keep the existing Xn connection

★ Mobility procedures are used during the Xn handover procedure. Handover Preparation is used to initiate the handover by requesting resources at the target Base Station. The Sequence Number (SN) Status Transfer procedure is used immediately after sending the handover command to the UE, i.e. during handover execution. This procedure provides the target Base Station with information regarding PDCP Sequence Numbers and the status of successfully received uplink PDCP SDU. This information helps to ensure that Sequence Numbering is preserved during the handover and that the handover is lossless. The target Base Station uses the UE Context Release procedure during handover completion, i.e. to instruct the source Base Station to release the UE context after a successful handover. The source Base Station can use the Handover Cancel procedure to stop an ongoing Handover Preparation, e.g. due to the UE moving back towards the source Base Station

★ The Retrieve UE Context procedure may be necessary when a UE makes the transition from RRC Inactive to RRC Connected. If the UE has moved from one Base Station to another after making the transition from RRC Connected to RRC Inactive then its new serving Base Station will not have a record of the relevant UE context. In this case, the new serving Base Station has to retrieve the UE context from the old serving Base Station. This requires an Xn interface between the pair of Base Stations

★ The Retrieve UE Context procedure can also be used during RRC Connection Re-establishment. If a UE experiences radio link failure on one Base Station and then recovers on another Base Station, the new Base Station needs to retrieve the UE context from the old Base Station. The UE initiates the procedure at the new Base Station by sending an RRC Connection Re-establishment Request which includes the PCI of the old Base Station. The new Base Station queries all neighbouring Base Stations which have a matching PCI and an Xn interface

★ The Data Forwarding Address Indication procedure can be used after the Retrieve UE Context procedure. The new serving Base Station uses this procedure to provide the old serving Base Station with a forwarding address for downlink data which is buffered at the old Base Station. The old Base Station can then forward the data across the user plane of the Xn interface to help avoid packet loss

★ The RAN Paging procedure is used to transfer paging messages across the Xn interface. This becomes necessary when a UE is paged while in the RRC Inactive state. The UE is CM Connected while in the RRC Inactive state and the serving Base Station which stores the UE context maintains a UE specific signalling connection with the AMF. The AMF forwards paging messages for the UE to the serving Base Station. However, the UE may have moved to any location within the RAN Notification Area without informing the network. This means that the paging message must be broadcast by all Base Stations belonging to the relevant RAN Notification Area. The serving Base Station distributes the paging message to other Base Stations within the RAN Notification Area using the XnAP RAN Paging procedure

★ Dual Connectivity allows a UE to benefit from resource allocations provided by two Base Stations. Within the context of the Xn interface, Dual Connectivity is applicable to a pair of gNode B, or to a gNode B neighbouring a 'Next Generation eNode B (ng-eNode B). It is not applicable to a gNode B neighbouring an eNode B because the X2 interface is used for Dual Connectivity in that scenario

★ Secondary Node management procedures allow a Secondary Node to be added, modified and released. These procedures are all UE specific, i.e. a Secondary Node is added, modified or released for a specific UE connection. The signalling associated with Secondary Node addition is illustrated in Figure 42. This includes two XnAP signalling procedures – S-NG-RAN Node Addition Preparation and S-NG-RAN Node Reconfiguration Complete. The former uses the *S-Node Addition Request* / *S-Node Addition Request Acknowledge* messages, whereas the latter uses the *S-Node Reconfiguration Complete* message. The Reconfiguration Complete procedure is used to acknowledge that the UE has completed its RRC Connection Reconfiguration

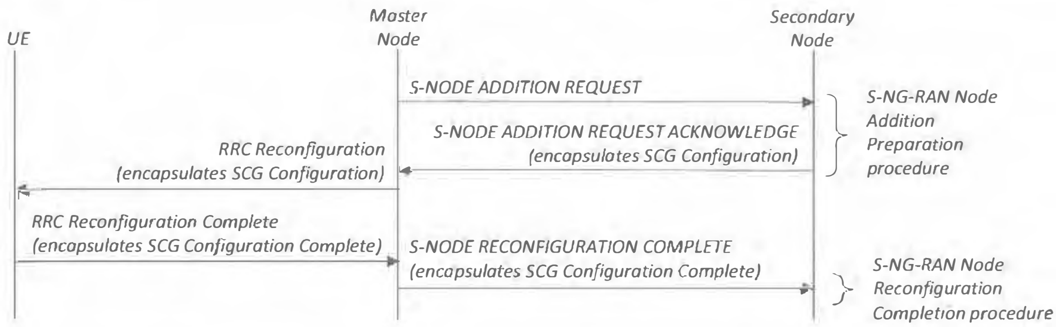


Figure 42 – Signalling procedure for Secondary Node Addition

★ The S-NG-RAN Node Modification procedure can be initiated by either the Master Node or the Secondary Node. The procedure initiated by the Master Node uses the *S-Node Modification Request* / *S-Node Modification Request Acknowledge* handshake. The procedure initiated by the Secondary Node uses the *S-Node Modification Required* / *S-Node Modification Confirm* handshake. In both cases, the S-NG-RAN Node Reconfiguration Complete procedure is used to acknowledge that the UE has completed its corresponding RRC Connection Reconfiguration procedure

★ The S-NG-RAN Node Release procedure can be initiated by either the Master Node or the Secondary Node. The procedure initiated by the Master Node uses the *S-Node Release Request* / *S-Node Release Request Acknowledge* handshake. The procedure initiated by the Secondary Node uses the *S-Node Release Required* / *S-Node Release Confirm handshake*. In both cases, the Master Node uses the UE Context Release procedure to release the UE context at the Secondary Node. This is done after the Secondary Node configuration has been released at the UE using an RRC Connection Reconfiguration procedure

★ The S-NG-RAN Node Counter Check procedure is used as a mechanism for local authentication. The procedure allows the detection of packet insertion by an intruder. The Secondary Node sends an *S-Node Counter Check Request* message to the Master Node. This message includes uplink and downlink PDCP COUNT values for the set of Data Radio Bearers (DRB). The Master Node is responsible for verifying that the COUNT values are the expected values

★ The RRC Transfer procedure is used to relay downlink RRC messages from the Master Node to the Secondary Node, and uplink RRC messages from the Secondary Node to the Master Node. This procedure also allows the Secondary Node to provide a delivery status for RRC messages which have originated from the Master Node. The Master Node can configure SRB1 and SRB2 as 'Split' SRB (described in section 1.12). This allows RRC messages to be transferred using both the Master and Secondary Nodes

★ The Notification Control Indication procedure can be used by either the Master or Secondary Node to indicate that the Guaranteed Flow Bit Rate (GFBR) belonging to an existing GBR QoS Flow can no longer be achieved. Alternatively, the procedure can be used to indicate that the GFBR can be achieved after previously indicating that it could not be achieved. The *Notification Control Indication* message specifies the relevant PDU Session and QoS Flow(s) in combination with a flag to indicate whether or not the GFBR can be achieved

★ The Activity Notification procedure can be used to indicate activity for a specific UE, or for a specific QoS Flow. Alternatively, the procedure can be used to indicate inactivity. Both indications can be used to support Radio Resource Management, e.g. the release of resources due to inactivity

★ The E-UTRA – NR Cell Resource Coordination procedure is used to exchange information between a gNode B and a Next Generation eNode B (ng-eNode B) regarding the allocation of radio resources when the two Base Stations are sharing spectrum with overlapping coverage areas. The gNode B uses the NR air-interface while the ng-eNode B uses the LTE air-interface. The two Base Stations exchange information to indicate which uplink and downlink Resource Blocks have been selected for future scheduling during specific subframes. Bitmaps are used to signal the set of selected Resource Blocks, where each bit represents a pair of Resource Blocks belonging to a specific subframe, i.e. the minimum resolution is 2 Resource Blocks. The bitmap is extended when providing information for multiple subframes

★ The user plane of the Xn interface (Xn-U) transfers application data between Base Stations. For example, data forwarding during an ongoing handover procedure, or data forwarding for a connection using Dual Connectivity. GTP-U tunnels are used to transfer the application data. These tunnels are identified using their Tunnel Endpoint Identifier (TEID). A tunnel is setup for each Data Radio Bearer (DRB)

★ The user plane protocol which runs above the GTP-U layer provides various control mechanisms associated with the transfer of downlink data. These control mechanisms include flow control, packet loss detection and successful delivery reporting. A single user plane protocol which is applicable to the Xn, F1 and X2 interfaces is specified within 3GPP TS 38.425

★ The frame formats used by the user plane protocol are illustrated in Figure 31 (section 1.5.3). PDU Type 0 is sent by the Base Station hosting the PDCP layer, i.e. the Base Station receiving the downlink data from the Core Network and sending it across the Xn interface. PDU Type 1 is sent by the Base Station receiving the downlink data across the Xn interface, i.e. it provides feedback information. PDU Type 0 is sent across the Xn interface from the node which is hosting the user plane PDCP layer. PDU Type 0 is used to add a sequence number to each downlink data packet. The receiving node uses this sequence number to detect lost packets. The node hosting the user plane PDCP layer can also use PDU Type 0 to provide various discard instructions. If the receiving node reports Radio Link outage then the node hosting the user plane PDCP layer may attempt re-transmission using a second node. If the second node reports successful delivery of the PDCP PDU, the original node can be instructed to discard the successfully delivered packets to avoid unnecessary transmission

★ The receiving node uses PDU Type 1 to report any lost packets and also to control the rate at which downlink data is sent by the node hosting the user plane PDCP layer, i.e. it provides a mechanism for flow control to avoid the downlink buffers becoming too full. The receiving node signals the sequence number of the highest successfully delivered PDCP PDU, the desired buffer level and the desired data rate. The desired data rate is specified as the number of bytes which the receiving node would like to receive within a 1 second time interval. The transmitting node uses these information elements to determine the quantity of data to forward

★ The receiving node can also use PDU Type 1 to indicate 'Radio Link Outage' or 'Radio Link Resume'. This status information is signalled using the 'Cause Value' field. The transmitting node stops forwarding data for the UE if the receiving node reports Radio Link Outage. The transmitting node can start forwarding data for the UE if the receiving node reports Radio Link Resume

★ 3GPP References: TS 38.420, TS 38.421, TS 38.422, TS 38.423, TS 38.424, TS 38.425

1.6.2 F1 INTERFACE

★ The F1 interface connects a gNode B Centralised Unit (CU) to a gNode B Distributed Unit (DU). This is applicable to the CU-DU Split Base Station architecture presented in section 1.5.3. The control plane of the F1 (F1-C) allows signalling between the CU and DU, whereas the user plane of the F1 (F1-U) allows the transfer of application data

★ Figure 43 illustrates the control plane and user plane protocol stacks belonging to the F1 interface. The control plane uses SCTP over IP, whereas the user plane uses GTP-U over UDP over IP, i.e. the transport layers are the same as those used for the Xn interface

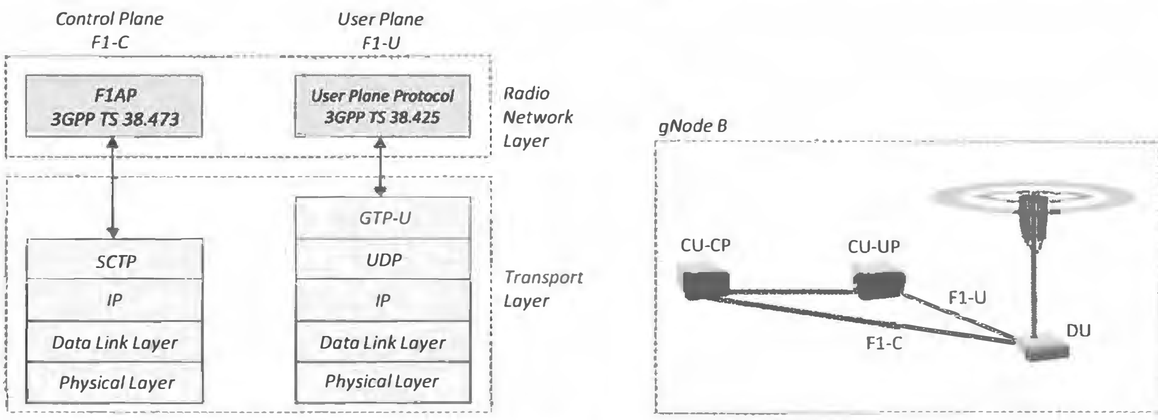


Figure 43 – Protocol stacks for F1 interface

★ Control plane signalling across the F1 interface is based upon the F1 Application Protocol (F1AP). Signalling procedures are categorised as Interface Management, UE Context Management, RRC Message Transfer, Warning Message Transmission, System Information and Paging. Table 6 presents the procedures belonging to each of these categories

★ The F1 Setup procedure is used to create a logical F1 connection between the CU and DU. It is necessary to establish an SCTP connection between the CU and DU before the F1 Setup procedure can be initiated. The DU initiates the procedure by sending an *F1 Setup Request* message, while the CU completes the procedure by returning an *F1 Setup Response*. The *F1 Setup Request* is used to inform the CU of the DU identity and the set of cells supported by the DU. The *F1 Setup Response* is used to indicate which DU cells should be activated. The CU can also use the response message to allocate a specific PCI to each cell

★ The Reset procedure can be initiated by either the CU or DU. It is used to reset either all F1AP UE contexts, or a specific subset of F1AP UE contexts. When the procedure is initiated by the CU, the DU releases all relevant resources on the F1 interface and all relevant radio resources. When the procedure is initiated by the DU, the CU releases all relevant resources on the F1 interface. The procedure uses the *Reset / Reset Acknowledge* handshake. It does not cause the F1 interface itself to reset

Interface Management Procedures
F1 Setup
Reset
Error Indication
gNB-DU Configuration Update
gNB-CU Configuration Update
gNB-DU Resource Coordination
gNB-DU Status Indication

UE Context Management Procedures
UE Context Setup
UE Context Modification (gNB-CU initiated)
UE Context Modification Required (gNB-DU initiated)
UE Context Release (gNB-CU initiated)
UE Context Release Request (gNB-DU initiated)
UE Inactivity Notification
Notify

RRC Message Transfer Procedures
Initial UL RRC Message Transfer
DL RRC Message Transfer
UL RRC Message Transfer

Warning Message Transmission Procedures
Write-Replace Warning
PWS Cancel
PWS Restart Indication
PWS Failure Indication

System Information Procedures
System Information Delivery

Paging Procedures
Paging

Table 6 – F1 Application Protocol (F1AP) Procedures

★ The Error Indication procedure can be initiated by either the CU or DU. It is used to report that an error has been detected within an incoming F1AP message. It is applicable when the error cannot be reported using a failure message belonging to the relevant signalling procedure. The procedure uses only the *Error Indication* message

★ The gNB-DU Configuration Update procedure is used by the DU to provide the CU with updated information regarding its set of supported cells. The *GNB-DU Configuration Update* message allows new cells to be added, existing cells to be modified, or existing cells to be deleted. The CU acknowledges the update using the *GNB-DU Configuration Update Acknowledge* message

★ The gNB-CU Configuration Update procedure is used by the CU to provide the DU with updated information regarding the set of cells to be activated or deactivated. The CU is able to specify the PCI to be used when activating a cell. The CU initiates the procedure using the *GNB-CU Configuration Update* message, whereas the DU acknowledges the update using the *GNB-CU Configuration Update Acknowledge* message

★ The gNB-DU Resource Coordination procedure is applicable when a gNode B and a Next Generation eNode B (ng-eNode B) share spectrum with overlapping coverage areas. The F1AP procedure is used as part of the corresponding XnAP procedure, i.e. the F1AP procedure is used to relay the XnAP messages between the CU and DU. The F1AP: *GNB-DU Resource Coordination Request* message is used to encapsulate the XnAP: *E-UTRA - NR Cell Resource Coordination Request* message. Similarly, the F1AP response encapsulates the XnAP response. The DU is the target for this procedure rather than the CU because it impacts the Packet Scheduler which is located within the DU

★ The DU can use the gNB-DU Status Indication procedure to inform the CU that it is overloaded. The *gNB-DU Status Indication* message simply includes a flag to indicate whether or not the DU is overloaded

★ The Initial UL RRC Message Transfer procedure is used to forward the initial uplink RRC message from the DU to the CU. This initial uplink message belongs to the Common Control Channel (CCCH), e.g. an *RRC Setup Request* message. The procedure is also used to inform the CU of the C-RNTI which has been allocated by the DU, and to provide the CU with the *CellGroupConfig* parameter structure which includes information regarding the RLC, MAC and Physical Layer configurations for the new connection. In addition, the procedure is used to initiate the establishment of a UE-associated connection across the F1 interface. This is done by providing the CU with a 'gNB-DU UE F1AP Identity' which can be used to address the UE-associated connection during any subsequent message transfer. The CU provides a corresponding 'gNB-CU UE F1AP Identity' within the first *DL RRC Message Transfer*.

★ The DL RRC Message Transfer procedure is used to transfer downlink RRC messages from the CU to the DU. The CU generates the RRC messages and processes them within the PDCP layer. They are then transferred to the DU as PDCP PDU. The *DL RRC Message Transfer* message can include a flag which instructs the DU to apply SRB duplication. This is applicable when the connection has been configured with duplication across multiple NR carriers. Duplication improves reliability by transmitting the same RRC message using multiple carriers. In addition, the *DL RRC Message Transfer* message can include a *RAT-Frequency Priority* information element to support prioritisation decisions within the DU when transmitting the RRC message across the air-interface

★ The UL RRC Message Transfer procedure is used to transfer uplink RRC messages from the DU to the CU. The DU receives RRC messages from the UE and processes them within the Physical, MAC and RLC layers. They are then transferred to the CU as PDCP PDU

★ Figure 44 illustrates examples of the Initial UL RRC Message Transfer, DL RRC Message Transfer and UL RRC Message Transfer procedures during connection setup

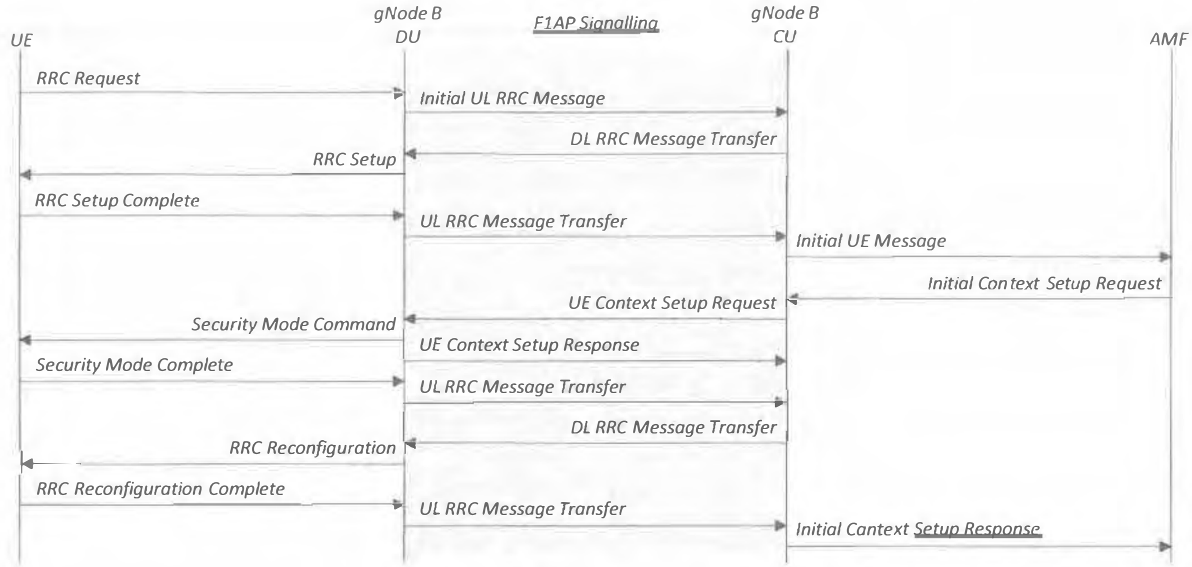


Figure 44 – F1AP signalling during Initial Connection Setup

- The F1AP: UE Context Setup procedure is also visible within Figure 44 (*UE Context Setup Request / UE Context Setup Response* handshake). This procedure is always initiated by the CU. In the case of initial connection setup, the F1AP: *UE Context Setup Request* follows the NG-C: *Initial UE Context Setup Request* from the AMF. The F1AP: *UE Context Setup Request* message can be used to configure a set of Signalling Radio Bearers (SRB) and a set of Data Radio Bearers (DRB). The DU is provided with an uplink GTP-U Tunnel Endpoint Identity (TEID) for each DRB to allow the transfer of uplink user plane data towards the CU. The F1AP: *UE Context Setup Response* message specifies the corresponding downlink GTP-U TEID. The F1AP: *UE Context Setup Request* message can also specify a set of Secondary Cells. The DU is also provided with a range of supporting information, e.g. UE capability information, DRX configuration, Resource Coordination information, serving PLMN identity and gNB-DU UE Aggregate Maximum Uplink Bit Rate
- The F1AP UE Context Setup procedure is also used during incoming handover procedures, i.e. to create a new UE context at the target DU. The signalling for an intra-CU, inter-DU handover is illustrated in Figure 45. The CU requests a new UE context at the target DU immediately after the handover decision, i.e. after receiving the RRC: *Measurement Report* from the UE

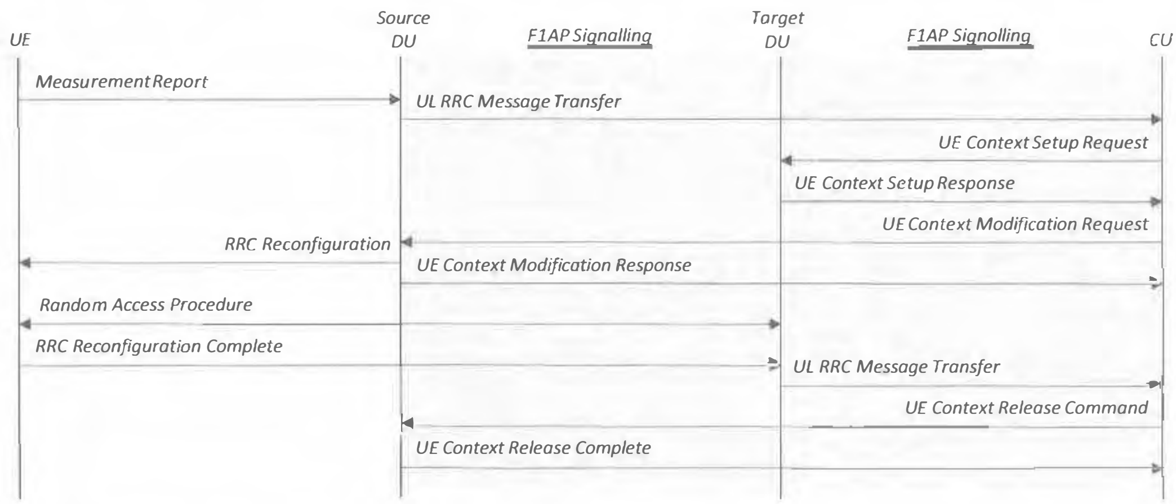


Figure 45 – F1AP signalling during Intra-CU Inter-DU handover

- An existing UE context can be modified by either the CU or DU. The CU uses the UE Context Modification procedure whereas the DU uses the UE Context Modification Required procedure
  - the CU uses the UE Context Modification procedure to update the configuration provided during Initial UE Context Setup. It can also be used to instruct the DU to stop or re-start transmission towards the UE. The *UE Context Modification Request* can be used to encapsulate an RRC message which the DU subsequently transmits to the UE. Figure 45 illustrates an example of this - the source DU transmits an *RRC Reconfiguration* after receiving it from the CU within *a UE Context Modification Request*
  - the DU uses the UE Context Modification Required procedure to update the set of downlink GTP-U TEID. It can also specify a requirement to release specific SRB and DRB. In addition, it can provide updated information regarding its cells and it can specify a requirement to update the resource co-ordination information which is applicable when a gNode B and a Next Generation eNode B (ng-eNode B) share spectrum with overlapping coverage areas (Dynamic Spectrum Sharing described in section 17)

★ An existing UE context can be released by the CU using the UE Context Release procedure. This procedure uses the *UE Context Release Command / UE Context Release Complete* handshake. The DU is able to request that the CU initiates this procedure by sending a *UE Context Release Request* message. Sending this message corresponds to the UE Context Release Request procedure

★ The UE Inactivity Notification procedure allows the DU to report the inactivity status of a UE. The DU indicates either 'Active' or 'Not Active' for each individual Data Radio Bearer (DRB)

★ The Notify procedure allows the DU to inform the CU when a specific DRB no longer satisfies its Guaranteed Flow Bit Rate (GFBR). This is applicable to GBR QoS Flows which have Notification Control enabled. The DU is also able to inform the CU if the GFBR is subsequently fulfilled again

★ The System Information Delivery procedure allows the CU to provide the DU with a list of 'Other System Information' types to be broadcast across a specific cell. 'Other System Information' includes SIB2 to SIB9. It is assumed that the actual SIB content has already been provided to the DU using an *F1 Setup Response*, a *GNB-CU Configuration Update* or a *GNB-DU Configuration Update Acknowledge* message (in contrast, the Master Information Block (MIB) and SIB1 are owned by the DU and can be provided to the CU using the *F1 Setup Request* or *GNB-DU Configuration Update* messages. The System Information Delivery procedure can be triggered by a UE request for the broadcast of Other System Information

★ The Write-Replace Warning procedure allows the CU to initiate or to overwrite the broadcast of warning messages. These messages are applicable to a Public Warning System (PWS). The procedure uses the *Write-Replace Warning Request / Write-Replace Warning Response* handshake between the CU and DU. The *Write-Replace Warning Request* message includes the PWS System Information to be broadcast. The CU can use the PWS Cancel procedure to instruct a DU to stop broadcasting PWS System Information. The DU uses the PWS Restart Indication procedure to provide a list of cells to the CU which have PWS information available. The DU uses the PWS Failure Indication procedure to provide a list of cells to the CU where PWS transmission has failed

★ The CU uses the Paging procedure when requesting the DU to page a specific UE. The *Paging* message includes the UE Identity Index which can be used to calculate the Paging Frame for the target UE. The *Paging* message also includes either a RAN UE Paging Identity (I-RNTI) or a Core Network UE Paging Identity (S-TMSI). An I-RNTI is allocated to a UE when using the RRC Inactive state. The DU is also provided with the paging DRX cycle length, the paging priority and the list of cells which are required to transmit the paging message

★ The user plane of the F1 interface (F1-U) transfers application data between CU and DU. GTP-U tunnels are used to transfer the application data. These tunnels are identified using their Tunnel Endpoint Identifier (TEID). A tunnel is setup for each Data Radio Bearer (DRB). The user plane protocol which runs above the GTP-U layer provides various control mechanisms associated with the transfer of downlink data. These control mechanisms include flow control, packet loss detection and successful delivery reporting. A single user plane protocol which is applicable to the Xn, F1 and X2 interfaces is specified within 3GPP TS 38.425. The frame formats used by the user plane protocol are illustrated in Figure 31 (section 1.5.3). PDU Type 0 is sent by the CU, whereas PDU Type 1 is sent by the DU.

★ 3GPP References: TS 38.470, TS 38.471, TS 38.472, TS 38.473, TS 38.474, TS 38.425

1.6.3 E1 INTERFACE

★ The E1 interface connects the Centralised Unit Control Plane (CU-CP) to the Centralised Unit User Plane (CU-UP). The E1 interface is only required to transfer control plane signalling. Application data is not transferred across the E1 interface

★ Figure 46 illustrates the control plane protocol stack belonging to the E1 interface. The protocol stack uses SCTP over IP, i.e. the transport layers are the same as those used for the control planes of the Xn and F1 interfaces

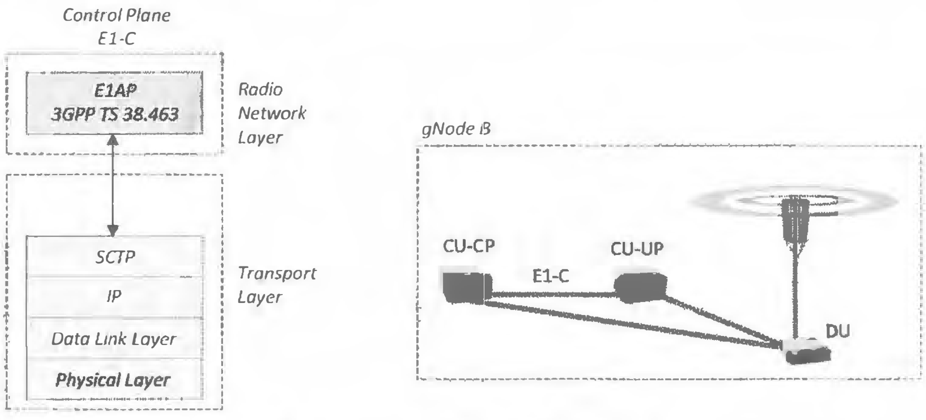


Figure 46 – Protocol stack for E1 interface

- Control plane signalling across the E1 interface is based upon the E1 Application Protocol (E1AP). Signalling procedures are categorised as Interface Management or Bearer Context Management. Table 7 presents the procedures belonging to each category

- The gNB-CU-CP E1 Setup and gNB-CU-UP E1 Setup procedures are used to create a logical E1 connection between the CU-CP and CU-UP. The former is initiated by the CU-CP whereas the latter is initiated by the CU-UP. It is not necessary to complete both procedures. The unit which initiates the setup of the SCTP connection also initiates the E1 Setup procedure. In both cases, the majority of information is transferred from the CU-UP towards the CU-CP. The CU-CP only has to provide its name during the handshake. The CU-UP provides its name in addition to Core Network support and PLMN support. Core Network support indicates support for the EPC and/or 5G Core Network. PLMN support provides a list of PLMN identities and for each PLMN the CU-UP can specify a list of Network Slices, a list of cells and a set of supported QoS parameters

- The gNB-CU-CP E1 Configuration Update and gNB-CU-UP E1 Configuration Update procedures are used to modify an existing E1 connection. The former is initiated by the CU-CP whereas the latter is initiated by the CU-UP. The procedure initiated by the CU-CP can be used to update E1 transport network layer information. The procedure initiated by the CU-UP can be used to update the set of supported PLMN

Interface Management Procedures
gNB-CU-CP E1 Setup
gNB-CU-UP E1 Setup
gNB-CU-CP E1 Configuration Update
gNB-CU-UP E1 Configuration Update
Reset
Error Indication
E1 Release

Bearer Context Management Procedures
Bearer Context Setup
Bearer Context Modification
Bearer Context Modification Required
Bearer Context Release
Bearer Context Release Request
Bearer Context Inactivity Notification
DL Data Notification
Data Usage Report
gNB-CU-UP Counter Check

Table 7 – E1 Application Protocol (E1AP) Procedures

- The CU-CP uses the Bearer Context Setup procedure to setup the resources for a new connection at the CU-UP. The CU-CP generates the security keys for user plane ciphering and integrity protection. These are provided to the CU-UP within the *Bearer Context Setup Request* message. This message also specifies the serving PLMN identity and the UE Downlink Aggregate Maximum Bit Rate. The *Bearer Context Setup Request* message can also specify whether the bearer context is to be suspended or resumed. The set of DRB are configured by providing PDCP layer information when connected to the EPC, and by providing SDAP and PDCP layer information when connected to the 5G Core Network. Inactivity timers can be provided for each DRB, or each PDU Session

- The CU-CP can use the Bearer Context Modification procedure to modify the majority of parameters which were configured during the Bearer Context Setup procedure, e.g. security keys, UE Downlink Aggregate Maximum Bit Rate, inactivity timers, PDCP and SDAP parameters. In contrast, the serving PLMN cannot be reconfigured using this procedure. The Bearer Context Modification procedure can also be used to add new PDU Sessions and new DRB, or it can be used to remove any of the existing PDU Sessions and DRB

- The CU-UP can use the Bearer Context Modification Required procedure to remove any of the existing PDU Sessions and DRB. It can also use the procedure to modify downlink transport network layer information

- The Bearer Context Release procedure can be initiated by the CU-CP. It is used to release the E1 connection for a specific UE. The CU-UP can use the Bearer Context Release Request procedure to request the CU-CP to initiate the Bearer Context Release procedure

- The CU-UP uses the Bearer Context Inactivity Notification procedure to report inactivity based upon the inactivity timers which were configured during the Bearer Context Setup or Bearer Context Modification procedures. The UE reports inactivity for specific DRB if inactivity timers were configured for individual DRB. Similarly, the UE reports inactivity for specific PDU Sessions if inactivity timers were configured for individual PDU Sessions. Alternatively, the UE reports inactivity at the UE level if a UE level inactivity timer was configured

- The CU-UP uses the DL Data Notification procedure to indicate that downlink data has arrived for a specific UE. The *DL Data Notification* message only includes the CU-CP and CU-UP UE E1AP identities

- The CU-UP uses the Data Usage Report procedure to provide the CU-UP with information regarding the quantity of uplink and downlink data transferred by a specific DRB. Data volumes are reported for one or more time windows

- The CU-UP uses the gNB-CU-UP Counter Check procedure to verify the PDCP COUNT values associated with one or more DRB. The current PDCP COUNT values are provided to the CU-CP within a *GNB-CU-UP Counter Check Request* message. The CU-CP is then responsible for checking these values with the UE, i.e. the CU-CP sends an RRC: *CounterCheck* message to the UE. The UE checks the PDCP count values and reports any differences using an RRC: *CounterCheckResponse* message. If differences are found, the CU-CP can either release the connection or report the differences to the AMF or O&M server

- 3GPP References: TS 38.460, TS 38.461, TS 38.462, TS 38.463

1.6.4 NG INTERFACE

★ The NG interface connects a gNode B to the 5G Core Network. The control plane of the NG (NG-C) allows signalling between a gNode B and an AMF. The user plane of the NG (NG-U) allows the transfer of application data between a gNode B and a UPF

★ If the CU-DU Split Base Station architecture is used, then these interfaces connect the CU to the 5G Core Network. If the CP-UP Separation Base Station architecture is used then the NG-C connects the CU-CP to one or more AMF, while the NG-U connects the CU-UP to one or more UPF

★ Figure 47 illustrates the control plane and user plane protocol stacks belonging to the NG interface. The control plane uses SCTP over IP, whereas the user plane uses GTP-U over UDP over IP, i.e. the transport layers are the same as those used for the Xn interface

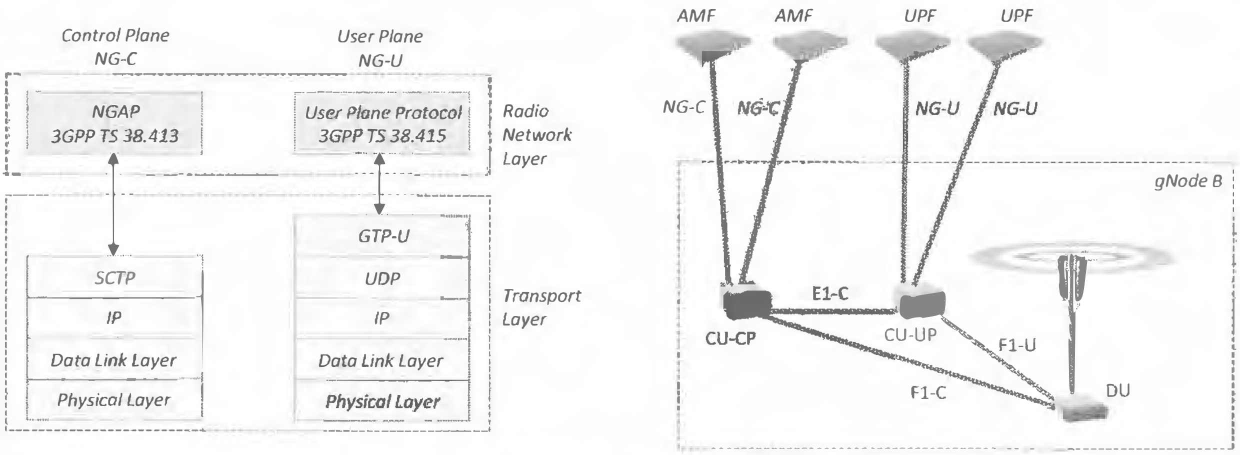


Figure 47 – Protocol stack for NG interface

★ A single Base Station can be connected to one or more AMF. The Base Station is responsible for selecting an initial AMF using its Non-Access Stratum (NAS) Node Selection function. The 5G S-TMSI can be used as an input for AMF selection if provided by the UE during RRC Connection setup. A UE can include 39 bits of its S-TMSI within the *RRC Setup Request* message and the remaining 9 bits within the *RRC Setup Complete* message. The S-TMSI is a concatenation of the AMF Set Identity, the AMF Pointer and the 5G-TMSI. This information allows the Base Station to identify the AMF to which the UE has previously registered. If the 5G S-TMSI is not provided, the Base Station can use Network Slicing information from the *RRC Setup Complete* message, i.e. the UE can provide a list of S-NSSAI within the *RRC Setup Complete* message

★ A single Base Station can be connected to one or more UPF. The SMF is responsible for selecting an appropriate UPF during the setup of a PDU Session. The selection algorithm can account for UPF load, geographic location, Network Slicing, supported features and PDU Session Type (IPv4, IPv6, Ethernet, Unstructured). Load information can help the SMF to balance network load across multiple UPF. The SMF provides information to the AMF regarding the selected UPF and the AMF informs the Base Station

★ Control plane signalling across the NG interface is based upon the NG Application Protocol (NGAP). Table 8 presents the set of NGAP signalling procedures grouped into categories

★ The NG Setup procedure is used to create a logical NG-C connection between the Base Station and an AMF. The NG Setup procedure is always initiated by the Base Station. The Base Station must know the IP address of the AMF and must establish an SCTP connection in advance of the NG Setup procedure. The procedure is based upon an *NG Setup Request / NG Setup Response* handshake

- the *NG Setup Request* is used to inform the AMF of the Base Station identity, supported Tracking Area information and the default paging DRX cycle. Tracking Area information includes the Tracking Area Code (TAC), the set of supported PLMN identities and the set of supported Network Slices for each PLMN

- the *NG Setup Response* is used to provide the Base Station with a list of supported PLMN, a list of Globally Unique AMF Identities (GUAMI) and a relative AMF capacity. A set of supported Network Slices is specified for each PLMN. Including a list of GUAMI rather than a single GUAMI highlights the possibility of a single AMF having multiple identities. The GUAMI is a concatenation of the MCC, MNC, AMF Region Identity, AMF Set Identity and AMF Pointer. All AMF within a specific AMF Set support the same Network Slices. Configuring an AMF to belong to multiple AMF Sets allows the AMF to support different combinations of Network Slices. The *NG Setup Response* can also specify a back-up AMF for each GUAMI to be applied in case of failure. The relative AMF capacity can be used by the Base Station when load balancing connections across AMF

★ The NG Reset procedure can be initiated by either the Base Station or the AMF. The Base Station initiates the procedure if there has been a failure at the Base Station resulting in the loss of NGAP UE context information. Similarly, the AMF initiates the procedure if there has been a failure at the AMF. The procedure allows the removal of all NGAP UE contexts, or a specific subset of NGAP UE contexts

Interface Management Procedures
NG Setup
NG Reset
RAN Configuration Update
AMF Configuration Update
Error Indication
AMF Status Indication
Overload Start
Overload Stop

UE Mobility Management Procedures
Handover Preparation
Handover Resource Allocation
Handover Notification
Path Switch Request
Handover Cancellation
Uplink RAN Status Transfer
Downlink RAN Status Transfer

Paging Procedures
Paging

Transport of NAS Messages Procedures
Initial UE Message
Downlink NAS Transport
Uplink NAS Transport
NAS Non Delivery Indication
Reroute NAS Request

Trace Procedures
Trace Start
Trace Failure Indication
Cell Traffic Trace
Deactivate Trace

UE Radio Capability Management Procedures
UE Radio Capability Info Indication
UE Radio Capability Check

UE Context Management Procedures
Initial Context Setup
UE Context Modification
RRC Inactive Transition Report
UE Context Release Request
UE Context Release

PDU Session Management Procedures
PDU Session Resource Setup
PDU Session Resource Modify
PDU Session Resource Modify Indication
PDU Session Resource Notify
PDU Session Resource Release

Configuration Transfer Procedures
Uplink RAN Configuration Transfer
Downlink RAN Configuration Transfer

Warning Message Transmission Procedures
Write-Replace Warning
PWS Cancel
PWS Restart Indication
PWS Failure Indication

NRPPa Transport Procedures
Downlink UE Associated NRPPA Transport
Uplink UE Associated NRPPA Transport
Downlink Non-UE Associated NRPPA Transport
Uplink Non-UE Associated NRPPA Transport

Location Reporting Procedures
Location Reporting Control
Location Report
Location Report Failure Indication

UE TNLA Binding Procedures
UE TNLA Binding Release

Table 8 – NG Application Protocol (NGAP) Procedures

★ The RAN Configuration Update procedure is initiated by the Base Station. It is used to provide updates regarding the supported Tracking Area information and the default paging DRX cycle. The Tracking Area information includes the Tracking Area Code (TAC), the set of supported PLMN identities and the set of supported Network Slices for each PLMN

★ The AMF Configuration Update procedure is initiated by the AMF. It is used to provide updates regarding the supported PLMN, a list of Globally Unique AMF Identities (GUAMI) and a relative AMF capacity. It can also be used to add, remove or update Transport Network Layer (TNL) Associations which include an IP address, usage information (UE associated signalling, non-UE associated signalling, or both) and a Weight Factor used for load balancing

★ The Error Indication procedure can be initiated by either the Base Station or AMF. It is used to report that an error has been detected within an incoming message. It is applicable when the error cannot be reported using a failure message belonging to the relevant signalling procedure. The procedure uses only the *Error Indication* message

★ The AMF Status Indication procedure allows the AMF to provide the Base Station with information regarding unavailable GUAMI and to specify an appropriate back-up AMF

★ The AMF uses the Overload Start procedure to restrict the signalling load from the Base Station. Overload can be indicated for the AMF as a whole or for specific Network Slices. The *Overload Start* message can include an 'AMF Overload Response' information element which specifies the types of signalling traffic to reject, e.g. reject RRC Connection establishments for non-emergency mobile originated data. The *Overload Start* message can also include an 'AMF Traffic Load Reduction Indication' to specify the percentage of traffic to reject. The AMF uses the Overload Stop procedure to subsequently indicate that the overload situation has ended and normal operation can resume

★ The Initial Context Setup procedure uses the *NGAP: Initial Context Setup Request / Initial Context Setup Response* handshake to generate a UE context at the Base Station. An example of this procedure based upon UE registration is illustrated in Figure 48. The NGAP: *Initial UE Message* triggers the AMF to start the procedure. The AMF uses the *Initial Context Setup Request* to signal the UE security capabilities and a security key. The AMF also specifies the set of Network Slices which the UE is permitted to use and the Globally Unique AMF Identity (GUAMI). In addition, the message can include the UE Radio Capability; a Mobility Restriction List; a request for the Base Station to inform the AMF when the UE enters or leaves the RRC Inactive State; and an Emergency Fallback Indicator. The *Initial Context Setup Request* can also encapsulate a NAS message to be forwarded to the UE. The example in Figure 48 illustrates the *Registration Accept* encapsulated within the *Initial Context Setup Request*. In addition, the *Initial Context Setup Request* can be used to request the setup of a PDU Session, and in this case a second NAS PDU can be included for the UE. The Base Station uses the *Initial Context Setup Response* message to acknowledge the setup of any PDU sessions which were requested by the AMF

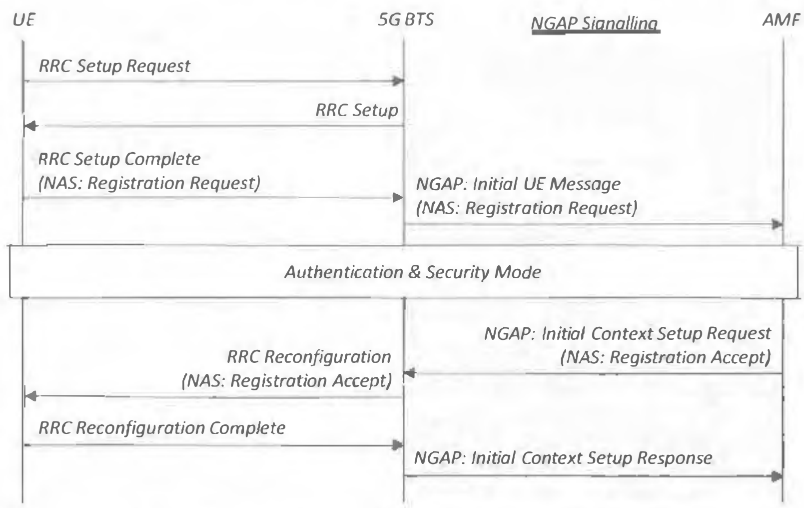


Figure 48 – Example of NGAP Initial Context Setup procedure

★ The Base Station uses the RRC Inactive Transition Report procedure to inform the AMF when the UE moves between the RRC Connected and RRC Inactive states. The *RRC Inactive Transition Report* includes a flag to indicate that the UE has moved into RRC Connected or has moved into RRC Inactive. The report also specifies the UE location in terms of Tracking Area Identity (TAI) and Cell Global Identity (CGI). The age of the location is also specified using a time stamp

★ The Base Station uses the UE Context Release Request procedure to trigger the AMF to initiate the UE Context Release procedure. The UE Context Release Request procedure involves the Base Station sending an NGAP: *UE Context Release Request* message to the AMF. The AMF then initiates the UE Context Release by sending an NGAP: *UE Context Release Command* to the Base Station. The Base Station completes the procedure by returning an NGAP: *UE Context Release Complete* message. Alternatively, the AMF can initiate the UE Context Release procedure without being triggered by the Base Station

★ PDU Sessions are managed by the SMF whereas NGAP messages are exchanged between the Base Station and AMF. This means that NGAP messages are used to package the messages being sent to and from the SMF. The AMF is responsible for packaging these messages in the downlink direction, and for extracting them in the uplink direction, i.e. the AMF acts as a router between the Base Station and AMF

★ The PDU Session Resource Setup procedure involves the SMF providing the AMF with a *PDU Session Resource Setup Request Transfer* parameter structure. The AMF packages this parameter structure within an NGAP: *PDU Session Resource Setup Request* message and forwards it to the Base Station. The parameter structure from the SMF specifies the set of QoS Flows to be setup for the PDU Session. It also provides the Base Station with the IP address and GTP Tunnel Endpoint Identity (TEID) for forwarding uplink data towards the User Plane Function (UPF). In addition, the Base Station is told the PDU Session type (IPv4, IPv6, IPv4v6, Ethernet or Unstructured) and the PDU Session Aggregate Maximum Bit Rate (AMBR). The Base Station responds by packaging a *PDU Session Resource Setup Response Transfer* parameter structure within an NGAP: *PDU Session Resource Setup Response* message. The AMF extracts this parameter structure and forwards it to the SMF

★ The PDU Session Resource Notify procedure allows the Base Station to inform the SMF (via the AMF) that a GBR QoS Flow is no longer achieving its Guaranteed Flow Bit Rate (GFBR). The SMF may then modify or release the QoS Flow. The Base Station can also use the procedure to inform the SMF that a GBR QoS Flow is achieving its GFBR after previously failing to achieve its GFBR. Alternatively, the Base Station can use the procedure to inform the SMF that resources for a specific PDU Session have been released

★ Figure 49 illustrates the combination of three NGAP UE Mobility Management procedures: Handover Preparation, Handover Resource Allocation and Handover Notification. These procedures are illustrated as part of an NG based handover (in contrast to an Xn based Handover)

★ The NGAP Handover Preparation procedure is applicable to both intra and inter-system NG based handovers. The procedure is initiated by the source Base Station sending an NGAP: *Handover Required* message to the AMF. This message includes content which is read by the AMF. It also includes content which is forwarded to the SMF and content which is forwarded to the target Base Station. The AMF is provided with information regarding the handover type and cause, as well as the identity of the target Base Station. The handover type can be set to {intra-NR, NR to LTE-EPC, NR to LTE-5GC, LTE to NR}. The SMF is informed whether or not the source Base Station has a direct path for forwarding data towards the target Base Station, i.e. an Xn interface for intra-NR handovers. The target Base Station is provided with information regarding the set of incoming PDU Sessions and QoS Flows. This includes the mapping between QoS Flows and Data Radio Bearers (DRB). The target Base Station is also provided with information regarding the UE capability, the Access Stratum configuration and the Radio Resource Management configuration

★ The NGAP Handover Resource Allocation procedure involves signalling between the AMF and the target Base Station. The example illustrated in Figure 49 assumes that a single AMF serves both the source and target Base Stations. It is also possible that the handover procedure triggers a change of serving AMF. The Handover Resource Allocation procedure is initiated by the AMF sending an NGAP: *Handover Request* to the target base station. The NGAP: *Handover Request Acknowledge* includes the *RRC Connection Reconfiguration* message which will be sent to the UE as a handover command

★ The NGAP Handover Preparation procedure is completed when the AMF responds to the source Base Station with an NGAP: *Handover Command* message. This message is used to start the handover execution phase. The NGAP: *Handover Command* forwards the *RRC Connection Reconfiguration* message to the source Base Station. The source Base Station is then able to use SRB1 to transmit the *RRC Connection Reconfiguration* towards the UE

★ The Handover Notification procedure is used to inform the AMF that the UE has been identified at the target Base Station and that the handover has been completed

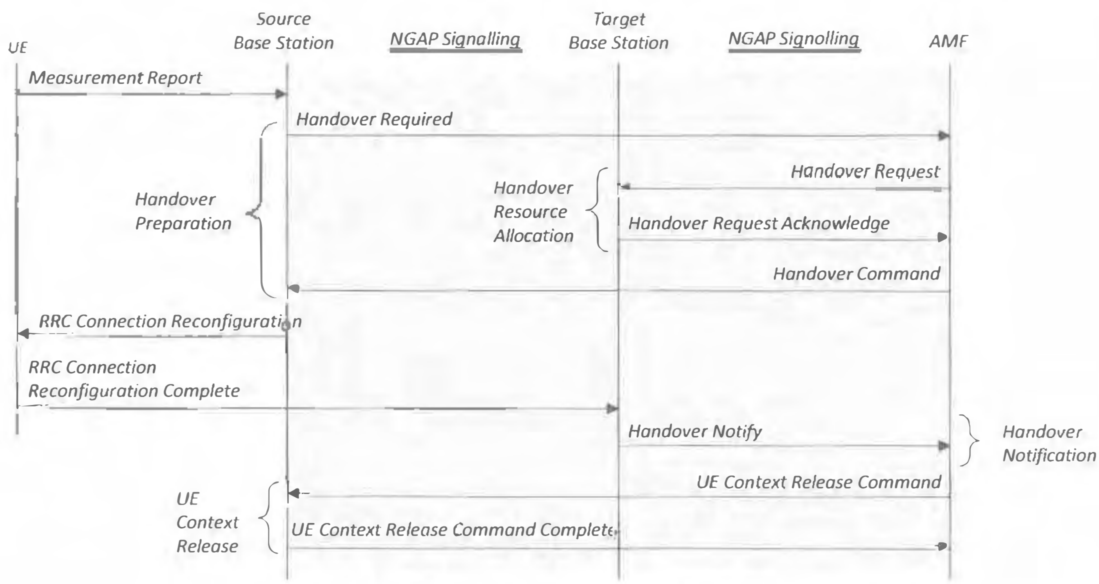


Figure 49 – NGAP signalling during an NG based handover

★ The Path Switch Request procedure can be used as part of an Xn based handover to relocate the NG-U connection from the source Base Station to the target Base Station. This procedure can also be used when resuming a connection from RRC Inactive if the connection is being resumed on a new Base Station

★ The Paging procedure is used to forward an NGAP: *Paging* message to a Base Station. This message includes the UE identity, the target Tracking Area Identities and information regarding the timing of the paging DRX cycle. The message can also specify recommended cells for paging and a paging priority

★ Non Access Stratum (NAS) signalling procedures are completed between the UE and AMF/SMF. The NGAP procedures for the Transport of NAS Messages are used to transfer NAS messages between the Base Station and AMF, i.e. the NGAP messages are used to package NAS messages. The Base Station uses the Initial UE Message procedure to forward the first uplink NAS message to the AMF. This procedure initiates the setup of an NG-C connection for the UE. The AMF can use the Reroute NAS Request procedure to request that the Base Station sends the NGAP: *Initial UE Message* to a different AMF. The NAS Non-Delivery Indication procedure allows the Base Station to report a failure to deliver a downlink NAS message to a UE

★ 3GPP References: TS 38.413

1.6.5 X2 INTERFACE

★ The X2 interface was originally introduced within the release 8 version of the 3GPP specifications. Its primary function is to provide control plane and user plane connectivity between two LTE Base Stations (eNode B). The X2 interface was updated within the release 15 version of the specifications to allow connectivity between an eNode B and a gNode B. This is a requirement for the Non-Standalone Base Station architectures 3, 3a and 3x

★ Figure 50 illustrates the control plane and user plane protocol stacks belonging to the X2 interface. The control plane uses SCTP over IP, whereas the user plane uses GTP-U over UDP over IP

★ The X2 interface can be internal to a Base Station cabinet rather than using the transport network. The eNode B and gNode B belonging to the Non-Standalone Base Station architecture can be co-sited. The hardware implementation may allow both Base Stations to be accommodated within a single cabinet. In this case, the cabinet is likely to provide direct connectivity between the two Base Stations. This direct connection is still an X2 interface but does not require the use of a transport network

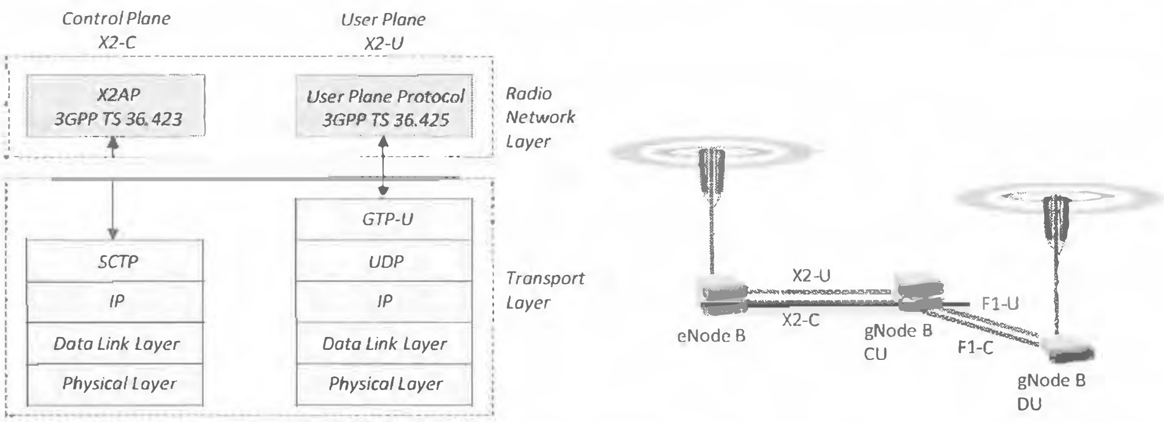


Figure 50 – Protocol stacks for X2 interface

★ Control plane signalling across the X2 interface is based upon the X2 Application Protocol (X2AP) specified within 3GPP TS 36.423. Signalling procedures are categorised as Global, Mobility, Dual Connectivity or E-UTRAN - NR Dual Connectivity. Table 9 presents the set of E-UTRAN - NR Dual Connectivity procedures

E-UTRAN - NR Dual Connectivity Procedures	E-UTRAN - NR Dual Connectivity Procedures
EN-DC X2 Setup	MeNB Initiated SgNB Release
EN-DC Configuration Update	SgNB Initiated SgNB Release
EN-DC Cell Activation	SgNB Counter Check
SgNB Addition Preparation	RRC Transfer
SgNB Reconfiguration Complete	Secondary RAT Data Usage Report
MeNB Initiated SgNB Modification Preparation	Partial Reset of EN-DC
SgNB Initiated SgNB Modification	E-UTRA – NR Cell Resource Coordination
SgNB Change	SgNB Activity Notification

Table 9 – X2 Application Protocol (X2AP) Procedures for E-UTRAN – NR Dual Connectivity

★ The RRC Transfer procedure is used to relay RRC messages between the eNode B and gNode B. The eNode B hosts the RRC protocol stack layer for SRB1 and SRB2 when using the Non-Standalone Base Station architectures 3, 3a and 3x. The eNode B can configure SRB1 and SRB2 as 'Split' SRB which requires SRB messages to be forwarded across the X2 interface

★ The Secondary RAT Data Usage Report allows the gNode B to report uplink and downlink data volumes transferred by each E-RAB. The eNode B can forward this information to the MME for charging purposes. The S1 Application Protocol (S1AP) has been updated to allow the transfer of these reports

★ The SgNB Activity Notification procedure allows the gNode B to indicate activity for a specific UE, or for a specific E-RAB. Alternatively, the gNode B can use the procedure to indicate inactivity. Both indications can be used to support Radio Resource Management, e.g. the release of resources due to inactivity

★ The user plane of the X2 interface (X2-U) transfers application data between the gNode B and eNode B using GTP-U tunnels. The LTE user plane protocol specified within 3GPP TS 36.425 is used for this purpose. Only minor changes were made for the purposes of the Non-Standalone Base Station architecture

★ 3GPP References: TS 36.423, TS 36.425

1.7 PROTOCOL STACKS

1.7.1 USER PLANE

★ The user plane protocol stack is responsible for transferring application data between the end user and the application server

★ Figure 51 illustrates the user plane protocol stack when assuming a TCP/IP application and a Standalone Base Station connected to the 5G Core Network. The use of a TCP/IP application means that the UE has setup a PDU Session with the type configured as 'IPv4', 'IPv6' or 'IPv4v6'. Other examples could be based upon PDU Sessions which have been setup with the type configured as 'Ethernet' or 'Unstructured'

★ Unstructured packets do not have headers to support routing towards the application server, i.e. there is no IP header specifying a target IP address, nor is there an Ethernet header specifying a target MAC address. Unstructured packet transfer may be appropriate for applications generating large volumes of small packets. In this case, the overhead generated by an IP or Ethernet header is very high and data transfer with these headers would be inefficient. In the case of Unstructured packet transfer, the anchor UPF establishes a tunnel across the N6 interface between itself and the application server. This tunnel may use UDP/IP so headers are added for transfer across the N6 interface, but headers are not transferred across the air-interface nor the core network

★ The example illustrated in Figure 51 illustrates that application data is relayed between the UE and Application Server using a Base Station (gNode B) and a pair of User Plane Functions (UPF). The UPF providing connectivity towards the Application Server is known as the Anchor UPF. The Anchor UPF supports the Data Network Name (DNN) which represents the exit point towards the Data Network (DN) which hosts the Application Server. The PDU Session terminates at the DNN within the Anchor UPF

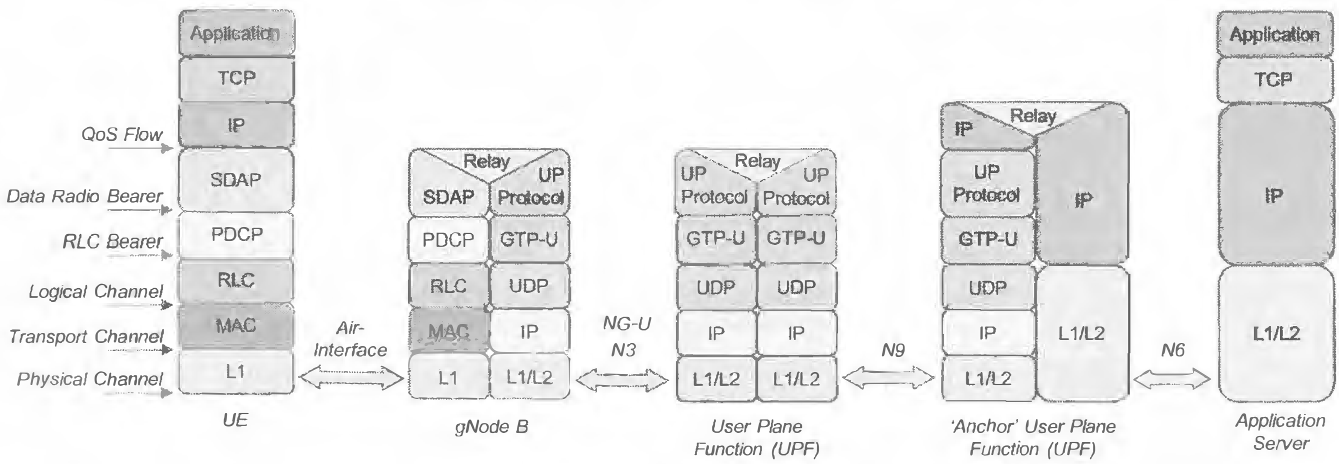


Figure 51 – User plane protocol stack for Standalone Base Station (assuming TCP/IP application)

★ The application layer represents the highest layer within the user plane protocol stack and is present at both the UE and Application Server. The application layer uses the lower layers to provide a data transfer service. A TCP or UDP layer may be immediately below the application layer. Example applications using either TCP or UDP are:

- o Hypertext Transfer Protocol (HTTP) over TCP can be used for internet browsing
- o File Transfer Protocol (FTP) over TCP can be used to transfer files
- o Simple Mail Transfer Protocol (SMTP) over TCP can be used to send and receive email
- o Telnet over TCP can be used for remote access
- o Real-time Transport Protocol (RTP) over UDP can be used to stream audio and video content
- o RTP over UDP can also be used for Voice over IP (VoIP) connections

★ Transmission Control Protocol (TCP) provides reliable data transfer between the UE and application server. Re-transmissions can be triggered when packets are not received successfully. Re-transmissions at the RLC and MAC layers should help to minimise the requirement for TCP re-transmissions. TCP includes a flow control mechanism to ensure that the rate at which data is sent matches the bandwidth of the connection. TCP headers include a sequence number to allow in-order delivery of the packets. TCP headers are typically 20 bytes but can be larger if optional content is included

★ User Datagram Protocol (UDP) provides less reliable data transfer between the UE and application server. UDP does not trigger re-transmissions, nor does the header include a sequence number so packets can be delivered out-of-order. UDP is relatively lightweight because it does not require any signalling to establish a connection, i.e. UDP is a connectionless protocol, in contrast to TCP which is a connection oriented protocol. The application layer above UDP may have its own flow control and error checking mechanisms. UDP generates a lower overhead than TCP with a header size of 8 bytes

- ★ The Internet Protocol (IP) layer at the UE, anchor UPF and Application Server is used to route user plane data across the packet switched network. Figure 51 illustrates a direct connection between the anchor UPF and application server. In practice, there may be a series of IP routers which use the IP layer to forward traffic in the appropriate direction. The UE uses the IP address allocated by the SMF during connection establishment. The IP layer can be based upon either IPv4 or IPv6. IPv4 headers are typically 20 bytes whereas IPv6 headers are typically 40 bytes. Header sizes can be greater if optional content is included

- ★ The Service Data Adaptation Protocol (SDAP) layer is specified in 3GPP TS 37.324. This protocol belongs to the 37 series of specifications rather than the 38 series because a common SDAP protocol has been defined for both E-UTRAN and New Radio (NR). The SDAP layer is the highest of the Radio Access Network protocol stack layers, i.e. it is the highest layer which operates between the UE and Base Station. The SDAP layer is applicable to E-UTRAN when an eNode B is connected to the 5G core network. The SDAP layer provides the mapping between QoS Flows belonging to a PDU Session (at the top of the SDAP layer) and Data Radio Bearers (at the bottom of the SDAP layer)

- ★ The Packet Data Convergence Protocol (PDCP) layer is specified by 3GPP TS 38.323. The PDCP layer provides header compression, ciphering and integrity protection for user plane data. Header compression is completed using the Robust Header Compression (RoHC) protocol. RoHC is capable of compressing IP, UDP, RTP and TCP headers. Header compression is important because the overheads generated by the higher layers can become large and without compression they would consume valuable air-interface resources. Header compression is less important across the fixed network because bandwidths are significantly greater. The PDCP header for user plane data is either 2 or 3 bytes depending upon the length of Sequence Number. In addition, integrity protection may add 4 bytes of MAC-I data to the end of the packet. The PDCP layer is also responsible for re-ordering packets and providing in-sequence delivery to the higher layers

- ★ The Radio Link Control (RLC) layer is specified by 3GPP TS 38.322. Similar to the SDAP and PDCP layers, it belongs to the Radio Access Network and operates between the UE and Base Station. The RLC layer can be used to transfer user plane data in one of two modes – Unacknowledged Mode or Acknowledged Mode (Transparent Mode RLC is not applicable to the user plane):

    - o Unacknowledged Mode (UM) supports segmentation of higher layer packets. This allows large packets to be divided into smaller packets when the allocated air-interface resources are not sufficient to accommodate the original packet size. The header size is a single byte when the RLC PDU includes a complete RLC SDU, i.e. segmentation has not been necessary. In this case, the RLC header does not include a Sequence Number. When segmentation is applied, the RLC PDU which transfers the first segment includes either a 6 bit or 12 bit Sequence Number (the RLC Sequence Number size is configured by the RRC layer). These Sequence Numbers lead to header sizes of 1 or 2 bytes respectively. RLC PDU which transfer subsequent segments also include a 16 bit Segmentation Offset leading to header sizes of 3 or 4 bytes

    - o Acknowledged Mode (AM) supports an Automatic Repeat Request (ARQ) protocol to provide a reliable data transfer service, i.e. AM RLC supports re-transmissions. The receiver returns Status PDU to provide acknowledgement information to the sender. AM RLC also supports both segmentation and re-segmentation of higher layer packets. Segmentation is similar to that provided by UM RLC. Re-segmentation is necessary if a re-transmission is required but the capacity of the allocated air-interface resources has been reduced. AM RLC PDU always contain either a 12 bit or 18 bit Sequence Number leading to header sizes of 2 or 3 bytes respectively. The inclusion of a 2 byte Segmentation Offset increases the header size to 4 or 5 bytes

- ★ The Medium Access Control (MAC) layer is specified by 3GPP TS 38.321. It also belongs to the Radio Access Network and operates between the UE and Base Station. The MAC layer is responsible for prioritising and multiplexing logical channel data received from the RLC layer. The MAC layer generates Transport Blocks from the logical channel data and passes them down to the Physical layer. The MAC layer supports the Hybrid Automatic Repeat Request (HARQ) protocol for reliable data transfer with fast re-transmissions. In addition, the MAC layer supports fast layer 2 signalling between the UE and Base Station. This is achieved by including MAC Control Elements within the Transport Blocks passed to the Physical layer. 3GPP has specified a relatively large set of MAC Control Elements for a range of signalling purposes, e.g. providing Timing Advance Commands, reporting Buffer Status and Power Headroom, activation/deactivation of Secondary Cells, triggering Semi-Persistent SRS transmissions and triggering Semi-Persistent CSI reporting. When using the Centralised Unit – Distributed Unit Base Station architecture, layer 3 signalling is managed by the Centralised Unit, while layer 2 signalling is managed by the Distributed Unit. The MAC header has a variable size dependent upon the number of logical channels being multiplexed, the inclusion of any Length Indicators and the inclusion of any MAC Control Elements

- ★ Layer 1 (L1) between the UE and Base Station is specified by 3GPP TS 38.211, 38.212, 38.213 and 38.214. Layer 1 provides Physical layer processing as well as transmission and reception across the air-interface. Cyclic Redundancy Check (CRC) bits are added to each Transport Block at the transmitter to allow error detection at the receiver. Channel coding is applied to generate redundancy and increase resilience to the radio propagation channel. Interleaving is applied to improve the performance of decoding at the receiver by randomising bursts of contiguous bit errors generated by fades in the propagation channel. Modulation is applied prior to mapping onto the air-interface resources, using CP-OFDM in the downlink and either CP-OFDM or DFT-S-FDMA in the uplink

- ★ The NG-U interface between the Base Station and User Plane Function (UPF) makes use of the PDU Session User Plane protocol specified by 3GPP TS 38.415. This protocol is responsible for adding header information which identifies the QoS Flow. The remaining protocol stack layers provide a GTP-U tunnel for each PDU Session, i.e. the header information added by the PDU Session User Plane protocol identifies the QoS Flow while the GTP-U Tunnel Endpoint Identifier (TEID) identifies the PDU Session

- ★ The GPRS Tunnelling Protocol User Plane (GTP-U) is specified by 3GPP TS 29.281. GTP-U tunnels are used to transfer user plane data between a pair of GTP-U tunnel endpoints. The Base Station and UPF represent one pair of endpoints. The TEID within the GTP-U header defines the tunnel to which the data belongs. TEID values for the tunnel across the NG-U interface are communicated using NG Application Protocol (NGAP) signalling. GTP-U packets are transferred using UDP over IP

★ The N9 interface which provides the connection between a pair of UPF is also based upon the PDU Session User Plane protocol operating above a GTP-U tunnel. Similar to the NG-U interface, there is a GTP-U tunnel for each PDU Session. These GTP-U tunnels remain configured when a UE moves to CM-IDLE/RRC IDLE. This is in contrast to the NG-U interface where GTP-U tunnels are released when UE move to CM-IDLE/RRC IDLE. 3GPP is studying alternatives to GTP-U for the N9 interface so this protocol stack may change within the timescales of release 16 and release 17

★ There are additional user plane protocol stacks for the Xn and F1 interfaces. The Xn interface allows user plane data to be transferred between neighbouring Base Stations, while the F1 interface allows user plane data to be transferred between a Base Station Centralised Unit (CU) and a Base Station Distributed Unit (DU). These interfaces and protocol stacks are presented in section 1.6

★ Figure 52 illustrates the equivalent user plane protocol stack when a Non-Standalone Base Station is connected to the 4G Core Network. This example assumes that a 5G Base Station provides the user plane connectivity to the 4G Core Network

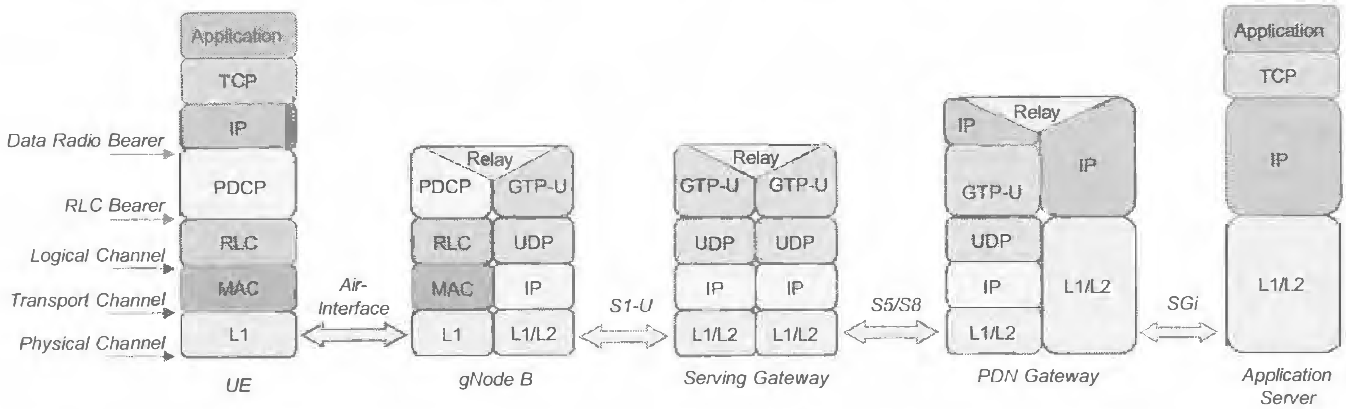


Figure 52 – User plane protocol stack for Non-Standalone gNode B (assuming TCP/IP application)

★ In this case, the 5G Base Station and UE do not require the SDAP layer. The SDAP layer is used to map QoS Flows onto Data Radio Bearers (DRB). QoS Flows do not exist when using the 4G Core Network so there is no requirement for the SDAP layer. The 4G Core Network uses EPS Bearers rather than PDU Sessions and QoS Flows

★ The pair of User Plane Functions (UPF) are replaced by the Serving Gateway and PDN Gateway but the protocol stacks are very similar, i.e. GTP-U tunnels are used to transport packets across the Core Network. QoS Flows do not exist so it is not necessary to use the User Plane protocol to identify QoS Flows within a GTP-U tunnel. There is a single GTP-U tunnel for each EPS Bearer

★ 3GPP References: TS 38.300, TS 38.414, TS 38.415, TS 29.281, TR 29.891

1.7.2 CONTROL PLANE

★ The control plane protocol stack is responsible for transferring signalling messages

★ The Radio Resource Control (RRC) control plane protocol stack is used for signalling between the UE and Base Station, i.e. the RRC control plane protocol stack is fully contained within the Radio Access Network, and is shown in Figure 53

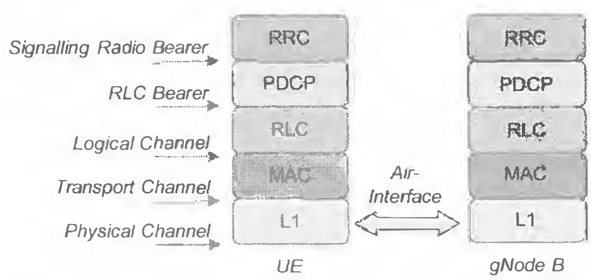


Figure 53 – RRC control plane protocol stack

★ The RRC layer is specified by 3GPP TS 38.331. RRC messages are transferred using the set of Signalling Radio Bearers (SRB) described in section 1.12. The set of SRB includes SRB 0 which transfers messages using the CCCH logical channel, and SRB 1, SRB 2 and SRB 3 which transfer messages using the DCCH logical channel. Example RRC signalling procedures include paging, RRC connection establishment, RRC connection reconfiguration, and RRC connection release

★ The Packet Data Convergence Protocol (PDCP) layer is specified by 3GPP TS 38.323. Similar to the User Plane protocol stack, the PDCP layer provides ciphering and integrity protection. The header compression function of the PDCP layer is not applicable to the control plane. The PDCP Sequence Number is always 12 bits when transferring signalling messages. A larger Sequence Number is not necessary because the SRB do not generate a continuous flow of packets, i.e. the Sequence Number range is unlikely to become exhausted. The Sequence Number generates a PDCP header size of 2 bytes. In addition, 4 bytes of MAC-I integrity protection information is added to the end of the packet

★ The Radio Link Control (RLC) layer is specified by 3GPP TS 38.322. The RLC layer can be used to transfer control plane signalling in one of two modes – Transparent Mode or Acknowledged Mode (Unacknowledged Mode is not applicable to the control plane):

- o Transparent Mode (TM) is used by SRB 0 and the CCCH logical channel. TM does not segment the higher layer PDU. Nor does it add any header information. This is important from the perspective of coverage and the success rate of the Random Access procedure. MSG3 belonging to the Random Access procedure uses SRB 0 and the CCCH logical channel, i.e. MSG3 cannot be segmented. This means that coverage must be sufficiently good to transfer MSG3 with a single resource allocation. The size of MSG3 is always kept to a minimum to help maximise the coverage

- o Acknowledged Mode (AM) supports an Automatic Repeat Request (ARQ) protocol to provide a reliable data transfer service, i.e. AM RLC supports re-transmissions. The receiver returns Status PDU to provide acknowledgement information to the sender. AM RLC also supports both segmentation and re-segmentation of higher layer packets. Re-segmentation is necessary if a re-transmission is required but the capacity of the allocated air-interface resources has been reduced. AM RLC PDU always contain either a 12 bit or 18 bit Sequence Number leading to header sizes of 2 or 3 bytes respectively. The inclusion of a 2 byte Segmentation Offset increases the header size to 4 or 5 bytes

★ The Medium Access Control (MAC) layer is specified by 3GPP TS 38.321. The MAC layer is responsible for prioritising and multiplexing logical channel data received from the RLC layer. The MAC layer generates Transport Blocks from the logical channel data and passes them down to the Physical layer. The MAC layer supports the Hybrid Automatic Repeat Request (HARQ) protocol for reliable data transfer with fast re-transmissions. In addition, the MAC layer supports fast layer 2 signalling between the UE and Base Station. This is achieved by including MAC Control Elements within the Transport Blocks passed to the Physical layer. The MAC header has a variable size dependent upon the number of logical channels being multiplexed, the inclusion of any Length Indicators and the inclusion of any MAC Control Elements

★ Layer 1 (L1) between the UE and Base Station is specified by 3GPP TS 38.211, 38.212, 38.213 and 38.214. It provides Physical layer processing as well as transmission and reception across the air-interface. Cyclic Redundancy Check (CRC) bits are added to each Transport Block at the transmitter to allow error detection at the receiver. Channel coding is applied to generate redundancy and increase resilience to the radio propagation channel. Interleaving is applied to improve the performance of decoding at the receiver by randomising bursts of contiguous bit errors generated by fades in the propagation channel. Modulation is applied prior to mapping onto the air-interface resources, using CP-OFDM in the downlink and either CP-OFDM or DFT-S-FDMA in the uplink

★ There are additional control plane protocol stacks for the Xn, F1, E1 and NG interfaces. The Xn interface allows control plane data to be transferred between neighbouring Base Stations, while the F1 interface allows control plane data to be transferred between a Base Station Centralised Unit (CU) and a Base Station Distributed Unit (DU). The E1 interface allows control plane data to be transferred between a CU-CP and a CU-UP when using the Control Plane (CP) – User Plane (UP) Separation Base Station architecture. These interfaces and protocol stacks are presented in section 1.6

★ The RRC protocol stack shown in Figure 53, and the NG protocol stack shown in section 1.6.4 can be combined to generate the control plane protocol stack used to transfer Non-Access Stratum (NAS) signalling messages between the UE and AMF/SMF. The NAS control plane protocol stack is shown in Figure 54

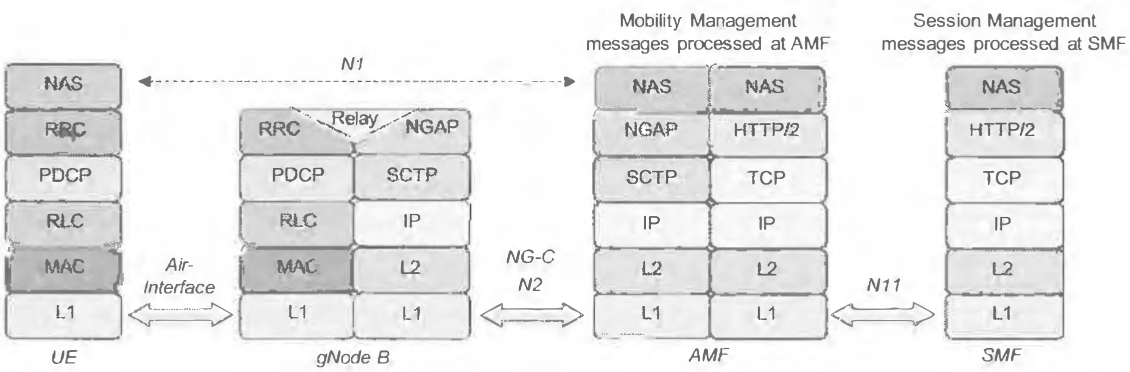


Figure 54 – Non-Access Stratum (NAS) control plane protocol stack

★ NAS messages allow signalling between the UE and AMF/SMF. Mobility Management messages are exchanged with the AMF, whereas Session Management messages are exchanged with the SMF. The logical N1 interface only connects the UE to the AMF but the AMF is responsible for providing connectivity towards the SMF, i.e. the AMF receives downlink Session Management messages from the SMF and forwards them towards the UE, and the AMF receives uplink Session Management messages from the UE and forwards them towards the SMF

★ The NG-C interface uses the NG Application Protocol (NGAP) to package NAS messages for transfer between the Base Station and AMF. NGAP messages are transferred using the Stream Control Transmission Protocol (SCTP) as specified by the IETF within RFC 4960. SCTP provides an alternative to TCP and UDP. SCTP provides a reliable data transfer service which supports re-transmissions. SCTP allows signalling messages to be transferred using parallel streams (multi-streaming capability). This avoids re-transmissions from one signalling procedure delaying the transfer of messages from other signalling procedures. SCTP also includes a flow control mechanism, similar to that used by TCP. An SCTP packet forms the payload of an IP packet. The SCTP layer adds a common header of 12 bytes. Additional header information is included for each 'chunk' of data within the SCTP packet. Chunks form the payload of the SCTP packet

★ The Internet Protocol (IP) layer is used to route SCTP data between the Base Station and AMF. Figure 54 illustrates a direct connection between the Base Station and AMF. In practice, there may be a series of IP routers which use the IP layer to forward traffic in the appropriate direction. The IP layer can be based upon either IPv4 or IPv6. IPv4 headers are typically 20 bytes, whereas IPv6 headers are typically 40 bytes. Header sizes can be greater if optional content is included

★ Session Management NAS messages are transferred between the AMF and SMF using a 'Service based Interface' (SBI). For example, when the AMF receives a Session Management: *PDU Session Establishment Request* from the UE, the AMF sends an HTTP POST message to the SMF which requests the '*Nsmf_PDUSession_CreateSMContext*' service. This service request includes the information provided by the UE within the original NAS message. Similarly, when responding to the UE, the SMF sends an HTTP POST message to the AMF which requests the '*Namf_Communication_N1N2MessageTransfer*' service. This service request provides the information to be sent back to the UE in response to the original NAS message, i.e. within a NAS: *PDU Session Establishment Accept* or *PDU Session Establishment Reject*

★ NAS signalling procedures and messages are specified within 3GPP TS 24.501. NAS messages are categorised as either 5GS Mobility Management or 5GS Session Management. These two groups of messages are presented in Table 10

5GS Mobility Management messages	Registration Request, Registration Accept, Registration Complete, Registration Reject
	Authentication Request, Authentication Response, Authentication Result, Authentication Reject, Authentication Failure
	Configuration Update Command, Configuration Update Complete
	De-Registration Request, De-Registration Accept
	Downlink NAS Transport, Uplink NAS Transport
	Notification, Notification Response
	Identity Request, Identity Response
	Security Mode Command, Security Mode Complete. Security Mode Reject
	Security Protected 5GS NAS Message
	Service Request, Service Reject, Service Accept
	5GMM Status
5GS Session Management messages	PDU Session Establishment Request, PDU Session Establishment Accept, PDU Session Establishment Reject
	PDU Session Authentication Command, PDU Session Authentication Complete, PDU Session Authentication Result
	PDU Session Modification Request, PDU Session Modification Reject, PDU Session Modification Command, PDU Session Modification Complete, PDU Session Modification Command Reject
	PDU Session Release Request, PDU Session Release Reject, PDU Session Release Command, PDU Session Release Complete
	5GSM Status

Table 10 – Non Access Stratum (NAS) messages for 5G System (5GS) Mobility Management and Session Management

★ Example 5GS Mobility Management NAS messages include those used to register with the network (*Registration Request/Accept*) and those used to Authenticate with the network (*Authenication Request/Response*). In the case of 4G, there are separate NAS messages to provide location updates (*Tracking Area Update Request/Accept*). In contrast, 5G does not use dedicated NAS messages to provide location updates. Instead, the *Registration Request/Accept* messages are re-used with the '5GS Registration Type' set to 'Mobility Registration Updating'

★ The Uplink and Downlink NAS Transport messages are used to transfer various payloads between the UE and AMF. These messages are used to transfer NAS Session Management messages which are being sent to and from the SMF, i.e. a Session Management NAS message is packaged inside a Mobility Management NAS message. The Uplink and Downlink NAS Transport messages can also be used to transfer SMS content or LTE Positioning Protocol (LPP) content

★ The RRC messages, *UL Information Transfer* and *DL Information Transfer* can be used to encapsulate NAS messages for transfer between the UE and Base Station. Other RRC messages also allow the encapsulation of NAS messages. For example, the *RRC Setup Complete* message can include a NAS message. The *UL Information Transfer* and *DL Information Transfer* messages are transferred using acknowledged mode RLC on SRB 2, although these messages can also be transferred using SRB 1 if SRB 2 is not available

★ The NGAP *Initial UE Message*, *Downlink NAS Transport* and *Uplink NAS Transport* messages are used to encapsulate NAS messages for transfer between the Base Station and AMF using the NG-C control plane protocol stack

★ 3GPP References: TS 38.300, TS 29.500, TS 38.331, TS 24.501, TS 38.413

1.8 RRC STATES

- The Radio Resource Control (RRC) state machine for New Radio (NR) is illustrated in Figure 55
- A UE starts from RRC Idle mode when it first camps on a 5G cell. For example, this could be immediately after the device has been switched-on, or it could be after an inter-system cell reselection from LTE. A UE makes the transition from RRC Idle to RRC Connected by completing the RRC Setup procedure (see section 15.3). An RRC Connection is a logical connection between the UE and Base Station
- A UE in RRC Connected mode is allocated one or two C-RNTI (Cell Radio Network Temporary Identifier). The C-RNTI is used to address the UE when making resource allocations. A single C-RNTI is allocated when the UE is connected to a single Base Station. Two C-RNTI are allocated when the UE is connected using Multi-RAT Dual Connectivity (MR-DC)
- A UE in RRC Connected mode is configured with at least one Signalling Radio Bearer (SRB) and typically one or more Data Radio Bearers (DRB). The SRB can be used to transfer signalling messages between the UE and Base Station. The signalling messages may belong to the RRC signalling protocol or the Non-Access Stratum (NAS) signalling protocol. The Base Station uses the NG Application Protocol (NGAP) to transfer NAS messages to and from the AMF. The DRB can be used to transfer application data between the UE and Base Station. The Base Station uses a GTP-U tunnel to transfer application data to and from the UPF
- A UE must make the transition to RRC Connected mode to register with the network, i.e. to make the transition from RM-DEREGISTERED to RM-REGISTERED (see section 1.9). Once a UE has registered with the network then the UE will normally remain RM-REGISTERED irrespective of the RRC state. The registration procedure allocates the UE with a temporary identity known as a 5G-S-TMSI. The use of a temporary identity rather than a permanent identity, e.g. IMSI, helps to improve security
- A UE must make the transition to RRC Connected Mode to make the transition from CM-IDLE to CM-CONNECTED (see section 1.10). A UE returns to CM-IDLE whenever the RRC Connection is released. The UE remains CM-CONNECTED when making the transition from RRC Connected to RRC Inactive
- A UE makes the transition from RRC Connected to RRC Inactive using the RRC Release procedure. A *suspendConfig* parameter structure is included within the *RRC Release* message to indicate that the UE is being moved to RRC Inactive rather than RRC Idle. The NG signalling connection between the Base Station and AMF is maintained while the UE is RRC Inactive. In addition, GTP-U tunnels between the Base Station and UPF are maintained (one GTP-U tunnel per PDU Session). The UE context is also maintained by both the network and UE
- The RRC Inactive state allows the UE to return to RRC Connected and start transferring application data or signalling messages with minimal latency. Signalling load is reduced relative to the RRC Idle to RRC Connected transition because the UE context is already established. The RRC Inactive state allows the UE to reduce battery power consumption relative to RRC Connected. This can be achieved with longer DRX cycles and by not having a requirement for channel quality reporting
- The AMF can request the Base Station to provide notifications when the UE moves between RRC Connected and RRC Inactive. This request can be included within the NGAP '*Initial Context Setup Request*' or '*UE Context Modification Request*' messages. The Base Station subsequently provides updates using the NGAP '*RRC Inactive Transition Report*'. The AMF can use this information regarding the UE's RRC state to adjust its supervision timers. For example, if the AMF knows that the UE is in RRC Connected then it can expect a rapid response to any downlink transactions and so it can apply relatively short supervision timers. If the AMF knows that the UE is in RRC Inactive then it can expect a less rapid response to any downlink transactions because the UE must be paged before those transactions can be forwarded to the UE. The AMF can thus apply longer supervision timers for UE which are RRC Inactive

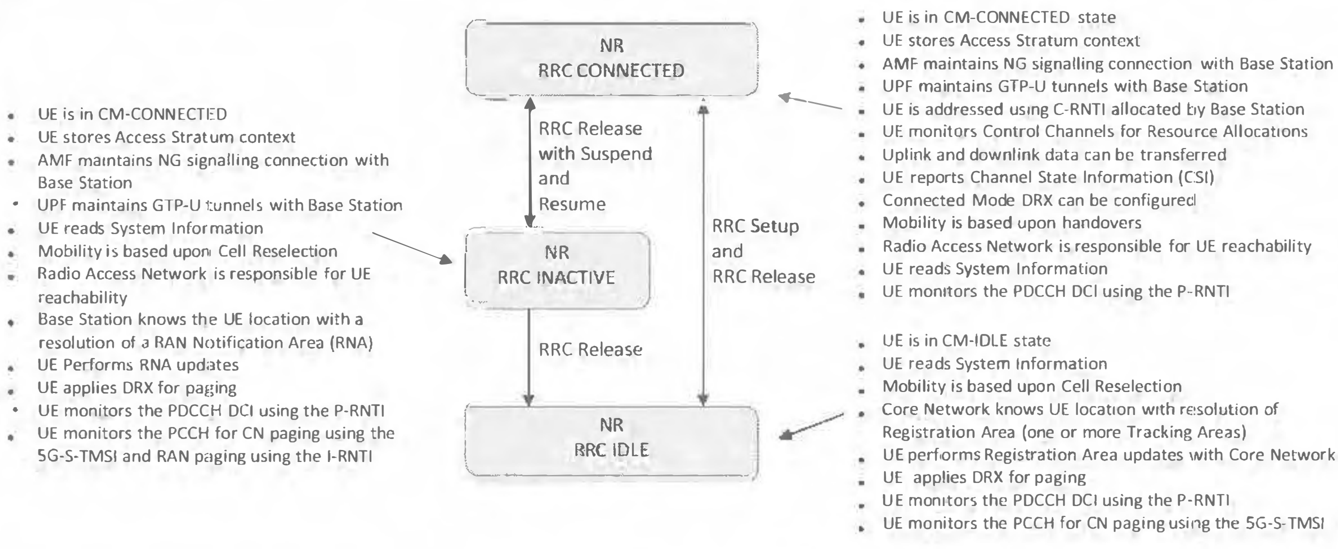


Figure 55 – Radio Resource Control (RRC) states for NR

★ A UE makes the transition to RRC Idle by completing the RRC Connection Release procedure. This involves releasing the allocated C-RNTI, all radio bearers and all radio resources. A UE may be provided with Redirected Carrier Information within the *RRC Release* message. This information can be used to redirect the UE towards either another NR carrier or towards an LTE carrier. Assuming coverage exists, the UE moves onto the target carrier in RRC Idle. The *RRC Release* message can also include Cell Reselection Priorities which are used instead of those broadcast within the System Information. In addition, the *RRC Release* message can include Deprioritisation information which leads to either the current carrier, or all NR carriers having the lowest priority for cell reselection

★ Figure 56 illustrates the RRC state transitions between LTE and NR. State transitions between NR and 2G / 3G are not defined by 3GPP. UE are able to complete handovers between the LTE and NR RRC Connected states. UE are able to complete cell reselections between the LTE and NR RRC Idle states. SIB24 belonging to the LTE system provides parameters for cell reselection towards NR, whereas SIB5 belonging to the NR system provides parameters for cell reselection towards LTE. UE are also able to complete cell reselection from RRC Inactive belonging to one technology towards RRC Idle belonging to the other technology. Legacy LTE solutions do not include the RRC Inactive state, i.e. RRC Inactive was not specified within the release 8 version of the specifications but was introduced within release 15

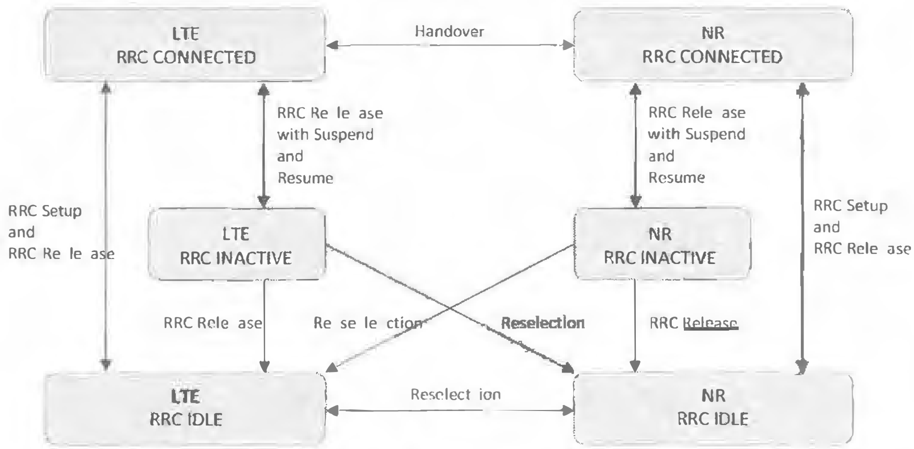


Figure 56 – Radio Resource Control (RRC) state transitions between 4G (LTE) and 5G (NR)

1.8.1 RRC IDLE

★ RRC Idle is characterised by:

- the UE reading System Information from the Broadcast Control Channel (BCCH). This is necessary to provide the UE with the information it requires to complete cell selection and cell reselection. System Information also provides the UE with all the information it requires to access the network, i.e. to complete the Random Access and RRC Connection Setup procedures
- UE controlled mobility based upon cell reselection. Parameters for cell reselection are configured by the network and are broadcast within the System Information. The UE completes serving cell and neighbour cell measurements before taking decisions regarding cell reselection. If beamforming is used by the Base Station then the UE will also select a beam to camp on
- the UE performing mobility triggered Registration Area updates to ensure that the UE is always reachable by the AMF, i.e. the AMF knows where to forward paging messages. A Registration Area includes one or more Tracking Areas, while a Tracking Area includes one or more cells. The UE completes a Tracking Area Update procedure when it moves into a Tracking Area to which it is not registered. Tracking Areas cannot overlap and so each cell belongs to only a single Tracking Area for a specific PLMN
- the UE performing periodic Registration Area updates with the AMF to confirm that it remains camped on the 5G network. These updates serve as a keep-alive mechanism. If a UE moves out of network coverage, or if a UE battery has run flat, then a UE will not be able to complete its next periodic Registration Area update and the network will recognise that the UE is no longer present
- the Radio Access Network does not track the location of the UE. The AMF is responsible for tracking the location of the UE with a resolution of the Registration Area. The Base Station can provide the AMF with a recommended RAN Node for paging within the *NGAP: UE Context Release Complete*. However, there is no guarantee that the UE remains within the coverage of that RAN Node after moving to RRC Idle
- the Base Station receives paging messages from the AMF, schedules air-interface resources and broadcasts them across the target coverage area. Paging across a complete Registration Area increases paging load. Depending upon implementation and network design, the AMF may direct the first transmission of a paging message towards the Base Station to which the UE was previously connected before moving to RRC Idle (based upon the recommended RAN Node for paging within the *NGAP: UE Context Release Complete*). If UE have low mobility, this first paging attempt should be successful and paging load is reduced. If this first paging attempt fails then the AMF may direct the second attempt across the entire Registration Area. This hierarchical approach to paging can reduce paging load but can also increase delay so different approaches may be applied to different service types

- the UE monitors the PDCCH Downlink Control Information (DCI) Format 1_0 using the P-RNTI during specific Paging Frames (PF) and Paging Occasions (PO) defined by the Discontinuous Reception (DRX) pattern. DCI Format 1_0 may include a 'Short Message' to indicate that System Information has changed or that there is an Earthquake and Tsunami Warning System (ETWS) primary notification on SIB6, or an ETWS secondary notification on SIB7, or a Commercial Mobile Alert System (CMAS) notification on SIB8. Otherwise DCI Format 1_0 may include a resource allocation for a paging message on the PDSCH
- the 5G-S-TMSI allocated by the AMF is used to address the UE within paging messages. 5G does not support IMSI based paging to help improve security, i.e. a temporary UE identity is used rather than a permanent UE identity
- the UE uses Discontinuous Reception (DRX) to help conserve UE battery power. Long DRX cycles conserve increased quantities of power but also increase mobile terminated connection setup delays. UE sleep during the DRX cycle so are unreachable during that time. UE wake at the end of each DRX cycle to monitor for paging messages. The UE and network must remain synchronised to ensure that the network only broadcasts paging messages when the UE is monitoring for them. The population of UE using DRX have time offsets applied to their DRX cycles so not all UE wake at the same time
- the UE is unable to transfer application data while in RRC Idle and there are no GTP-U tunnels for the UE between the Base Station and UPF, nor is there an NGAP signalling connection for the UE between the Base Station and AMF. The UE remains in the CM-IDLE state while in RRC Idle

1.8.2 RRC CONNECTED

* RRC Connected is characterised by:
  - the ability to transfer both application data and signalling between the UE and network. Application data can be transferred between the UE and Base Station using one or more Data Radio Bearers (DRB). Signalling can be transferred between the UE and Base Station using one or more Signalling Radio Bearers (SRB). In some cases, application data can be transferred using an SRB, e.g. SMS data can be transferred using Non-Access Stratum (NAS) signalling on an SRB
  - the Base Station allocates the UE with a Cell Radio Network Temporary Identifier (C-RNTI). When using a CU-DU Split Base Station architecture, the DU is responsible for allocating the C-RNTI during the Random Access procedure. The C-RNTI can be used to address the UE when making uplink and downlink resource allocations on the PDCCH. The Base Station may also allocate other types of RNTI, e.g. MCS-C-RNTI which can be used to allocate the low spectral efficiency MCS table, or the CS-RNTI which can be used to allocate configured grants on the PUSCH
  - the AMF and Base Station maintain a UE-specific signalling connection across the NG-C interface. This connection allows the transfer of NG Application Protocol (NGAP) signalling messages. These messages can be used for point-to-point signalling between the AMF and Base Station. Alternatively, they can be used to encapsulate Non-Access Stratum (NAS) signalling messages which are transferred between the UE and AMF/SMF
  - the UPF and Base Station maintain a GTP-U tunnel across the NG-U interface for each PDU Session. Each GTP-U tunnel can transfer packets belonging to one or more QoS Flows. The User Plane protocol adds a header to specify the QoS Flow associated with each individual packet
  - the UE reports Channel State Information (CSI) requested by the network. CSI can include Channel Quality Indicator (CQI), Rank Indicator (RI), Precoding Matrix Indicator (PMI), Layer Indicator (LI), CSI-RS Resource Indicator (CRI), SS/PBCH Block Resource Indicator (SSBRI) and Layer 1 RSRP. CSI reports can be used for link adaptation, MIMO rank and precoding selection, and beam management
  - the UE can be configured to apply a Connected Mode DRX pattern to help conserve UE battery power. Connected Mode DRX can be configured to use a series of short sleep cycles immediately after any data transfer. These short sleep cycles are followed by longer sleep cycles. The short cycles help to reduce latency in case any further data transfer is necessary, while the longer cycles help to conserve UE battery power. In general, the probability of additional data transfer is relatively high immediately after a period of activity, but the probability tends to decrease with time
  - network controlled mobility based upon handovers. Mobility can be categorised as cell level or beam level. Cell level handovers involve RRC signalling and are managed by layer 3. These handovers can be intra-system or inter-system towards LTE. The release 15 version of the specifications does not support handover towards 2G nor 3G. The Base Station configures the UE with thresholds for various reporting events. The UE uses the reporting events to trigger the transmission of Measurement Reports. The Base Station processes these reports and decides whether or not to initiate a handover procedure. Beam level mobility does not require RRC signalling (except for the initial configuration) and is managed by the lower layers. This allows beam level mobility to be completed more rapidly than cell level handovers
  - the UE monitors the PDCCH Downlink Control Information (DCI) Format 1_0 using the P-RNTI during specific Paging Frames (PF) and Paging Occasions (PO) defined by the Discontinuous Reception (DRX) pattern. DCI Format 1_0 may include a 'Short Message' to indicate that System Information has changed or that there is an Earthquake and Tsunami Warning System (ETWS) primary notification on SIB6, or an ETWS secondary notification on SIB7, or a Commercial Mobile Alert System (CMAS) notification on SIB8. The UE does not expect to receive any resource allocations for the Paging Control Channel (PCCH) while RRC Connected

1.8.3 RRC INACTIVE

★ RRC Inactive is characterised by:

- the UE starting from RRC Connected and receiving an *RRC Release* message which includes the *suspendConfig* parameter structure presented in Table 11. Reception of this parameter structure indicates that the UE should move to RRC Inactive rather than RRC Idle
- the *suspendConfig* parameter structure provides the UE with a full 'Inactive Radio Network Temporary Identifier' (I-RNTI) which has a length of 40 bits and a short I-RNTI which has a length of 24 bits. The network uses the full I-RNTI to address the UE within RRC *Paging* messages. The UE can use either the full I-RNTI or the short I-RNTI within the *RRC Resume Request* message when attempting to re-enter RRC Connected mode
  - if SIB1 does not broadcast the '*useFullResumeID*' flag, then the UE uses the short I-RNTI within the *RRC Resume Request* message on the Common Control Channel (CCCH). The *RRC Resume Request* is transmitted during the Random Access procedure as MSG3. This means that it cannot be segmented and must be transmitted using a single Transport Block. The message size must be kept relatively small to ensure that reception is reliable when the UE is at cell edge. Using the short I-RNTI generates a message size of 48 bits
  - if SIB1 broadcasts the '*useFullResumeID*' flag, then the UE uses the full I-RNTI within the *RRC Resume Request 1* message on the Common Control Channel 1 (CCCH1). The *RRC Resume Request 1* message has a size of 64 bits so it requires relatively good coverage for reliable reception. The 64 bit message could be used for indoor solutions or small cells where the coverage conditions are always relatively good
- the *suspendConfig* parameter structure also provides the UE with a *ran-PagingCycle* for Discontinuous Reception (DRX). This defines the duration of the sleep period while the UE is RRC Inactive. For example, a paging cycle of 128 radio frames means that the UE wakes once every 1.28 seconds to check for paging messages. It is likely that the UE also completes its measurements for cell reselection at the same time as waking to check for paging messages

<table>
<tr><th colspan="8">suspendConfig from RRCRelease message</th></tr>
<tr><td>full I-RNTI</td><td colspan="7">BIT STRING {40 bits}</td></tr>
<tr><td>short I-RNTI</td><td colspan="7">BIT STRING {24 bits}</td></tr>
<tr><td>ran-PagingCycle</td><td colspan="7">32, 64, 128, 256 radio frames</td></tr>
<tr><td rowspan="5">ran-NotificationAreaInfo</td><td colspan="7">CHOICE</td></tr>
<tr><td colspan="3">cellList</td><td colspan="4">ran-AreaConfigList</td></tr>
<tr><td rowspan="3">1 to 8 instances of PLMN-RAN-AreaCell</td><td colspan="2">plmn-Identity</td><td rowspan="3">1 to 8 instances of PLMN-RAN-AreaConfig</td><td colspan="3">plmn-Identity</td></tr>
<tr><td rowspan="2">1 to 32 instances of CellIdentity</td><td rowspan="2">BIT STRING (SIZE 36)</td><td rowspan="2">1 to 16 instances of RAN-AreaConfig</td><td colspan="2">TAC</td></tr>
<tr><td>1 to 32 instances of RAN-AreaCode</td><td>0 to 255</td></tr>
<tr><td>t380</td><td colspan="7">5, 10, 20, 30, 60, 120, 360, 720 mins</td></tr>
<tr><td>nextHopChainingCount</td><td colspan="7">0 to 7</td></tr>
</table>

Table 11 – Parameter structure used to indicate that a UE should move to RRC Inactive

- the *ran-NotificationAreaInfo* specifies the set of cells which are included within the RAN Notification Area (RNA). There are two options for defining this set of cells
  - the first option allows the Base Station to provide an explicit list of Cell Identities in combination with a PLMN identity. If the UE completes cell reselection while RRC Inactive, then the UE reads SIB1 from the target cell to determine whether or not the new cell identity is included within the RNA. This approach allows relatively small RNA to be configured, i.e. up to 32 cells for a specific PLMN identity
  - the second option allows the Base Station to provide a list of RAN Area Codes in combination with a Tracking Area Code (TAC) and PLMN identity. If the UE completes cell reselection while RRC Inactive, then the UE reads SIB1 from the target cell to determine whether or not the new combination of RAN Area Code and TAC is included within the RNA. This approach allows relatively large RNA to be configured, i.e. a large number of cells can be configured with the same combination of RAN Area Code and TAC

  in both cases, the UE can remain RRC Inactive if the target cell is included within the RNA. Otherwise, the UE must re-enter RRC Connected mode to inform the network that the UE has moved outside the RNA
- a large RNA allows increased UE mobility without requiring the UE to re-enter RRC Connected mode. However, the release 15 version of the 3GPP specifications requires that all Base Stations within an RNA must be inter-connected with Xn interfaces. In principle, this requirement is not complex but in practice, issues with the transport network or errors in the network configuration may lead to Xn interfaces being unavailable. Ensuring that all Base Stations are interconnected with Xn interfaces becomes more challenging as the RNA becomes larger. The use of large RNA may become more practical when using cloud solutions based

upon the CU-DU Split Base Station architecture. In this case, a large number of geographically distributed cells can belong to the same Base Station and thus remove the requirement for a large number of X2 interfaces

- Figure 57 illustrates the two options for configuring a RAN Notification Area. The second option demonstrates that a single RAN Notification Area can include multiple Tracking Areas and that each Tracking Area can use one or more RAN Area Codes. It also illustrates that RAN Area Code numbering can be re-used across different Tracking Areas
- Figure 57 also illustrates that the serving Base Station maintains the NG signalling connection with the AMF and the GTP-U tunnels with the UPF while the UE is RRC Inactive. The UE is unable to transfer application data while RRC Inactive, but these connections are maintained to avoid the requirement to re-establish them if the UE re-enters RRC Connected. It may be necessary to move them from the original serving Base Station to a new serving Base Station if the UE is mobile while RRC Inactive

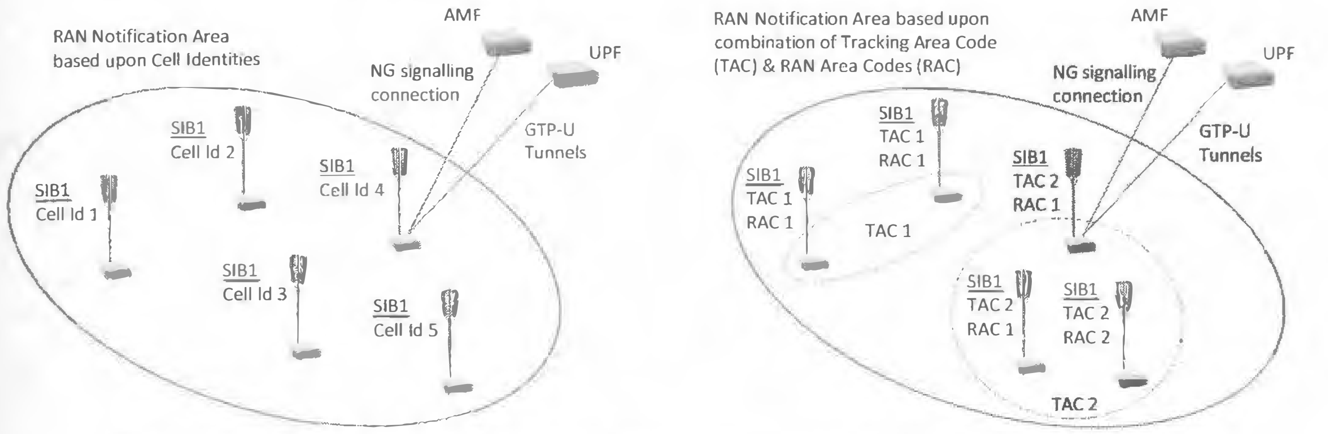


Figure 57 – RAN Notification Areas based upon Cell Identities or the combination of Tracking Area Code and RAN Area Code

- Returning to the content of Table 11, 't380' defines the timer for periodic RAN Notification Area Updates. These updates serve as a keep-alive mechanism to verify that the UE remains camped within the RAN Notification Area. Expiry of 't380' will have some dependence upon the device type. For example, if a smart phone transfers background data every 60 seconds while 't380' is set to 5 minutes, then 't380' will never expire because it will be stopped every time the UE moves to RRC Connected mode and reset every time the UE returns to RRC Inactive
- The 'nextHopChainingCount' is used to update the Base Station security key (NCC variable specified within 3GPP TS 33.501)
- Figure 58 illustrates the signalling used to resume an RRC Connection at a new serving Base Station. The UE initiates the procedure by sending either an *RRC Resume Request* or an *RRC Resume Request 1*. The content of these messages is presented in Table 12. Selection is based upon the '*useFullResumeID*' flag within SIB1. Both messages include an I-RNTI, a MAC-I and a cause value. The MAC-I information element is used to authenticate the UE before allowing the UE to re-enter RRC Connected

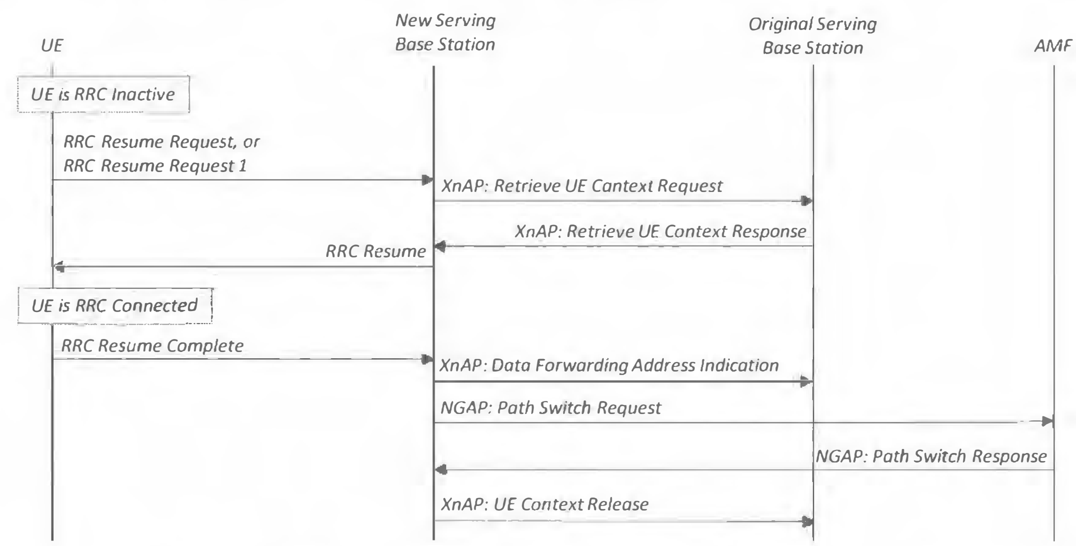


Figure 58 – Signalling used to resume an RRC Connection at a new serving Base Station

- the new serving Base Station extracts the I-RNTI from the *RRC Resume Request* or *RRC Resume Request 1* and uses it to identify the original serving Base Station. 3GPP does not specify a fixed mapping for including the Base Station identity within the I-RNTI. Instead, the network vendor is responsible for implementing a specific mapping. The network vendor may include controlling parameters within the Base Station databuild to provide flexibility, i.e. allowing the operator to configure a specific mapping. In general, the I-RNTI needs to include a Base Station identity and a UE identity. The mapping rules can be used to partition the total number of bits between each field. For example, the 24 bit I-RNTI could be partitioned into a 16 bit Base Station identity and an 8 bit UE identity. This partitioning would support 65506 Base Stations and 256 RRC Inactive UE at each Base Station. Supporting a large number of Base Stations and a large number of UE requires the 40 bit I-RNTI

RRCResumeRequest		
resumeIdentity	short I-RNTI	BIT STRING (SIZE 24)
resumeMAC-I	BIT STRING (SIZE 16)	
resumeCause	emergency, highPriorityAccess, mt-Access, mo-Signalling, mo-Data, mo-VoiceCall, mo-VideoCall, mo-SMS, rna-Update, mps-PriorityAccess, mcs-PriorityAccess	

RRCResumeRequest1		
resumeIdentity	I-RNTI	BIT STRING (SIZE 40)
resumeMAC-I	BIT STRING (SIZE 16)	
resumeCause	emergency, highPriorityAccess, mt-Access, mo-Signalling, mo-Data, mo-VoiceCall, mo-VideoCall, mo-SMS, rna-Update, mps-PriorityAccess, mcs-PriorityAccess	

Table 12 – RRC Resume Request and RRC Resume Request 1 messages

- once the original serving Base Station has been identified, an XnAP: *Retrieve UE Context Request* is sent across the Xn interface. This message includes the three fields from the *RRC Resume Request* and also specifies the cell which received the *RRC Resume Request*. The cause value 'rna-Update' (visible in Table 12) can refer to a periodic update or it can refer to a mobility based update after moving outside the RAN Notification Area. It is not mandatory to relocate the UE Context when completing a periodic update, whereas the UE Context must be relocated if the UE moves outside the current RAN Notification Area
- the original serving Base Station may respond with an XnAP: *Retrieve UE Context Response* which provides the new serving Base Station with the content of the UE Context. It also specifies the AMF identity which allows the new serving Base Station to initiate the Path Switch procedure. If the 'cause' within the *RRC Resume Request* is 'rna-Update' and the original serving Base Station deduces that it is a periodic update then the original serving Base Station may decide to keep the UE context and respond with a XnAp: *Retrieve UE Context Failure*. In that case, the new serving Base Station can move the UE back to RRC Inactive by sending an *RRC Release* message which includes the *suspendConfig* parameter structure
- assuming a 'cause' value other than 'rna-Update', the new serving Base Station moves the UE into RRC Connected by sending an *RRC Resume*. This message can include radio bearer, master cell group and measurement configurations. The UE responds with an *RRC Resume Complete* which may include a Non-Access Stratum (NAS) signalling message to be forwarded to the AMF
- the new serving Base Station uses the XnAP: *Data Forwarding Address Indication* to provide the original serving Base Station with transport network layer address information which can be used to forward downlink data towards the new serving Base Station. The new serving Base Station also uses NGAP signalling to complete the Path Switch procedure with the AMF. The NGAP: *Path Switch Request* provides the AMF with transport network layer address information for downlink data. The AMF forwards this information to the SMF, and the SMF forwards it to the UPF. Finally, the new serving Base Station instructs the original serving Base Station to release the UE Context by sending an XnAP: *UE Context Release*
- Figure 59 illustrates the distribution of a paging message after the serving Base Station receives some downlink data from the UPF. The Radio Access Network is responsible for providing reachability while the UE is RRC Inactive but the serving Base Station does not have precise knowledge of the UE location, i.e. the serving Base Station only knows that the UE is somewhere within the RAN Notification Area. The XnAP: *RAN Paging* message can be used to request other Base Stations to broadcast an RRC: *Paging* message. The XnAP: *RAN Paging* message provides each Base Station with both the full and short I-RNTI. The RRC: *Paging* message addresses the UE using the full I-RNTI whereas the UE may respond using an *RRC Resume Request* which contains only the short I-RNTI

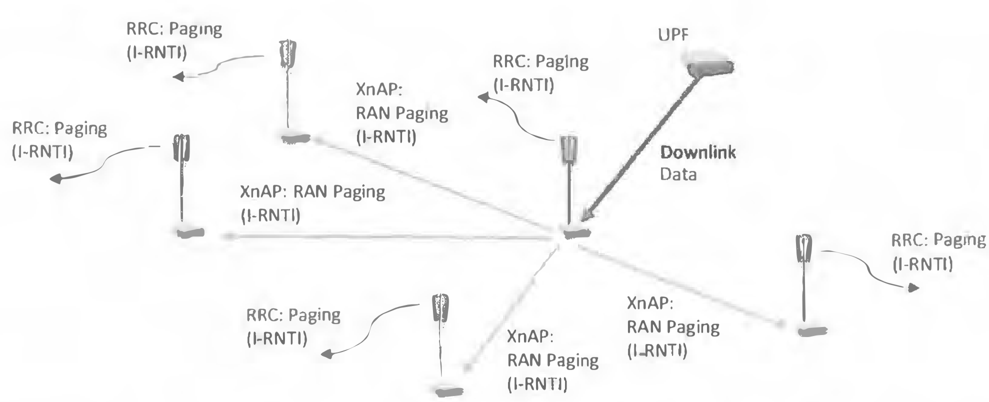


Figure 59 – Distribution of Paging message for UE which is RRC Inactive

- the UE reads System Information from the Broadcast Control Channel (BCCH) while RRC Inactive. This is necessary to provide the UE with the information it requires to complete cell reselection. System Information also provides the UE with all of the information it requires to access the network, i.e. to complete the Random Access procedure
- 3GPP References: TS 38.331

1.9 REGISTRATION MANAGEMENT

- 'Registration Management' (RM) states are maintained by the Non-Access Stratum (NAS) layers within both the UE and the Access and Mobility Management Function (AMF). The main two RM states are illustrated in Figure 60

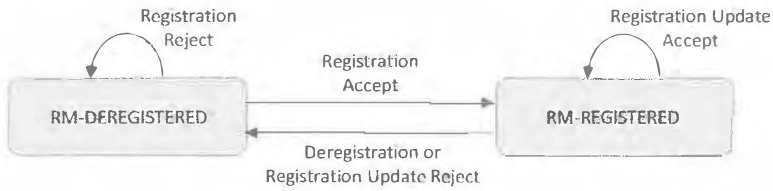


Figure 60 – Registration Management states from the perspective of the UE and AMF

- A UE is RM-DEREGISTERED when it is first switched on. The AMF does not have knowledge of the UE location so the UE cannot be paged. The UE cannot access the vast majority of 5G services while RM-DEREGISTERED, i.e. the UE can only use the 'limited service' state to make emergency calls
- UE move into the RM-REGISTERED state by completing the Registration procedure. This is possible after the UE has completed cell selection and is camping on the 5G network. The Registration procedure is a NAS signalling procedure between the UE and an AMF. The Base Station selects an appropriate AMF after receiving the NAS: *Registration Request* from the UE
- The AMF uses the NAS: *Registration Accept* message to provide the UE with a 5G Globally Unique Temporary Identifier (5G-GUTI). The 5G-GUTI is a concatenation of the MCC, MNC, AMF Region, AMF Set, AMF Pointer and 5G-TMSI. This allows the network to subsequently address the UE using its 5G-S-TMSI which is a shortened version of the 5G-GUTI (5G-S-TMSI is a concatenation of the AMF Set, AMF Pointer and 5G-TMSI)
- The registration procedure can be used to negotiate the set of Network Slices available to a UE. The NAS: *Registration Request* can include a list of requested 'Single Network Slice Selection Assistance Information' (S-NSSAI), i.e. a list of requested Network Slices. The AMF can use the NAS: *Registration Accept* message to specify corresponding lists of allowed and rejected S-NSSAI
- A UE which is RM-REGISTERED updates its registration with the AMF:
  - periodically based upon timer T3512. The UE receives the value of T3512 from the AMF within the NAS: *Registration Accept* message. The AMF uses a supervision timer based upon the value T3512. The AMF will implicitly deregister the UE if this supervision timer expires, i.e. the UE must complete a periodic registration before the timer expires. A periodic registration is completed using the NAS: *Registration Request* with the '5GS Registration Type' set to 'periodic registration updating'
  - based upon mobility if the UE moves outside the current registration area. The UE receives a list of one or more Tracking Areas from the AMF within the NAS: *Registration Accept* message. These Tracking Areas define the registration area. A UE initiates a registration update due to mobility if it completes a cell reselection onto a cell which does not belong to one of the Tracking Areas specified by the AMF. The registration update is completed using the NAS: *Registration Request* with the '5GS Registration Type' set to 'mobility registration updating'
  - if the UE wishes to update its capabilities or re-negotiate protocol parameters. In this case, the UE can use the NAS: *Registration Request* message to provide a new set of UE capabilities or a new set of protocol parameters
- The AMF's knowledge of the UE location depends upon both the Registration Management and Connection Management states:
  - RM-DEREGISTERED – the AMF has no knowledge of the UE location
  - RM-REGISTERED & CM-IDLE – the AMF knows the UE location in terms of the Registration Area
  - RM-REGISTERED & CM-CONNECTED – the AMF knows the UE location in terms of the serving Base Station (although RRC Inactive allows the UE to roam within a RAN Notification Area without information the serving Base Station, nor the AMF)
- A UE make the transition from RM-REGISTERED to RM-DEREGISTERED by completing the De-registration procedure, or by having a registration update rejected. The De-registration procedure is initiated using the NAS: *De-registration Request* message. There are two versions of this message so the procedure can be initiated by either the UE or the AMF
- 3GPP References: TS 23.501, TS 24.501

1.10 CONNECTION MANAGEMENT

- Connection Management (CM) reflects the UE status in terms of its signalling connection with the AMF. A UE which is CM-IDLE does not have a signalling connection with the AMF, whereas a UE which is CM-CONNECTED has a signalling connection with the AMF. This signalling connection is used to transfer Non-Access Stratum (NAS) signalling messages
- The signalling connection between the UE and AMF is based upon the N1 logical interface. This logical interface can be viewed as a combination of the signalling connection between the UE and the Base Station (RRC signalling connection), and the signalling connection between the Base Station and the AMF (N2 logical interface which corresponds to an NGAP signalling connection)
- The CM-IDLE and CM-CONNECTED states are maintained by the NAS layers within both the UE and the AMF. These states are illustrated in Figure 61

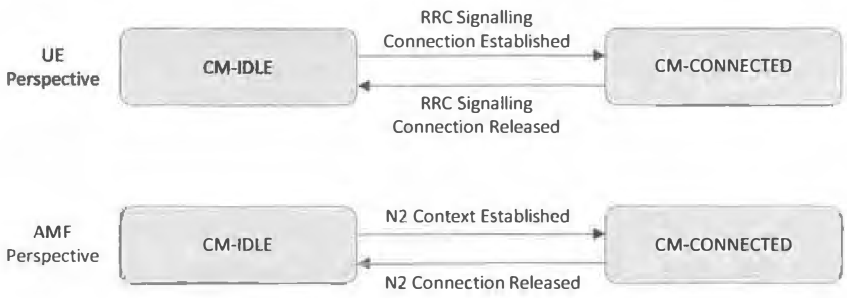


Figure 61 – Connection Management states from the perspective of the UE and AMF

- A UE moves itself into CM-CONNECTED once an RRC signalling connection has been established. The AMF moves the UE into CM-CONNECTED once an N2 signalling connection (NGAP signalling connection) has been established. The transmission of an initial NAS message, e.g. *Registration Request* or *Service Request*, triggers the transition from CM-IDLE to CM-CONNECTED because it initiates the setup of signalling connections between the UE and Base Station, and between the Base Station and AMF
- A UE which is RRC Idle is also CM-IDLE. A UE which is RRC Connected or RRC Inactive is CM-CONNECTED
- A UE which is CM-IDLE uses UE controlled mobility based upon cell reselection, i.e. RRC Idle mode mobility
- The network broadcasts an RRC: *Paging* message if there is downlink data to transfer towards a CM-IDLE UE. The *Paging* message triggers the UE to establish an RRC Connection and to send a NAS: *Service Request* to the AMF. The NAS: *Service Request* initiates the setup of the N2 signalling connection which then moves the UE to CM-CONNECTED. Similarly, the UE establishes an RRC Connection and sends a NAS: *Service Request* to the AMF if the UE has uplink data to transfer
- A UE makes the transition from CM-CONNECTED to CM-IDLE when its signalling connection is released, or when its signalling connection fails
- 3GPP References: TS 23.501, TS 24.501

1.11 ACCESS CONTROL

- There are two high level solutions for controlling network access attempts:
  - Cell Reservations and Access Restrictions which impact the permissions for cell selection and cell reselection
  - Unified Access Control (UAC) which impacts the permission to send initial messages from the RRC Idle, RRC Connected and RRC Inactive modes
- Cell Reservations and Access Restrictions are based upon a set of 3 flags included within the MIB and SIB1:
  - *cellBarred* can be broadcast with a value of 'barred' or 'notBarred'. This flag is included within the MIB to allow early detection of the status without requiring the UE to receive and decode SIB1. If a cell is barred then the UE is not permitted to select nor reselect the cell. This applies to all UE and prevents emergency calls from being initiated
  - *cellReservedForOperatorUse* can be broadcast with a value of 'reserved' or 'notReserved'. This flag is included within SIB1 and a separate instance can be broadcast for each PLMN (if the cell is configured with multiple PLMN). If a cell is reserved then a UE with an Access Identity of 11 (PLMN Use) or an Access Identity of 15 (PLMN Staff) is permitted to use the cell for selection and reselection, if that UE is within its Home PLMN or an Equivalent Home PLMN. If a cell is reserved then a UE with Access Identity 0, 1, 2, 12, 13 or 14 treats the cell as 'barred', i.e. the UE is not permitted to select nor reselect the cell
  - *cellReservedForOtherUse* can be broadcast within SIB1 with a value of 'true' or can be excluded from SIB1. When this flag is broadcast by SIB1 then all UE treat the cell as 'barred', i.e. it has the same impact as the *cellBarred* flag within the MIB. There is a single instance of the flag which is applicable to all PLMN. *cellReservedForOtherUse* does not have a specific purpose within the release 15 version of the 3GPP specifications but has been introduced to provide forward compatibility with services which may be introduced in the future. The example of Closed Subscriber Group (CSG) cells can be used to illustrate how this flag provides forward compatibility. The release 15 version of the 3GPP specifications does not support CSG cells for New Radio. If the release 16 version of the specifications introduces support for CSG cells then a release 16 UE will understand the rules for accessing a CSG cell (only subscribers belonging to the closed subscriber group are permitted to access the cell). Release 15 UE will not have any knowledge of these rules but the *cellReservedForOtherUse* flag can be used to ensure that a release 15 UE does not attempt to access the CSG cell
- If the MIB indicates that a cell is barred then the UE will also check the *intraFreqReselection* flag which is also included within the MIB. If this flag is set to 'notAllowed' then the UE is not permitted to reselect another cell on the same frequency. Otherwise, if this flag is set to 'Allowed' then the UE is permitted to reselect another cell on the same frequency
- A UE also treats a cell as barred if the UE fails to decode the MIB. In this case, the UE is permitted to reselect another cell on the same frequency. In addition, a UE treats a cell as barred if the UE fails to decode SIB1. In this case, the UE uses the *intraFreqReselection* flag from within the MIB to determine whether or not reselection to another cell on the same frequency is permitted. A UE treats the cell as barred for up to 300 seconds when it fails to decode the MIB or SIB1
- 2G, 3G and 4G networks have used Access Class Barring (ACB) to control access. This relies upon all SIM having an Access Class within the range 0 to 9. In addition, a limited group of users may be allocated SIM which have been provisioned with a special Access Class within the range 11 to 15, where AC11 is intended for PLMN Use; AC12 is intended for Security Services; AC13 is intended for Public Utilities; AC14 is intended for Emergency Services; AC15 is intended for PLMN Staff. A UE adopts Access Class 10 when initiating an emergency call. Various Access Class Barring solutions have evolved over time, e.g. barring specific Access Classes within the range 0 to 9; specifying a probability that access is permitted for a UE with Access Class 0 to 9; barring access for specific services and connection establishment causes; barring access in general but then allowing specific services to 'skip' the barring
- The release 15 version of the 3GPP specifications introduces the concept of Unified Access Control (UAC) which is based upon the use of 'Access Identities' and 'Access Categories'. A UE associates itself with an Access Identity based upon the rules presented in Table 13. Access Identities 11 to 15 are mapped directly from Access Classes 11 to 15. Access Identities 1 and 2 are linked to subscribers permitted to use the MPS and MCS services. Access Identity 0 is linked to all other cases. In general, Access Identity 0 will capture Access Classes 0 to 9

Access Identity	UE Configuration
0	UE is not configured with any parameters from this table
1	UE is configured for Multimedia Priority Service (MPS)
2	UE is configured for Mission Critical Service (MCS)
3 to 10	Reserved
11	UE has Access Class 11
12	UE has Access Class 12
13	UE has Access Class 13
14	UE has Access Class 14
15	UE has Access Class 15

Table 13 – Mapping to set of Access Identities

- The '5GS Network Feature Support' field within a NAS: *Registration Accept* message includes an 'MPS Indicator' which can be set to '1' when providing permission to use the MPS service, i.e. this flag can be used to allocate Access Identity 1. Similarly, the same field includes an 'MCS Indicator' which can be set to '1' when providing permission to use the MCS service, i.e. this flag can be used to allocate Access Identity 2. Alternatively, the 'EF_{UAC_AIC}' USIM file can be used to provision Access Identity 1 or 2

- A UE links a specific connection attempt to a specific Access Category using the rules presented in Table 14. If a connection attempt matches more than a single rule, the Access Category belonging to the lowest rule number is selected. UE with Access Category 0 are not subject to Access Barring because the network is responsible for managing the transmission of Paging messages, i.e. the network should not page the UE if the connection is not permitted

Rule	Type of Access	Access Category
1	Response to Paging Response to Notification over non-3GPP Access 5GMM Connection Management procedure for transfer of an LPP message	0 (MT Access)
2	Emergency	2 (Emergency)
3	Operator defined Access Categories	32 to 63 (Operator Defined)
4	Delay Tolerant Service	1 (Delay Tolerant)
5	MO MMTel Voice Call	4 (MO MMTel Voice)
6	MO MMTel Video Call	5 (MO MMTel Video)
7	MO SMS over NAS or SMSoIP	6 (MO SMS & SMSoIP)
8	UE NAS initiated 5GMM procedure	3 (MO Signalling)
9	UE NAS initiated 5GMM Connection Management procedure UE NAS initiated 5GMM NAS Transport procedure	7 (MO Data)
10	Uplink User Plane Packet transfer for PDU Session with suspended User Plane Resources	7 (MO Data)

Table 14 – Mapping to set of Access Categories

- Access Categories 32 to 63 can be configured by the operator. The NAS: *Registration Accept* message provided by the AMF can include the 'Operator Defined Access Category Definitions' field which specifies a set of mapping rules. The content of this field is presented in Table 15. The precedence value is applied as a priority when a connection attempt matches more than a single set of the operator defined Access Categories. In this case, the UE selects the Access Category with the lowest precedence value

Operator Defined Access Category Definitions	
Precedence Value	
Operator Defined Access Category Number (32 to 63)	
Criteria	DNN
	OS ID + OS App ID
	S-NSSAI
Standardised Access Category	

Table 15 – Operator defined Access Category criteria

- The criteria for selecting a specific operator defined Access Category is based upon a combination of the Data Network Name (DNN), the identity of the UE operating system, the identity of the application which is triggering the connection attempt and the Network Slice

- A Standardised Access Category can be linked to the operator defined Access Category for the purposes of selecting a 'cause' value for the *RRC Setup Request* message. Table 338 in section 15.3 presents the mapping from Access Identity and Access Category to RRC Setup cause value. This mapping table does not include any operator defined Access Categories so the inclusion of a standardised Access Category within Table 15 allows an appropriate cause value to be identified

- Access Control Checks based upon Access Identity and Access Category are required when a UE initiates the transition from RRC Idle mode to RRC Connected mode. Access Control Checks are also required for UE in RRC Connected and RRC Inactive modes when specific events occur, e.g. a mobile originated voice or video call is initiated, a mobile originated SMS is initiated, an uplink NAS message is used to setup or modify a PDU Session, uplink data transfer which requires the use of a suspended PDU Session

- The *uac-BarringInfo* within SIB1 provides the parameters to determine when an Access Barring check is required. These parameters are described in section 6.2 (Table 152). An access barring check involves the UE generating a uniformly distributed random number between 0 and 1. If the random number is less than the value of *uac-BarringFactor*, then the access attempt is permitted. Otherwise, the access attempt is barred. Configuring a value of '0' for *uac-BarringFactor* means that all checks will lead to barred access attempts

- If an access attempt is barred, the UE generates a second uniformly distributed random number between 0 and 1. The value of T390 is then set equal to $(0.7 + 0.6 \times rand) \times$ *uac-BarringTime* seconds, where 'rand' is the random number. T390 defines the duration that the UE treats the cell as barred for the corresponding Access Category

- 3GPP References: TS 24.501, TS 38.304, TS 38.331

1.12 SIGNALLING RADIO BEARERS

- The RRC signalling protocol operates between the UE and Base Station
- The Non Access Stratum (NAS) signalling protocol operates between the UE and AMF/SMF
- Signalling Radio Bearers (SRB) are used to transfer RRC messages between the UE and Base Station. RRC messages can encapsulate NAS messages so SRB are also responsible for transferring NAS messages between the UE and Base Station. The NG Application Protocol (NGAP) is used to transfer NAS messages between the Base Station and AMF. NAS messages associated with Session Management terminate at the SMF rather than the AMF. The AMF acts a relay between the Base Station and SMF for Session Management NAS messages
- Figure 62 illustrates the protocol stacks used for both RRC and NAS signalling. The set of SRB provide a logical connection between the RRC layers within the UE and Base Station

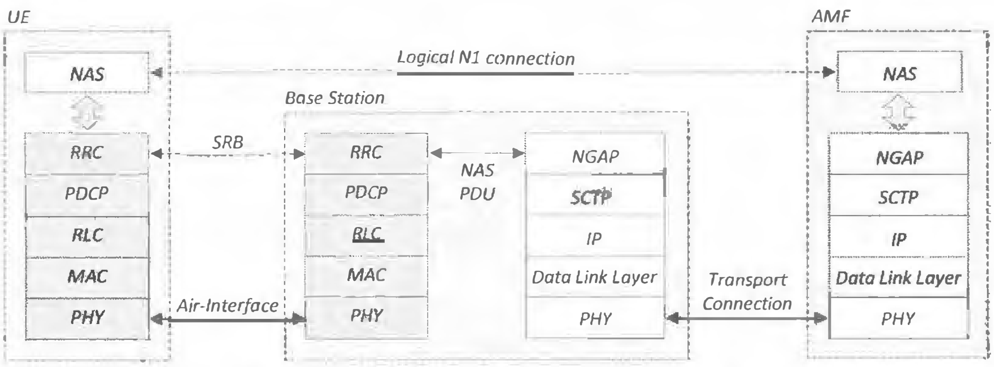


Figure 62 – Protocol stacks for RRC and NAS signalling

- 3GPP has specified 4 types of SRB for New Radio (NR):
  - SRB 0 transfers RRC messages which use the Common Control Channel (CCCH) logical channel
  - SRB 1, 2 and 3 transfer RRC messages which use the Dedicated Control Channel (DCCH) logical channel
  - SRB 1 supports RRC signalling between the UE and Base Station but can also encapsulate NAS messages prior to the setup of SRB 2
  - SRB 2 is always setup after security activation and is used to encapsulate NAS messages. SRB 2 messages are handled with lower priority relative to SRB 1 messages
  - SRB 3 is applicable when using the 'E-UTRAN New Radio Dual Connectivity' (EN-DC) configuration. In this case, SRB 0, 1 and 2 are managed by the E-UTRAN Master Node while SRB 3 is managed by the NR Secondary Node. SRB 3 allows RRC messages to be transferred directly between the Secondary Node and the UE. SRB 3 is limited to transferring *RRC Reconfiguration* and *Measurement Report* messages. These messages are a subset of those transferred by SRB 1
- Figure 63 illustrates the concept of a 'Split SRB' which is applicable to SRB 1 and SRB 2 when using a Dual Connectivity configuration. A split SRB means that RRC messages can be transferred using the Master Node air-interface, the Secondary Node air-interface or both air-interfaces. The use of both air-interfaces helps to improve reliability. The concept is applicable to both the uplink and downlink so the UE can be instructed to transmit uplink RRC messages on both air-interfaces

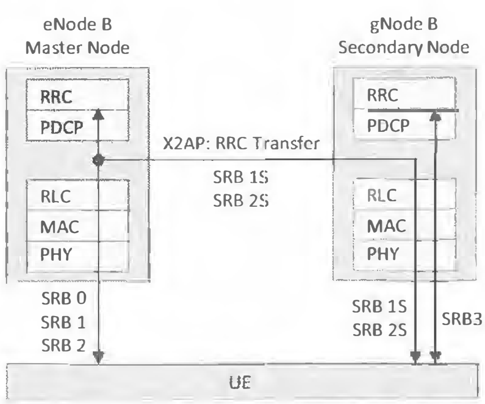


Figure 63 – Split SRB for Non-Standalone EN-DC Base Station architecture

★ Figure 63 is based upon the Non-Standalone EN-DC configuration so SRB 3 is also shown within the Secondary Node. SRB 0 is only applicable to the Master Node. Splitting SRB 1 and SRB 2 creates SRB 1S and SRB 2S which use the X2 Application Protocol (X2AP) to transfer RRC messages to and from the Secondary Node

★ The RRC messages associated with each SRB are presented in Table 16

SRB	Direction	Message	RLC Mode
SRB0 CCCH	Downlink	RRCSetup	Transparent Mode RLC
		RRCReject	
	Uplink	RRCSetupRequest	
		RRCResumeRequest	
		RRCResumeRequest1 (uses CCCH1)	
		RRCReestablishmentRequest	
		RRCSystemInfoRequest	
SRB1 DCCH	Downlink	RRCReconfiguration	Acknowledged Mode RLC
		RRCResume	
		RRCReestablishment	
		RRCRelease	
		SecurityModeCommand	
		DLInformationTransfer (if SRB2 has not been setup)	
		UECapabilityEnquiry	
		CounterCheck	
		MobilityFromNRCommand	
	Uplink	RRCSetupComplete	
		RRCResumeComplete	
		RRCReestablishmentComplete	
		RRCReconfigurationComplete	
		SecurityModeComplete	
		SecurityModeFailure	
		ULInformationTransfer (if SRB2 has not been setup)	
		MeasurementReport	
		UECapabilityInformation	
		LocationMeasurementIndication	
		UEAssistanceInformation	
		CounterCheckResponse	
SRB2 DCCH	Downlink	DLInformationTransfer	
	Uplink	ULInformationTransfer	
SRB3 DCCH	Downlink	RRCReconfiguration (also on SRB1)	
	Uplink	RRCReconfigurationComplete (also on SRB1)	
		MeasurementReport (also on SRB1)	

Table 16 – Mapping between RRC messages and SRB

★ SRB 0 uses Transparent Mode (TM) RLC while SRB 1 and 2 use Acknowledged Mode (AM) RLC

★ SRB 0 transfers messages associated with establishing, re-establishing and resuming a connection. The uplink messages are transmitted as MSG3 within the Random Access procedure, while the downlink messages can be transmitted as MSG4. The UE is allocated a DCCH logical channel once an RRC connection has been established so SRB 1 and 2 are able to transfer subsequent messages

★ The *RRCResumeRequest1* message is an exception which has been specified to use the CCCH1 logical channel rather than the CCCH logical channel. The CCCH1 logical channel is intended to transfer larger messages than the CCCH logical channel

★ After security activation, all messages transferred by SRB 1, 2 and 3 are integrity protected and ciphered by the Packet Data Convergence Protocol (PDCP). In addition, NAS messages use integrity protection and ciphering between the UE and AMF

★ The Uplink Information Transfer and Downlink Information Transfer messages are dedicated to sending NAS messages and do not include any RRC signalling content. These messages are transferred using SRB 2 unless SRB2 has not yet been configured

★ 3GPP References: TS 38.331, TS 37.340

1.13 PDU SESSIONS

★ 4G uses an 'EPS Bearer' to provide end-to-end user plane connectivity between the UE and an Access Point Name (APN) within the Packet Gateway (P-GW). The APN defines the interface to the external data network. There is a one-to-one mapping between EPS Bearer and QoS profile, i.e. all packets belonging to a specific EPS Bearer have the same 'Quality of Service Class Identifier' (QCI)

★ 5G uses a 'PDU Session' to provide end-to-end user plane connectivity between the UE and a Data Network Name (DNN) within the User Plane Function (UPF). The DNN defines the interface to the external data network. A PDU Session supports one or more QoS Flows. There is a one-to-one mapping between QoS Flow and QoS profile, i.e. all packets belonging to a specific QoS Flow have the same '5G Quality of Service Identifier' (5QI)

★ 'PDU Sessions' are applicable when using a 5G Core Network. A Non-Standalone Base Station architecture connected to a 4G Core Network uses 'EPS Bearers'

★ The concept of a 'PDU Session' is illustrated in Figure 64. The Anchor UPF is responsible for mapping each downlink packet onto a specific QoS Flow belonging to a specific PDU Session. The SDAP layer within the UE is responsible for mapping each uplink packet onto a specific QoS Flow belonging to a specific PDU Session. The SDAP layer within the UE is also responsible for mapping each uplink QoS Flow onto a specific Data Radio Bearer (DRB). The SDAP layer within the Base Station Centralised Unit (CU) is responsible for mapping each downlink QoS Flow onto a specific DRB

★ GTP-U tunnels are used to transfer packets across transport connections. The transport connection between two UPF uses a single GTP-U tunnel per PDU Session. Similarly, the transport connection between the Base Station and UPF uses a single GTP-U tunnel per PDU Session. In contrast, the transport connection between the Base Station CU and DU uses a single GTP-U tunnel per DRB

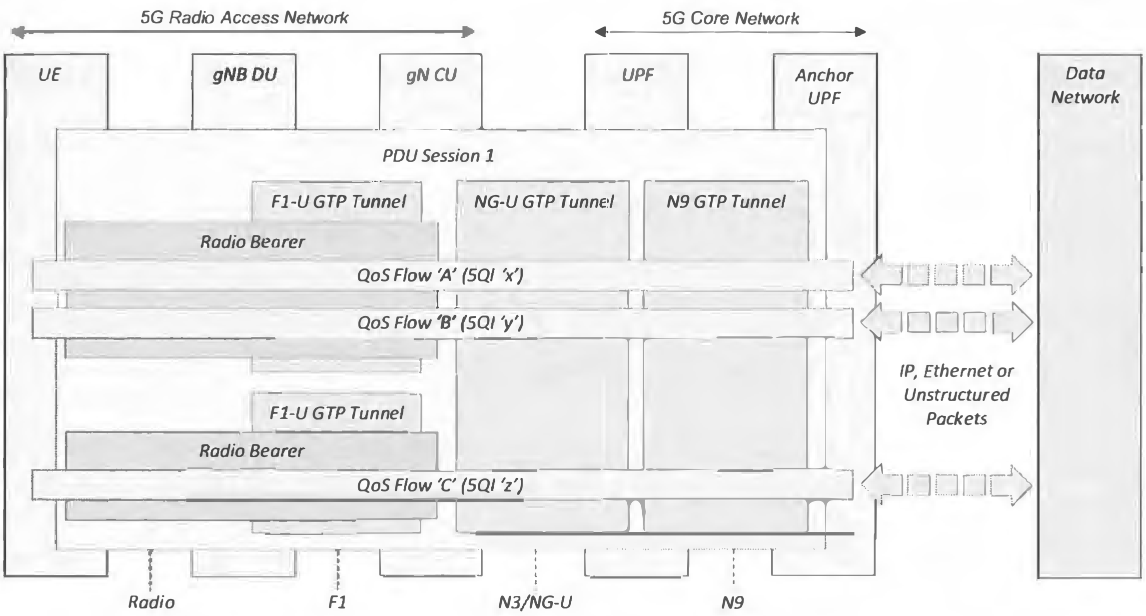


Figure 64 – Hierarchy for a PDU Session

★ The SDAP header includes a field to identify the QoS Flow. This header is present between the UE and Base Station CU. Similarly, the User Plane protocol includes a field to identify the QoS Flow. This header is present between the Base Station CU and the Anchor UPF. The GTP-U header specifies a Tunnel Endpoint Identifier (TEID) which links each packet to a DRB within a PDU Session when the GTP-U tunnel connects the Base Station CU and DU. The TEID links each packet to a PDU Session when the GTP-U tunnel connects the Base Station to a UPF or connects a pair of UPF

★ A specific PDU Session can be configured to transfer a specific type of packet. The release 15 version of the 3GPP specifications supports PDU Sessions which transfer IPv4, IPv6, IPv4v6, Unstructured or Ethernet packets. The UE can request a particular packet type within the NAS: *PDU Session Establishment Request* message. The SMF specifies the allocated packet type within the NAS: *PDU Session Establishment Accept* message

★ A 'PDU Session' transferring IP packets means that an IP address is used to route the packets once they leave the 5G network. Similarly, a 'PDU Session' transferring Ethernet packets means that a MAC address is used to route the packets once they leave the 5G network. The IPv4v6 category means that the PDU Session can be used to transfer both IPv4 and IPv6 packets. In this case, the UE is allocated both an IPv4 address and an IPv6 address

★ The 'Unstructured' category refers to packets which do not have header information. This can be attractive for applications which transfer large volumes of small packets, i.e. cases where the overhead generated by the header information is the most significant. This could be applicable to Internet of Things (IoT) applications. Use of 'Unstructured' data means that it is not necessary to transfer the usual higher layer headers across the air-interface, nor across the transport and core network. Applications using 'Unstructured' packets require a solution for delivering those packets to the application server once they leave the 5G Core Network, i.e. they leave the User Plane Function (UPF) across the N6 interface. Point-to-Point tunnelling based upon UDP/IP can be used for this purpose, i.e. a UDP/IP tunnel is established between the UPF and application server so UDP and IP headers are added at this stage to transfer packets across the N6 interface

★ A PDU Session can be setup specifically as an 'always-on' PDU Session. The UE can request that a PDU Session is 'always-on' by including a flag within the NAS: *PDU Session Establishment Request*. The SMF specifies whether or not a PDU Session is 'always-on' by including a flag within the NAS: *PDU Session Establishment Accept*. An 'always-on' PDU Session means that the user plane resources are setup every time the UE makes the transition from CM-IDLE to CM-CONNECTED

★ A PDU Session is configured to use a specific 'Session and Service Continuity' (SSC) mode.

★ The UE can request a specific mode using the 'SSC Mode' field within the NAS: *PDU Session Establishment Request*. The SMF specifies the allocated mode using the 'Selected SSC Mode' field within the NAS: *PDU Session Establishment Accept*. The SSC mode does not change during the lifetime of a PDU Session. 3GPP has specified the following modes:

  o Mode 1: the network preserves the connectivity provided to the UE. When using a PDU Session to transfer IP packets, the IP address allocated to the UE is preserved. The UPF acting as the PDU Session Anchor is maintained throughout the lifetime of the PDU Session

  o Mode 2: the network may release the connectivity provided to the UE, i.e. the PDU Session can be released. If the PDU Session is being used to transfer IP packets, then the allocated IP address is also released. As an example scenario, the network may release connectivity if there is a requirement for load balancing at the anchor UPF. In this case, the PDU Session may be moved onto a different anchor UPF by releasing the existing PDU Session and subsequently establishing a new PDU Session

  o Mode 3: the network preserves the connectivity provided to the UE but there may be some impact during certain procedures. For example, the IP address allocated to the UE will be updated if the Anchor UPF changes but the change procedure will ensure that connectivity is preserved, i.e. connectivity towards the new Anchor UPF is established before releasing the connection to the old Anchor UPF. The release 15 version of the 3GPP specifications only supports Mode 3 for IP based PDU Sessions

★ A PDU Session can be configured to have multiple 'Anchor UPF' providing connectivity to the same data network. An example of this configuration is illustrated in Figure 65. In this example, the first 'Anchor UPF' is assumed to be local, while the second UPF is assumed to be more remote. This type of configuration can be used for Multi-Access Edge Computing (MEC) (section 1.16). The SMF can instruct the third UPF illustrated in Figure 65 to act as an 'Uplink Classifier' (UL CL). The SMF provides the UL CL with a set of traffic filters which can be used to determine which packets should be routed to each Anchor UPF. The use of an UL CL is transparent to the UE

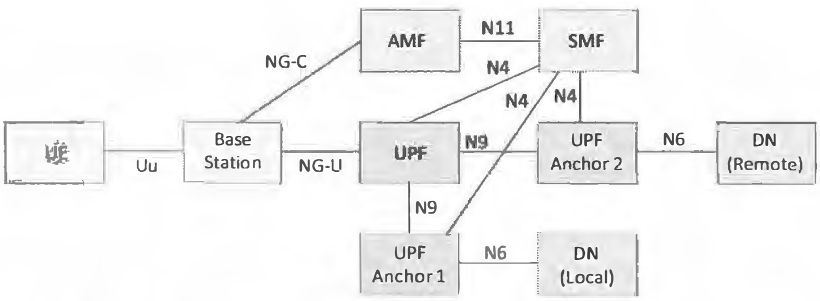


Figure 65 – Example of single PDU Session using multiple UPF Anchors

★ Figure 66 illustrates a second configuration using multiple 'Anchor UPF'. This example is based upon a 'Multi-Homing' scenario which is applicable to IPv6. 'Multi-Homing' can be used as a solution to improve reliability by adding redundancy to a connection. A PDU Session transferring IPv6 packets can be configured with multiple IPv6 prefixes (a prefix is the part of the IPv6 address used to identify the network/subnet). The prefix can then be used to route the packets to a specific UPF

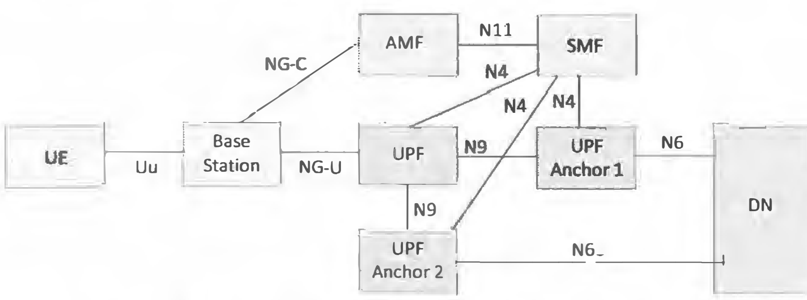


Figure 66 – Example of Multi-Homed PDU Session for service continuity

★ 'Multi-Homing' is not transparent to the UE and requires UE support. A UE uses the '5GSM Capability' field within the NAS: *PDU Session Establishment Request* to indicate whether or not Multi-Homing for IPv6 is supported. When Multi-Homing is used, the SMF provides the UE with an additional IPv6 prefix using an 'IPv6 Router Advertisement' message (specified by IETF RFC 4861). This message is sent to the UE using the NG-U connection between the UPF and Base Station, i.e. it is not sent using a NAS signalling message. The SMF can also use the 'IPv6 Router Advertisement' message to provide the UE with routing rules to influence the selection of the IPv6 prefix. This procedure is based upon IETF RFC 4191

★ A PDU Session belongs to a single Network Slice within a PLMN (Network Slicing is described in section 1.15). The UE can request a specific Network Slice when forwarding the NAS: *PDU Session Establishment Request*. The requested Network Slice is identified using its Single Network Slice Selection Assistance Information (S-NSSAI). The S-NSSAI is not included within the NAS: *PDU Session Establishment Request* itself because this message is forwarded transparently to an SMF, i.e. the AMF does not read the contents of this message. The AMF needs to have visibility of the requested Network Slice to ensure that an appropriate SMF is selected. The UE specifies the requested S-NSSAI within the NAS: *UL NAS Transport* message which is used to encapsulate the NAS: *PDU Session Establishment Request*. This allows the AMF to read the requested S-NSSAI before extracting the *PDU Session Establishment Request* and forwarding to an appropriate SMF. Figure 67 illustrates the concepts of SMF selection based upon the S-NSSAI and the packaging of the *PDU Session Establishment Request* within an *UL NAS Transport* message

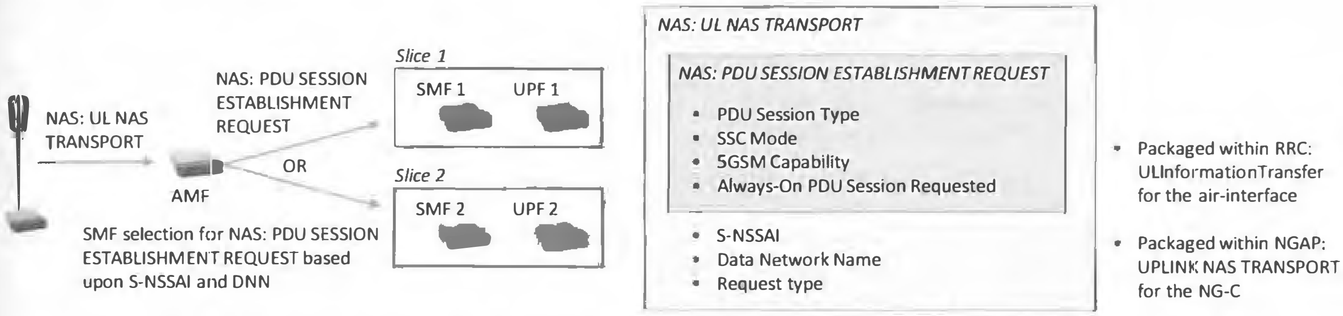


Figure 67 – SMF selection based upon Network Slice and packaging of a NAS: PDU Session Establishment Request

★ Encapsulating Session Management NAS messages within *UL NAS Transport* messages means that there are multiple layers of message encapsulation. For example, these messages are packaged within an NGAP: *Uplink NAS Transport* message when forwarding across the NG-C interface so the NAS: *PDU Session Establishment Request* is packaged within a NAS: *UL NAS Transport*, and the NAS: *UL NAS Transport* is packaged within an NGAP: *Uplink NAS Transport*

★ The SMF specifies the allocated Network Slice for a PDU Session within the NAS: *PDU Session Establishment Accept*. This message includes an S-NSSAI field for this purpose. If the UE is roaming outside its Home PLMN then the S-NSSAI identifies the Network Slice allocated within the Visited PLMN and a 'mapped' S-NSSAI can also be specified to indicate the corresponding Network Slice within the Home PLMN

★ 3GPP References: TS 38.300, TS 23.501, TS 23.502, TS 24.501,

1.14 QUALITY OF SERVICE

★ Quality of Service (QoS) is based upon uplink and downlink QoS Flows. A PDU Session can transfer one or more QoS Flows. Each QoS Flow is associated with a QoS Flow Identifier (QFI). All packets belonging to the same PDU Session and with the same QFI receive the same packet handling treatment, i.e. they are prioritised equally

★ There are three categories of QoS Flow:

  o Guaranteed Bit Rate (GBR) QoS Flow: provides a Guaranteed Flow Bit Rate (GFBR) to the end-user. This type of QoS Flow is typically used for time sensitive applications, e.g. voice and video calls, real time gaming, V2X

  o non-Guaranteed Bit Rate (non-GBR) QoS Flow: does not provide a GFBR to the end-user. This type of QoS Flow is typically used for non-time sensitive applications, e.g. web browsing, buffered streaming and instant messenger applications. Non-GBR QoS Flows are also used to transfer IMS signalling. In this case, it is recognised that the non-GBR QoS Flow is being used for signalling purposes and the QoS Flow is treated with higher priority

  o Delay Critical GBR QoS Flow: provides significantly lower latencies than a GBR QoS Flow. For example, a GBR QoS Flow may permit a 100 ms delay budget while a Delay Critical GBR QoS Flow may permit a 10 ms delay budget. Delay Critical GBR QoS Flows also have low Packet Error Rates to provide improved reliability. Typical applications include automation and intelligent transport systems

★ The Base Station commits to providing the GFBR when admitting a GBR QoS Flow, i.e. the Base Station must have sufficient air-interface, transport and processing resources available to support the GFBR

★ Packets belonging to a GBR QoS Flow are prioritised over packets belonging to a non-GBR QoS Flow, at least until the GFBR has been achieved. The Base Station does not commit to providing more than the GFBR, so GBR packets can be given lower priority once the GFBR has been achieved. Packets belonging to one GBR QoS Flow can be prioritised over packets belonging to another GBR QoS Flow based upon the priorities and packet delay budgets specified for each QoS Flow

★ Packets belonging to a non-GBR QoS Flow are generally treated as 'best effort' relative to packets belonging to GBR QoS Flows, i.e. any remaining resources after GBR QoS Flows have been scheduled are allocated to non-GBR QoS Flows. Packets belonging to one non-GBR QoS Flow can be prioritised over packets belonging to another non-GBR QoS Flow based upon priorities and packet delay budgets

★ Each QoS Flow is associated with a set of QoS parameters and a set of QoS characteristics Table 17 presents the set of QoS parameters and characteristics associated with each category of QoS Flow

		GBR	Delay Critical GBR	non-GBR
QoS Parameters	5G QoS Identifier (5QI)	✓	✓	✓
	Allocation and Retention Priority (ARP)	✓	✓	✓
	Guaranteed Flow Bit Rate (GFBR)	✓	✓	-
	Maximum Flow Bit Rate (MFBR)	✓	✓	-
	Notification Control	✓	✓	-
	Maximum Packet Loss Rate*	✓	✓	-
	Session Aggregate Maximum Bit Rate (Session-AMBR)	-	-	✓
	UE Aggregate Maximum Bit Rate (UE-AMBR)	-	-	✓
	Reflective QoS Attribute (RQA)	-	-	✓
QoS Characteristics	Resource Type	✓	✓	✓
	Priority Level	✓	✓	✓
	Packet Delay Budget	✓	✓	✓
	Packet Error Rate	✓	✓	✓
	Averaging Window	✓	✓	-
	Maximum Data Burst Volume	-	✓	-

* Maximum Packet Loss Rate is only applicable to QoS Flows transferring voice media within the release 15 version of the specifications

Table 17 – QoS Parameters and Characteristics associated with each QoS Flow category

★ The 5G QoS Identifier (5QI) is a pointer to a set of QoS characteristics. QoS characteristics can either be standardised or non-standardised. 5QI values 1, 2, 3, 4, 65, 66, 67 and 75 correspond to standardised GBR QoS Flows; 5QI values 5, 6, 7, 8, 9, 69, 70, 79 and 80 correspond to standardised non-GBR QoS Flows; 5QI values 82, 83, 84 and 85 correspond to standardised Delay Critical GBR QoS Flows; 5QI values 128 to 254 are non-standardised and can be used for operator specific configurations. Table 18 presents the QoS characteristics for each of the standardised values. The columns belonging to Table 18 reflect the 'QoS characteristics' rows within Table 17

★ The Priority Level allows prioritisation between QoS Flows belonging to an individual UE, and prioritisation between QoS Flows belonging to different UE. The Priority Level can be used to distribute resources between GBR and non-GBR QoS Flows once the Guaranteed Flow Bit Rate (GFBR) has been achieved for all GBR QoS Flows. A low numerical value corresponds to a high priority. The values in Table 18 are standardised defaults which can be overwritten by the network

★ The Packet Delay Budget associated with each 5QI defines an upper bound for the packet delay between the UE and the Anchor User Plane Function (UPF) which provides the N6 interface towards the Data Network. The delay budget figure is applicable to both the uplink and downlink directions. In the case of GBR and non-GBR QoS Flows, 98 % percent of packets should have a delay which is less than the Packet Delay Budget. Packets which arrive late are not discarded and do not contribute towards the Packet Error Rate. In the case of Delay Critical GBR QoS Flows, packets which arrive late contribute towards the Packet Error Rate. These late packets may be discarded or may be delivered depending upon the application

★ The Packet Delay Budget can be used for time sensitive packet scheduling. Time sensitive packet scheduling is typically applied to GBR QoS Flows. It means that the scheduling weight for a specific packet increases over time as the packet waits to be transmitted from the buffer, i.e. the packet receives an increasing priority as the time spent within the transmit buffer approaches the target Packet Delay Budget

★ The Packet Error Rate defines the percentage of higher layer packets which are not successfully transferred to the receiver. The error rate does not include packets which are lost due to congestion. In the case of Delay Critical GBR QoS Flows, packets which are delayed by more than the Packet Delay Budget are counted as lost unless the data burst exceeds the Maximum Data Burst Volume within the period of the Packet Delay Budget or the QoS Flow is exceeding the Guaranteed Flow Bit Rate. The target Block Error Rates (BLER) used by the RLC and HARQ re-transmission protocols should be aligned with the Packet Error Rate. If the RLC and HARQ re-transmission protocols operate with a high target BLER then it may not be possible to achieve the Packet Error Rate

★ The Maximum Data Burst Volume is only applicable to Delay Critical GBR QoS Flows. Its value defines the maximum quantity of data that the Base Station is required to serve within a time window equal to the Base Station's contribution towards the total Packet Delay Budget. The Base Station's contribution towards the total Packet Delay Budget is assumed to be 9 ms, 9 ms, 25 ms and 3 ms for 5QI values 82, 83, 84 and 85 respectively. The Maximum Data Burst Volume sizes of 1358 and 1354 bytes have been calculated to help avoid segmentation of packets across the transport network after GTP-U/UDP/IPv6/IPSec headers have been added, i.e. avoiding a total packet size which exceeds 1500 bytes. The Maximum Data Burst Volume values in Table 18 are standardised defaults which can be overwritten by the network

5QI	Resource Type	Default Priority Level	Packet Delay Budget	Packet Error Rate	Default Maximum Data Burst Volume	Default Averaging Window	Example Services
1	GBR	20	100 ms	10^{-2}	Not Applicable	2 seconds	Conversational Voice
2		40	150 ms	10^{-3}			Conversational Video (live streaming)
3		30	50 ms				Real Time Gaming, V2X messages
4		50	300 ms	10^{-6}			Non-Conversational Video (buffered streaming)
65		7	75 ms	10^{-2}			Mission Critical Push To Talk User Plane Voice
66		20	100 ms				Non-Mission Critical Push To Talk User Plane Voice
67		15	100 ms	10^{-3}			Mission Critical User Plane Video
75		25	50 ms	10^{-2}			V2X messages
5	Non-GBR	10	100 ms	10^{-6}	Not Applicable	Not Applicable	IMS Signalling
6		60	300 ms				Video (buffered streaming), TCP based applications
7		70	100 ms	10^{-3}			Voice, Video (live streaming), Interactive Gaming
8		80	300 ms	10^{-6}			Video (buffered streaming), TCP based applications
9		90					Sharing, Progressive Video
69		5	60 ms				Mission Critical Delay Sensitive Signalling
70		55	200 ms				Mission Critical Data (e.g. voice and video streaming)
79		65	50 ms	10^{-2}			V2X messages
80		68	10 ms	10^{-6}			Low Latency eMBB, Augmented Reality
82	Delay Critical GBR	19	10 ms	10^{-4}	255 bytes	2 seconds	Discrete Automation
83		22	10 ms		1358 bytes		
84		24	30 ms	10^{-5}	1354 bytes		Intelligent Transport Systems
85		21	5 ms		255 bytes		Automation for Electricity Distribution

Table 18 – Standardised QoS Characteristics associated with each 5QI

* The Averaging Window is applicable to GBR and Delay Critical GBR QoS Flows. It represents the duration over which the Guaranteed Flow Bit Rate (GFBR) and Maximum Flow Bit Rate (MFBR) are measured. The objective of specifying an Averaging Window is to prevent the Base Station achieving the GFBR by making a large, short term resource allocation followed by a long period of no resource allocation. A short Averaging Window forces the Base Station to make smaller, more frequent resource allocations, rather than larger, less frequent resource allocations. The Averaging Window values in Table 18 are standardised defaults which can be overwritten by the network

* Returning to Table 17, the Allocation and Retention Priority (ARP) defines:

  - Pre-emption Capability ('shall not trigger pre-emption' or 'may trigger pre-emption'). This parameter determines whether or not the QoS Flow is allowed to pre-empt an existing QoS Flow

  - Pre-emption Vulnerability ('not pre-emptable' or 'pre-emptable'). This parameter determines whether or not the QoS Flow can be pre-empted by another QoS Flow

  - Priority (1 to 15), where 15 corresponds to no priority, 14 corresponds to the lowest priority and 1 corresponds to the highest priority. This parameter can be used to identify which of the existing pre-emptable QoS Flows should be targeted for pre-emption. If the new QoS Flow has relatively low priority (high numerical value) then it may not be able to pre-empt any of the existing QoS Flows. This priority is independent of the Priority Level shown in Table 18 which is linked to packet handling

* The Guaranteed Flow Bit Rate (GFBR) is only applicable to GBR and Delay Critical GBR QoS Flows. It defines the minimum bit rate which can be expected from the QoS Flow, when measured across the Averaging Window. The GFBR can be specified independently for the uplink and downlink

* The Maximum Flow Bit Rate (MFBR) is only applicable to GBR and Delay Critical GBR QoS Flows. It defines the maximum bit rate which can be expected from the QoS Flow, when measured across the Averaging Window. Packets may be dropped by a throughput shaping function within the Base Station once the MFBR has been achieved. The MFBR can be specified independently for the uplink and downlink

* The Notification Control is only applicable to GBR and Delay Critical GBR QoS Flows It indicates whether or not the Base Station should inform the SMF if the QoS Flow fails to achieve its GFBR. If a QoS Flow fails to achieve its GFBR then the Base Station should continue attempting to achieve it, while the SMF which has been notified (assuming Notification Control is enabled) may decide to reconfigure or release the QoS Flow. If conditions subsequently improve and the Base Station is then able to achieve the GFBR then the SMF is informed (assuming Notification Control is enabled)

* The Maximum Packet Loss Rate is only applicable to GBR and Delay Critical GBR QoS Flows. In addition, within the release 15 version of the 3GPP specifications it is only applicable to QoS Flows being used to transfer voice media. The Maximum Packet Loss Rate defines the maximum rate of lost packets that can be tolerated in the uplink and downlink directions

* The Session Aggregate Maximum Bit Rate (Session-AMBR) defines the maximum permitted bit rate summed across all non-GBR QoS Flows belonging to a specific PDU Session. It can be specified independently for the uplink and downlink, and is enforced by the User Plane Functions (UPF) transferring data for the relevant PDU Session. The Session-AMBR is a subscription parameter which is retrieved by the SMF from the Unified Data Management (UDM). The SMF may modify the value according to local policies, or according to instructions received from the Policy Control Function (PCF). The final value is provided to any User Plane Functions (UPF) involved with the relevant PDU Session

* The UE Aggregate Maximum Bit Rate (UE-AMBR) defines the maximum permitted bit rate summed across all non-GBR QoS Flows belonging to a specific UE. It can be specified independently for the uplink and downlink, and is enforced by the serving Base Station. The UE-AMBR is a subscription parameter which is retrieved from the Unified Data Management (UDM) and is provided to the Base Station by the AMF. The Base Station applies a UE-AMBR which is set equal to the minimum of the value received from the AMF, and the sum of the active Session-AMBR for that UE

* The Reflective QoS Attribute indicates whether or not packets belonging to the QoS Flow may require the UE to apply Reflective QoS. Reflective QoS operates at 2 levels:

  - higher layer packet to QoS Flow mapping

  - QoS Flow to Data Radio Bearer (DRB) mapping

  Reflective QoS refers to the UE learning the rules to be applied for the uplink mappings from the patterns observed in the downlink. For example, if the UE receives QoS Flow 1 on DRB 3 in the downlink, then the UE will transmit QoS Flow 1 on DRB 3 in the uplink

* Reflective QoS is applicable to PDU Sessions used to transfer IP or Ethernet Packets (it is not applicable to the transfer of Unstructured packets). UE support for Reflective QoS is optional and is signalled to the SMF during the PDU Session setup procedure

* 3GPP References: TS 38.300, TS 23.501, TS 24.501

1.15 NETWORK SLICING

★ Network Slicing refers to the selection and allocation of network resources to suit the requirements of a specific service. For example, an eMBB user is likely to require high throughputs so that user should be allocated network resources which support high throughputs. In contrast, a URLLC user is likely to require low latency so that user should be allocated network resources which support low latency

★ A Network Slice includes resources from both the Core Network and Access Network

★ A Base Station using the Control Plane (CP) – User Plane (UP) Separation architecture may support multiple CU-UP. Each CU-UP can support a different set of Network Slices. For example, one CU-UP may be dedicated to eMBB services, while another CU-UP may be dedicated to URLCC services. A CU-UP provides the CU-CP with its list of supported Network Slices within the E1 Application Protocol (E1AP) signalling used to establish the E1 interface, e.g. using the E1AP: *GNB-CU-UP E1 Setup Request* message

★ A Base Station provides the AMF with a list of supported Network Slices per Tracking Area within the NGAP: *NG Setup Request* message. Similarly, the AMF provides the Base Station with a list of supported Network Slices per PLMN within the NGAP: *NG Setup Response* message, i.e. the Base Station and AMF exchange their supported Network Slices when establishing their NG interface connection. The information exchanged can be subsequently updated using the NGAP: *RAN Configuration Update* and NGAP: *AMF Configuration Update* messages

★ Network Functions within the 5G Core Network provide the Network Function Repository Function (NRF) with a list of supported Network Slices when registering with the NRF. The set of supported Network Slices is stored by the NRF as part of the Network Function profile. Other Network Functions subsequently use the NRF's Network Function Discovery service to identify the set of Network Slices supported by each registered Network Function

★ A PDU Session belongs to only one Network Slice per PLMN. When a UE is roaming, a PDU Session may use one Network Slice in the Visited PLMN and a second Network Slice in the Home PLMN. A UE can use multiple Network Slices by establishing multiple PDU Sessions with different service requirements

★ A Network Slice is identified by its Single Network Slice Selection Assistance Information (S-NSSAI) which is a concatenation of:

  - o a Slice/Service Type (SST) – 8 bits
  - o a Slice Differentiator (SD) – 24 bits

★ The SST refers to the expected Network Slice behaviour in terms of the features and services that it supports. 3GPP has standardised the SST values presented in Table 19. These standardised values address the three main use cases for 5G. Standardised values are particularly useful for roaming, i.e. they allow each network to interpret SST values in the same way. 3GPP has reserved values 0 to 127 for standardised SST. Non-standardised values can also be used for the SST. Non-standardised values allow operators to introduce Network Slices which support their own specific service requirements. 3GPP has reserved values 128 to 255 for non-standardised SST

SST	Service Type
1	enhanced Mobile Broadband (eMBB)
2	Ultra Reliable Low Latency Communications (URLLC)
3	Massive Machine Type Communications (mMTC)

Table 19 – Slice/Service Type (SST) values standardised by 3GPP

★ The SD is optional but can be used to differentiate between Network Slices which have the same SST value. This may be used if an operator offers the same service type to multiple subscriber groups. For example, subscriber group 'A' may be offered the eMBB service using {SST = 1, SD = 1}, whereas subscriber group 'B' may be offered the eMBB service using {SST = 1, SD = 2}

★ A set of one or more S-NSSAI is known as an NSSAI. 3GPP has defined 3 categories of NSSAI:

  - o Configured NSSAI: a general set of S-NSSAI which are available within a specific PLMN. If a UE is provided with a Configured NSSAI on a Visited PLMN then the UE can also be provided with a mapping between the S-NSSAI on the visited network and the corresponding S-NSSAI on the home network. Up to 16 S-NSSAI can be included within a Configured NSSAI. The AMF uses the NAS: *Registration Accept* or NAS: *Configuration Update Command* messages to signal the Configured NSSAI to the UE
  - o Allowed NSSAI: the set of S-NSSAI which the 5G Core Network has authorised for a specific UE. There can be a maximum of 8 Network Slices within an Allowed NSSAI, i.e. a single UE can be served by a maximum of 8 Network Slices. Using all 8 Network Slices would require the UE to establish 8 PDU Sessions. Similar to the Configured NSSAI, the AMF uses the NAS: *Registration Accept* or NAS: *Configuration Update Command* messages to signal the Allowed NSSAI to the UE. The Allowed NSSAI is also signalled to the Base Station using the NGAP: *Initial Context Setup Request* message. The Base Station can use this information when allocating resources for the UE
  - o Requested NSSAI: the set of S-NSSAI which the UE would like to access. There can be a maximum of 8 Network Slices within a Requested NSSAI. The Requested NSSAI is provided to the Base Station within the *RRC Setup Complete* message. The Base Station can use this information during the AMF selection procedure if a 5G-S-TMSI has not been provided, i.e. the Base Station extracts an AMF identity from the 5G-S-TMSI if it is available, otherwise the Base Station attempts to select an AMF which

supports the set of requested Network Slices. The Requested NSSAI is provided to the AMF within the NAS: *Registration Request* message. The AMF can forward the Requested NSSAI to the Network Slice Selection Function (NSSF) which can verify that the UE is subscribed to the requested Network Slices and can determine the set of allowed Network Slices

★ The UE generates the Requested NSSAI from the Allowed NSSAI if the UE has already been provided with an Allowed NSSAI for the current serving PLMN. Otherwise, the UE generates the Requested NSSAI from the Configured NSSAI. The UE can also generate the Requested NSSAI using the Allowed NSSAI in combination with one or more S-NSSAI from the Configured NSSAI

★ The UE can request a specific Network Slice (S-NSSAI) when establishing a new PDU Session. Figure 67 in Section 1.13 illustrates the UE specifying a single S-NSSAI within the NAS: *UL NAS Transport* message when forwarding a NAS: *PDU Session Establishment Request* to the AMF (for subsequent forwarding to an SMF). The S-NSSAI corresponds to the Network Slice which the UE would like to have allocated to the requested PDU Session. The AMF is able to use the requested S-NSSAI to help select an appropriate SMF. The Network Slice allocated to a PDU Session is specified within the NAS: *PDU Session Establishment Accept* message

★ Figure 68 summarises the signalling procedures which involve Network Slices during interface and Network Function setup, UE registration and PDU Session establishment (message names are not shown for the interface and Network Function setup phase to help simplify the figure)

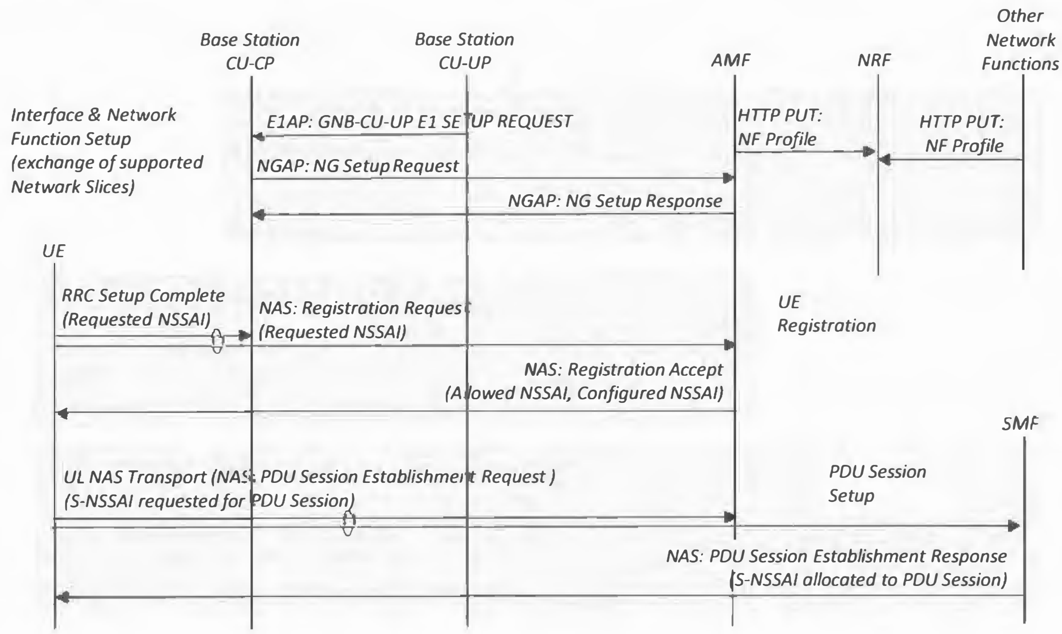


Figure 68 – Signalling procedures involving Network Slices

★ Figure 69 illustrates the use of network slice 'A' within a visited PLMN, combined with the use of network slice '2' within the Home PLMN. This figure corresponds to a 'Home Routed' roaming architecture rather than a 'Local Breakout' roaming architecture. The 'Local Breakout' roaming architecture provides connectivity to the Data Network directly from the visited PLMN

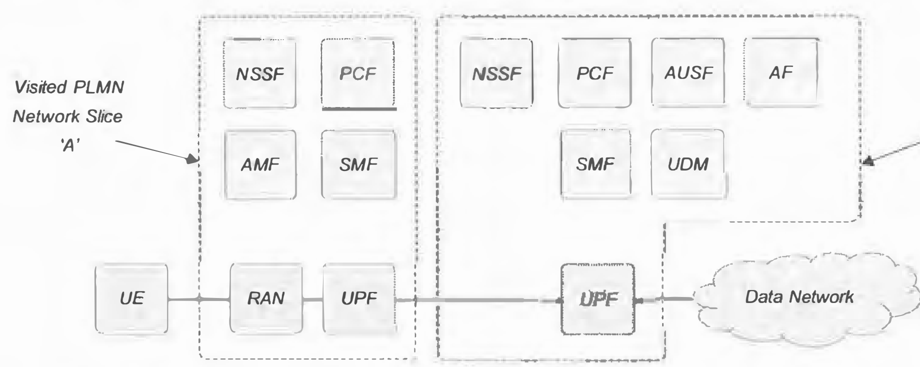


Figure 69 – 'Home Routed' roaming scenario using network slices within both Visited and Home PLMN

★ 3GPP References: TS 23.501, TS 24.501, TS 38.300, TS 38.413, TS 23.003

1.16 EDGE COMPUTING

★ Edge Computing allows a UE to access services which are hosted close to the serving Base Station. This approach helps to improve both end-user experience and network efficiency. End-user experience can be improved by lower latencies while network efficiency can be improved by reduced backhaul transport requirements

★ Hosting services close to the serving Base Station means that there is a User Plane Function (UPF) and a Data Network (DN) or Local Area Data Network (LADN) at a location which is geographically close to the serving Base Station. The UPF and DN/LADN could be co-located with the Base Station, or they could be co-located with a router within the transport network. Alternatively, they could be located at a regional data center

★ A Local Area Data Network (LADN) is a data network which provides services across a specific local area. This is in contrast to the public internet or a private network which can be accessed from anywhere. An LADN is specified to provide services across one or more specific Tracking Areas. A UE can request LADN information from the AMF when sending the NAS: *Registration Request*. The AMF can respond by providing LADN information within the NAS: *Registration Response*. LADN information includes a Data Network Name (DNN) and a list of one or more Tracking Areas. A UE can request a PDU Session which uses an LADN DNN while it remains within the specified Tracking Area(s). The SMF will release the PDU Session if the UE moves outside those Tracking Area(s)

★ Example applications for Edge Computing include:

  o real time delivery of video streams at a sporting event. For example, spectators at a Formula 1 Grand Prix may be able to view only part of the track. A video streaming service can be used to provide views around the remainder of the track. A spectator could select a specific driver and then follow the corresponding video stream. In this case, the video content is generated, distributed and accessed locally. The UPF and LADN could be co-located with the Centralised Unit of the Base Station serving the venue

  o augmented reality at places of interest. For example, a museum could use augmented reality to provide visitors with additional information as they tour the venue. The Edge Computing application could run on a local server which recognises and tracks the visitor location and provides information relevant to that location

  o local break-out for a corporate network. For example, a network providing services to a large office could be defined as an LADN and could be connected to a UPF which is co-sited with a Base Station serving that office. This would allow local access to the network without having to transfer data to and from the Core Network

  o Vehicle to Infrastructure (V2I). Road Side Units (RSU) can be positioned along highways and used to provide services to passing vehicles. The transfer of traffic signal timing information is an example of V2I. In this case, the RSU is aware of the timing used by nearby traffic signals. This timing is provided to vehicles approaching the signals so they are able to react appropriately. The transfer of car parking information is another example of V2I

★ An example architecture for Edge Computing is illustrated in Figure 70. This example assumes that a UPF and an LADN are co-sited with the Base Station. This example uses separate NG-U interfaces for the local UPF and the remote UPF. In this case, a PDU Session would be established specifically for connection to the LADN. Figure 65 in section 1.13 illustrates a different architecture which can also be used for Edge Computing. In that case, a single PDU Session can access both the local and remote Data Networks. An intermediate UPF provides routing between the local and remote networks. This routing can be based upon either IPv6 Multi-Homing which requires UE support or 'Uplink Classifier' (UL CL) traffic filtering functionality which is transparent to the UE

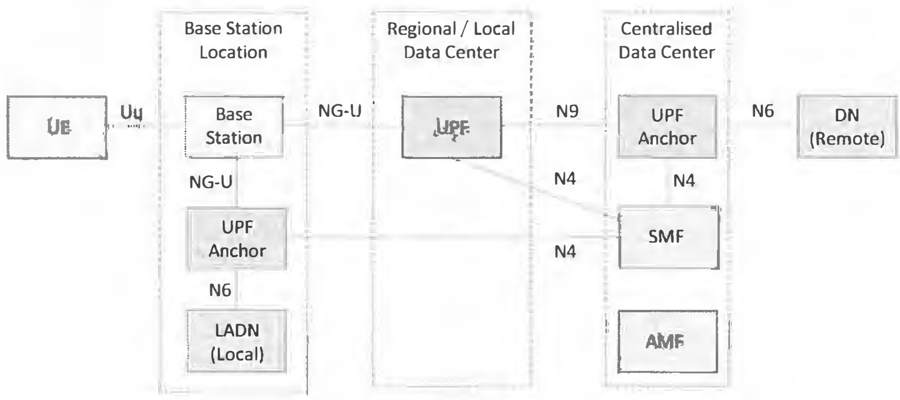


Figure 70 – Example network architecture for Edge Computing

★ The ETSI Industry Specification Group (ISG) for Multi-Access Edge Computing (MEC) has published a series of Group Reports and Group Specifications for MEC, e.g. ETSI GS MEC 003 Framework and Reference Architecture. 5G solutions can be based upon these specifications which include the definition of Application Programming Interfaces (API) for third party application developers

★ 3GPP References: TS 23.501, TS 24.501

1.17 MICO MODE

- Mobile Initiated Connection Only (MICO) refers to a mode of operation which allows only mobile originated data transfer while the UE is CM-IDLE. The UE is categorised as being unreachable and is not paged by the network (the UE does not listen for paging messages). Requests for downlink data transfer are rejected by the AMF. Likewise, the AMF does not proceed with downlink transport over NAS, e.g. mobile terminated SMS
- Both mobile originated and mobile terminated data transfer is possible for a MICO mode device while it is CM-CONNECTED
- A UE can indicate a preference for MICO mode during either the initial registration procedure, or during a registration update, i.e. within the NAS: *Registration Request* message. The AMF is responsible for deciding whether or not the UE is permitted to operate in MICO mode. The 'MICO Indication' within the NAS: *Registration Accept* message is used to inform the UE of whether or not MICO mode is permitted
- A UE which is CM-IDLE and using MICO mode can be provided with a registration area equal to the whole PLMN (if the AMF serves the whole PLMN). This means the UE does not trigger registration updates due to mobility. The UE will not be paged so it will not be necessary to broadcast paging messages across the whole PLMN
- If a MICO mode UE is allocated a registration area which is smaller than the whole PLMN, then the UE evaluates whether or not it has remained within the registration area when it has mobile originated data or mobile originated signalling to transfer, i.e. it does not provide an update immediately after completing a cell reselection outside its registration area
- A UE which is CM-IDLE and using MICO mode uses the periodic registration timer, T3512. This serves as a keep-alive to confirm that the UE remains connected to the network

1.18 UE CAPABILITIES

- The Base Station uses the RRC: *UE Capability Enquiry* message to request capability information from the UE. This message allows the Base Station to specify the Radio Access Technologies (RAT) of interest. In the case of 5G, the set of RAT for which UE capability information can be requested has been kept relatively small, i.e. information can be requested for NR, EUTRA-NR and EUTRA. This is aligned with the strategy to only allow inter-system handover from 5G to 4G. The EUTRA-NR information is applicable to the Non-Standalone Base Station architectures using Dual Connectivity. Table 20 provides a comparison with the equivalent 4G message which allows the 4G Base Station to request UE capability information for 2G, 3G, 4G and 5G technologies

5G, UE Capability Enquiry	NR, EUTRA-NR, EUTRA
4G, UE Capability Enquiry	EUTRA, UTRA, GERAN-CS, GERAN-PS, CDMA2000-1XRTT, NR, EUTRA-NR

Table 20 – RAT for which UE capability information can be requested

- The Base Station can also specify the NR and EUTRA operating bands of interest within the RRC: *UE Capability Enquiry* message. This prevents the UE sending large quantities of information for operating bands which are not relevant
- The UE responds to the Base Station using the RRC: *UE Capability Information* message. This message includes one or more instances of the *UE-CapabilityRAT-Container*. Each instance is applicable to either 'NR', 'EUTRA-NR' or 'EUTRA'. The 'NR' and 'EUTRA-NR' instances are specified within 3GPP TS 38.331 with descriptions of each information element within 3GPP TS 38.306. The 'EUTRA' instance is specified within 3GPP TS 36.331 with descriptions of each information element within 3GPP TS 36.306
- 3GPP TS 38.306 specifies which information elements correspond to mandatory UE capabilities. The reason for the UE having to indicate support for a mandatory capability is not immediately obvious, i.e. if a specific UE capability is mandatory then the UE would not normally have to signal its support for that capability _ the Base Station should be able to assume that it is supported. The requirement for a UE to signal its support for specific mandatory capabilities is based upon the potential lack of Interoperability Testing (IOT). A UE vendor may implement a mandatory capability before networks are available to test the implementation. In this case, the UE should report that the mandatory capability is not supported, i.e. UE only indicate that mandatory UE capabilities are supported if they have been both implemented and tested with network equipment
- In the case of 4G, a set of 'UE Categories' has been specified by 3GPP and each UE declares that it supports one or more of these categories. The 'UE Category' defines a subset of the UE capabilities including the supported modulation schemes, the maximum number of layers used for spatial multiplexing, the maximum number of bits which can be received during a Transmission Time Interval (TTI), the maximum number of bits which can be transmitted during a TTI, and the layer 2 buffer size. For example, UE Category 5 can support 64QAM in both the uplink and downlink directions, a maximum of 4 spatial multiplexing layers in the downlink, reception of 149 776 bits per 1 ms TTI in the downlink and transmission of 75 376 bits per 1 ms TTI in the uplink
- In the case of 5G, the concept of 'UE Categories' has not been specified by 3GPP. Instead, each individual UE capability is explicitly signalled. For example, the UE signals its support for a specific number of spatial multiplexing layers using the *MIMO-LayersDL* and

MIMO-LayersUL information elements. Similarly, the UE signals its support for uplink and downlink modulation schemes using the *ModulationOrder* information element

★ UE do not explicitly signal their maximum supported data rate. Instead, this information is calculated using an equation specified within 3GPP TS 38.306. This equation is applicable to both the uplink and downlink:

$$Data\ rate\ (Mbps) = 10^{-6} \times \sum_{j=1}^{J} \left[v_{layers}^{(j)} \times Q_m^{(j)} \times f^{(j)} \times R_{max} \times \frac{12 \times N_{PRB}^{BW(j),\mu}}{T_s^{\mu}} \times \left(1 - OH^{(j)}\right) \right]$$

where,

J	is the number of aggregated carriers
$v_{layers}^{(j)}$	is the maximum number of layers on carrier 'j'
$Q_m^{(j)}$	is the maximum modulation order on carrier 'j'
$f^{(j)}$	is a scaling factor for carrier 'j' which is signalled by the UE using the *scalingFactor* information element. Values of 1.0, 0.8, 0.75 and 0.4 can be signalled
R_{max}	= 948 /1024 is the maximum coding rate within the 64QAM and 256QAM MCS tables
$N_{PRB}^{BW(j),\mu}$	is the maximum Resource Block allocation within the bandwidth *BW(j)* when using numerology 'μ'. *BW(j)* is the maximum bandwidth supported by the UE on carrier 'j'
T_s^{μ}	is the OFDM symbol duration for numerology 'μ', i.e. $T_s^{\mu} = 0.001 / (14 \times 2^{\mu})$
$OH^{(j)}$	is an air-interface overhead given by: 0.14 for the downlink of Frequency Range 1; 0.18 for the downlink of Frequency Range 2; 0.08 for the uplink of Frequency Range 1; 0.10 for the uplink of Frequency Range 2

★ Some example results for Frequency Ranges 1 and 2 are presented in Table 21. These examples assume the maximum channel bandwidths for each numerology. They also assume the maximum UE capability from the perspective of the Scaling Factor, i.e. a Scaling Factor of 1 is assumed. Less powerful devices can signal a lower Scaling Factor to indicate that they are restricted to supporting lower throughputs

	Frequency Range 1		Frequency Range 2	
	50 MHz Channel	100 MHz Channel	200 MHz Channel	400 MHz Channel
Number of Layers	2	4	2	2
Modulation order	8	8	6	6
Scaling Factor	1	1	1	1
Resource Blocks	270	273	264	264
Numerology	15 kHz	30 kHz	60 kHz	120 kHz
Overhead	0.14	0.14	0.18	0.18
Throughput	578 Mbps	2.3 Gbps	1.6 Gbps	3.2 Gbps

Table 21 – Example maximum UE throughput capability calculations (downlink)

★ The UE also provides capability information to the Core Network:

- the NAS: *Registration Request* is sent to the AMF and can include the '5G Mobility Management (5GMM) Capability', 'UE Security Capability' and 'S1 UE Network Capability'. The 5GMM Capability indicates whether or not the UE supports 'S1 mode', i.e. connectivity to the 4G Core Network. It also indicates whether or not the UE supports handovers from 'N1 mode' to 'S1 mode'. The 'UE Security Capability' indicates the encryption and integrity protection algorithms supported by the UE. The 'S1 UE Network Capability' corresponds to the 'UE Network Capability' from the 4G NAS signalling protocol (specified within 3GPP TS 24.301)
- the NAS: *PDU Session Establishment Request* is sent to the SMF and can include the '5G Session Management (5GSM) Capability'. The 5GSM Capability indicates whether or not the UE supports Reflective QoS. It also indicates whether or not the UE supports IPv6 Multi-homing, i.e. the use of multiple IPv6 prefixes to route packets towards the same Data Network using different paths

★ The Base Station forwards the UE Radio Capability information obtained from the UE to the AMF. This is done using the NGAP: *UE Radio Capability Info Indication* message. The AMF stores this information as part of the UE context and subsequently provides it to other Base Stations serving the UE, i.e. a first Base Station obtains the capability information from the UE and this is then stored by the AMF. The UE can move to RRC Idle and then establish a connection with a new Base Station. The new Base Station does not need to request the UE capability information from the UE because it is provided by the AMF within the NGAP: *Initial Context Setup Request*

★ 3GPP References: TS 38.331, TS 38.306, TS 24.501

1.19 SPECTRUM

★ Congestion within the lower operating bands, combined with a requirement for wider channel bandwidths has led to the inclusion of both low and high operating bands for 5G, i.e. 5G targets spectrum allocations up to 100 GHz. The range of spectrum targeted by 5G is summarised in Figure 71

★ The good RF propagation associated with the lower operating bands allows those bands to be used for coverage solutions. The relatively small channel bandwidths within those bands means that there is a requirement for 5G to focus upon improving spectrum efficiency. The lower operating bands can be used for all 5G use cases, i.e. eMBB, URLLC and mMTC, although the relatively small channel bandwidths limit the peak connection throughputs achieved by eMBB applications

★ The wide channel bandwidths available in the higher operating bands allows those bands to be used for high throughput, capacity solutions. The relatively poor RF propagation within those bands means there is a requirement to focus upon improving the link budget

★ 5G has been standardised to provide sufficient flexibility to address the challenges associated with both the low and high operating bands, e.g. high order MIMO and multi-user MIMO solutions can be used within the lower operating bands to help improve spectrum efficiency while beamforming can be used within the higher operating bands to help improve the link budget

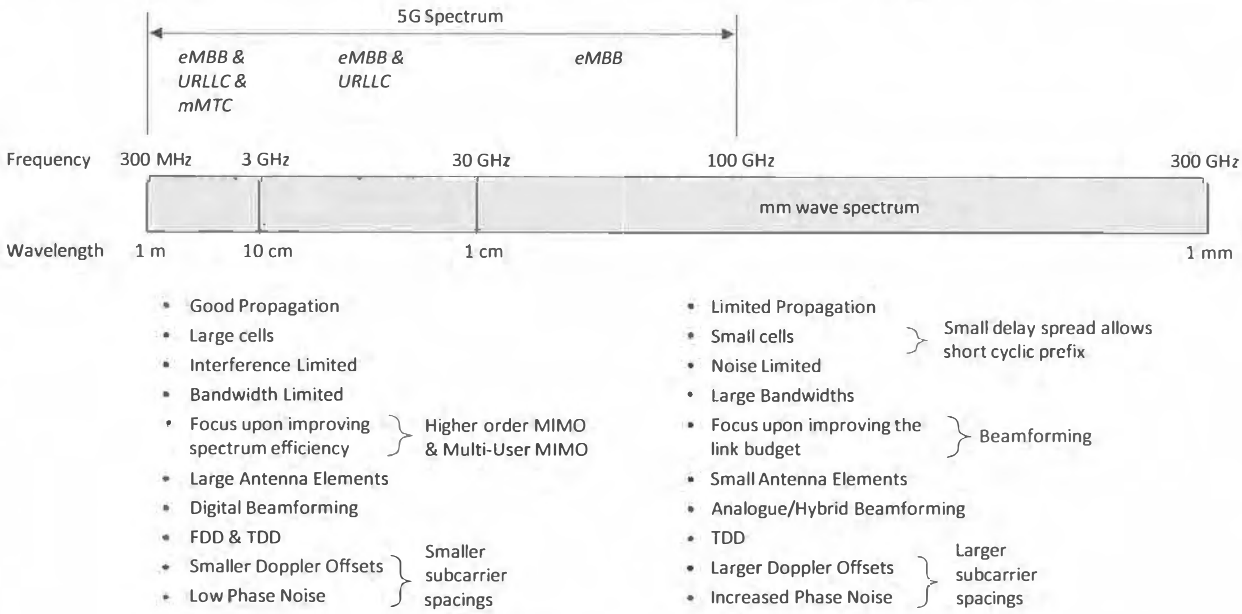


Figure 71 – Range of 5G spectrum

★ Characteristics associated with the high operating bands include:

- limited RF propagation leading to small cells and noise limited coverage conditions. Interference limited coverage conditions are less likely at the high operating bands because intercell interference is attenuated by the RF propagation channel. Beamforming also helps to restrict intercell interference by allowing both directional transmission and directional reception
- small cell sizes mean that delay spreads from the radio propagation channel are short. This allows the air-interface waveform to use a short cyclic prefix (this corresponds to a high subcarrier spacing)
- increased potential for wider channel bandwidths. The higher operating bands are generally less congested and have greater quantities of spectrum than the lower operating bands
- increased potential for frequency offsets which can reduce the signal to noise ratio at the receiver and thus degrade the bit error rate performance. Frequency offsets lead to rotations of the modulation constellation. This makes the use of higher order modulation schemes such as 256QAM more challenging. In addition, when using an OFDM based waveform and when frequency offsets are frequency selective (different offsets experienced by different subcarriers) then subcarrier orthogonality is lost and there can be interference between subcarriers. Frequency offsets require compensation within the receiver implementation to help reduce their impact. The larger frequency offsets in the higher operating bands provide an argument for using larger subcarrier spacings. Larger subcarrier spacings are less sensitive to frequency offsets. Frequency offsets can originate from:
  - Doppler frequency offsets, which increase proportionally with the RF carrier frequency, e.g. increasing the RF carrier frequency by a factor of 10 also increases the Doppler frequency offset by a factor of 10. Doppler offsets are dependent upon the relative velocities of the transmitter and receiver, i.e. they increase for high speed scenarios
  - phase noise which is generated by using non-ideal oscillators at both the transmitter and receiver. These oscillators do not generate completely perfect sine waves. Instead they generate sine waves which have small random phase variations, i.e. phase noise is superimposed upon the sine wave. It is more difficult to manufacture high frequency oscillators with good phase noise properties. The use of larger subcarrier spacings helps to increase resilience against phase noise

- the higher subcarrier spacings associated with the higher operating bands lead to a shorter subframe duration and provide the potential for lower latencies
- the wider channel bandwidths associated with the higher operating bands lead to higher power consumption by the D/A and A/D converters. In addition, power amplifier efficiency is likely to be lower within the higher operating bands
- smaller antenna elements which provide increased potential for practical antenna arrays at both the Base Station and UE. These antenna arrays can be used to generate directional beams at both the transmit and receive sides of the radio link, i.e. both the Base Station and UE apply beamforming rather than just the Base Station
- stronger argument for analogue or hybrid beamforming rather than digital beamforming
  - digital beamforming at the transmitter applies phase shifts before D/A conversion and requires an RF path (including D/A converter and power amplifier) 'per antenna element' or 'per antenna element group'. This becomes both expensive and power hungry when the number of antenna elements is high, i.e. it is not practical for the high operating bands where a large number of antenna elements are required to generate highly directional beams
  - analogue beamforming at the transmitter applies phase shifts after D/A conversion and requires an RF path 'per beam'. This type of solution is less flexible than digital beamforming because all Resource Blocks are transmitted using the same beam (digital beamforming allows different phase shifts to be applied to different Resource Blocks and so supports different beams for different Resource Blocks. In addition, digital beamforming allows a single set of Resource Blocks to be transmitted using multiple beams, i.e. towards different users for Multi-User MIMO). Analogue beamforming is generally limited to a small number of beams, e.g. 2 polarisation beams could be used to support 2×2 MIMO
  - hybrid beamforming is a compromise between digital and analogue beamforming to allow some flexibility with reasonable RF hardware requirements. Hybrid beamforming applies some phase shifts before D/A conversion and some phase shifts after D/A conversion
- TDD allows simpler beamforming solutions relative to FDD due to the channel reciprocity between the uplink and downlink, i.e. the uplink and downlink experience the same propagation channel. Channel reciprocity allows uplink measurements to be applied to downlink transmissions, and vice versa. TDD allows beamforming to be implemented without relying upon a feedback channel

1.19.1 DUPLEX MODES

★ The duplex mode determines that way in which a spectrum allocation is used for uplink and downlink transmissions

★ 5G has been specified to support the following duplex modes:

- Frequency Division Duplexing (FDD)
- Time Division Duplexing (TDD)
- Supplemental Downlink (SDL)
- Supplemental Uplink (SUL)

★ Each operating band is associated with a single duplex mode. However, there are examples of multiple operating bands with different duplex modes targeting the same block of spectrum. Two examples are presented in Table 22. Operating bands n50 and n75 target the same block of spectrum but operating band n50 specifies TDD operation while band n75 specifies SDL operation. A similar pattern exists for operating bands n51 and n76. This allows different operators to use the spectrum in different ways

Operating Band	Duplex Mode	Uplink Band (MHz)	Downlink Band (MHz)	Bandwidth (MHz)
n50	TDD	1432 - 1517		85
n51		1427 - 1432		5
n75	SDL	Not Applicable	1432 - 1517	85
n76			1427 - 1432	5

Table 22 – Different duplex modes associated with common blocks of spectrum

★ Figure 72 illustrates the general concept of each duplex mode. FDD requires paired spectrum, while TDD, SDL and SUL use unpaired spectrum. FDD uses two separate RF carriers - one for uplink and one for the downlink. The UE transmits using one RF carrier (uplink), while the Base Station transmits using the other RF carrier (downlink)

★ Supplemental Downlink refers to an RF carrier which is only used for downlink transmissions. In contrast, Supplemental Uplink refers to an RF carrier which is only used for uplink transmissions

★ TDD uses the same RF carrier for both the uplink and downlink transmissions. The UE and BTS cannot transmit simultaneously in the case of TDD because they share the same RF carrier

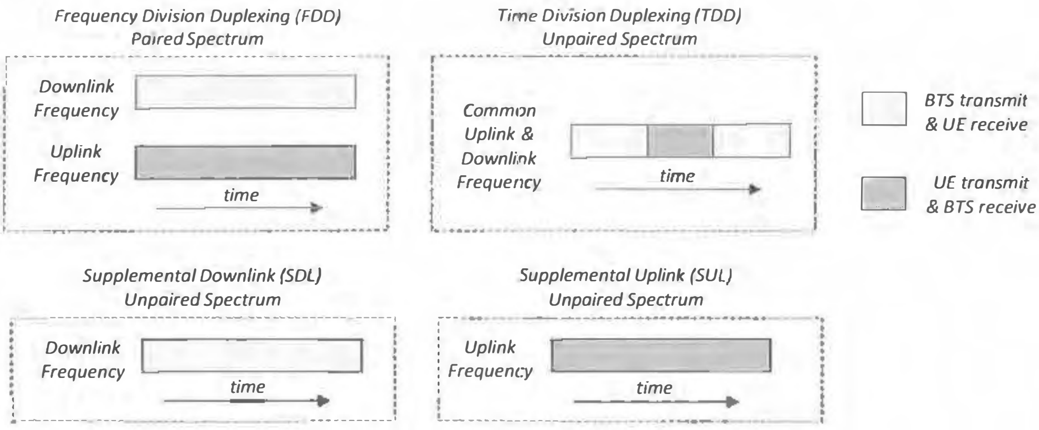


Figure 72 – Duplex mode concepts

★ TDD is attractive for systems where the data transfer is highly asymmetric because the ratio between the uplink and downlink transmissions can be adjusted appropriately and the RF carrier remains fully utilised. In the case of FDD, one of the RF carriers would be under utilised when the data transfer is highly asymmetric

★ 4G uses fixed uplink/downlink timing for TDD, i.e. the network is configured to use a specific uplink/downlink subframe configuration and once that configuration has been chosen then the timing of the uplink and downlink subframes is fixed. 5G supports dynamic uplink/downlink timing for TDD. This allows the Base Station to dynamically change symbols or slots between the uplink and downlink according to instantaneous requirements. For example, the number of uplink symbols can be increased while the number of downlink symbols is decreased if the volume of uplink traffic increases relative to the volume of downlink traffic

★ TDD devices benefit from not requiring a duplexer. This helps to reduce the cost of the device. A duplexer is required by FDD devices to extract the uplink signal from the antenna for reception, while at the same time inserting the downlink signal into the antenna for transmission. Duplexers tend to increase the receiver noise figure in the receive direction and generate an additional loss in the transmit direction

★ FDD is attractive for systems where the requirement for uplink and downlink capacity is relatively symmetric. FDD can offer higher throughputs because data transfer can be continuous in both directions. The capacity associated with a pair of FDD carriers is greater than the capacity associated with a single TDD carrier, but a greater quantity of spectrum is required (assuming equal channel bandwidths)

★ FDD can be simpler to deploy in terms of synchronisation requirements. In general, it is not necessary for neighbouring FDD Base Stations to be time synchronised. Neighbouring TDD Base Stations require time synchronisation to limit levels of interference between uplink and downlink transmissions

1.19.2 OPERATING BANDS

★ 3GPP has specified the following Frequency Ranges:

  - Frequency Range 1 (450 MHz to 6 GHz)
  - Frequency Range 2 (24.25 GHz to 52.60 GHz)

★ This categorisation allows a separate set of requirements to be specified for each Frequency Range. For example, separate sensitivity and out-of-band emission requirements are specified for each Frequency Range. These requirements account for the different UE and network implementations associated with each Frequency Range. For example, UE using Frequency Range 2 are likely to be equipped with highly integrated antenna panels providing a beamforming capability. In contrast, UE using Frequency Range 1 are likely to be equipped with a relatively small number of antenna elements distributed around the device

★ Operating bands belonging to Frequency Range 1 are shown in Table 23. These bands support Frequency Division Duplex (FDD), Time Division Duplex (TDD), Supplemental Downlink (SDL) and Supplemental Uplink (SUL)

★ All bands are numbered using the prefix 'n'. Bands n1 to n76 are re-farming bands which have already been specified for use by 4G, i.e. these existing 4G bands may be re-farmed for 5G. 5G operating band 'n1' corresponds to 4G operating band '1', etc

★ Operating bands n66 and n70 are FDD bands but have unequal uplink and downlink spectrum allocations. These bands have more downlink spectrum than uplink spectrum

★ The largest bands within FR1 are the new 5G TDD operating bands n77, n78 and n79. These bands have the potential to offer high throughputs at relatively low operating frequencies. Operating band n78 is a subset of operating band n77. Some countries may allocate operating band n78 if the full range of operating band n77 is not available

Operating Band	Duplex Mode	Uplink Band (MHz)	Downlink Band (MHz)	Bandwidth (MHz)	Category
n1	FDD	1920 - 1980	2110 - 2170	2 × 60	Re-farmed 4G bands
n2		1850 - 1910	1930 - 1990	2 × 60	
n3		1710 - 1785	1805 - 1880	2 × 75	
n5		824 - 849	869 - 894	2 × 25	
n7		2500 - 2570	2620 - 2690	2 × 70	
n8		880 - 915	925 - 960	2 × 35	
n12		699 - 716	729 - 746	2 × 17	
n20		832 - 862	791 - 821	2 × 30	
n25		1850 - 1915	1930 - 1995	2 × 65	
n28		703 - 748	758 - 803	2 × 45	
n34	TDD	2010 - 2025		15	
n38		2570 - 2620		50	
n39		1880 - 1920		40	
n40		2300 - 2400		100	
n41		2496 - 2690		194	
n50		1432 - 1517		85	
n51		1427 - 1432		5	
n65	FDD	1920 - 2010	2110 2200	2 × 90	
n66		1710 - 1780	2110 - 2200	70 + 90	
n70		1695 - 1710	1995 - 2020	15 + 25	
n71		663 - 698	617 - 652	2 × 35	
n74		1427 - 1470	1475 - 1518	2 × 43	
n75	SDL	Not Applicable	1432 - 1517	85	
n76			1427 - 1432	5	
n77	TDD	3300 - 4200		900	New 5G bands
n78		3300 - 3800		500	
n79		4400 - 5000		600	
n80	SUL	1710 - 1785	Not Applicable	75	
n81		880 - 915		35	
n82		832 - 862		30	
n83		703 - 748		45	
n84		1920 - 1980		60	
n86		1710 - 1780		70	

Table 23 – 5G operating bands for Frequency Range 1 (450 MHz to 6 GHz)

- ★ Each operating band is specified to support a specific set of channel bandwidths. These channel bandwidths depend upon the subcarrier spacing. Frequency Range 1 supports subcarrier spacings of 15, 30 and 60 kHz. Table 24 presents the set of channel bandwidths for each operating band and each subcarrier spacing
- ★ In the case of 4G, there is a one-to-one mapping between Base Station channel bandwidth and UE channel bandwidth. For example, a 4G Base Station channel bandwidth of 20 MHz requires all UE to also support a 20 MHz channel bandwidth
- ★ In the case of 5G, the Base Station channel bandwidth can be greater than or equal to the UE channel bandwidth. For example, a 5G Base Station could support a channel bandwidth of 100 MHz, while a UE could support a channel bandwidth of 20 MHz. In that case, the Base Station would recognise the UE capability and allocate Resource Blocks which are within a 20 MHz bandwidth. Different UE could use different 20 MHz sections of the total Base Station channel. UE which support the 100 MHz channel bandwidth could be allocated Resource Blocks from any location within the Base Station channel
- ★ In some cases, uplink and downlink channel bandwidths are not equal. FDD operating bands n66 and n70 support asymmetric uplink and downlink channel bandwidths. For example, operating band n66 supports a 20 MHz uplink channel combined with a 40 MHz downlink channel. Similarly, TDD operating band n50 supports asymmetric uplink and downlink channel bandwidths. In this case, a 60 MHz uplink channel can be used in combination with an 80 MHz downlink channel

Operating Band	Bandwidth (MHz)	15 kHz Subcarrier Spacing	30 kHz Subcarrier Spacing	60 kHz Subcarrier Spacing
n1	2 × 60	5,10,15,20	10,15,20	10,15,20
n2	2 × 60	5,10,15,20	10,15,20	10,15,20
n3	2 × 75	5,10,15,20,25,30	10,15,20,25,30	10,15,20,25,30
n5	2 × 25	5,10,15,20	10,15,20	-
n7	2 × 70	5,10,15,20	10,15,20	10,15,20
n8	2 × 35	5,10,15,20	10,15,20	-
n12	2 × 17	5,10,15	10,15	-
n20	2 × 30	5,10,15,20	10,15,20	-
n25	2 × 65	5,10,15,20	10,15,20	10,15,20
n28	2 × 45	5,10,15,20	10,15,20	-
n34	15	5,10,15	10,15	10,15
n38	50	5,10,15,20	10,15,20	10,15,20
n39	40	5,10,15,20,25,30,40	10,15,20,25,30,40	10,15,20,25,30,40
n40	100	5,10,15,20,25,30, 40,50	10,15,20,25,30, 40,50,60,80	10,15,20,25,30, 40.50,60,80
n41	194	10,15,20,40,50	10,15,20,40,50,60,80,100	10,15,20,40,50,60,80,100
n50	85	5,10,15,20,40,50	10,15,20,40,50,60,80	10,15,20,40,50,60,80
n51	5	5	-	-
n65	2 × 90	5,10,15,20	10,15,20	10,15,20
n66	70 + 90	5,10,15,20,40	10,15,20,40	10,15,20,40
n70	15 + 25	5,10,15,20,25	10,15,20,25	10,15,20,25
n71	2 × 35	5,10,15,20	10,15,20	-
n74	2 × 43	5,10,15,20	10,15,20	10,15,20
n75	85	5,10,15,20	10,15,20	10,15,20
n76	5	5	-	-
n77	900	10,15,20,40,50	10,15,20,40,50,60,80,90,100	10,15,20,40,50,60,80,90,100
n78	500	10,15,20,40,50	10,15,20,40,50,60,80,90,100	10,15,20,40,50,60,80,90,100
n79	600	40,50	40,50,60,80,100	40,50,60,80,100
n80	75	5,10,15,20,25,30	10,15,20,25,30	10,15,20,25,30
n81	35	5,10,15,20	10,15,20	-
n82	30	5,10,15,20	10,15,20	-
n83	45	5,10,15,20	10,15,20	-
n84	60	5,10,15,20	10,15,20	10,15,20
n86	70	5,10,15,20,40	10,15,20,40	10,15,20,40

Table 24 – Channel bandwidths in MHz supported by each operating band (Frequency Range 1)

★ Channel bandwidths belonging to Frequency Range 1 extend up to 50 MHz when using the 15 kHz subcarrier spacing, and up to 100 MHz when using the 30 or 60 kHz subcarrier spacings. The channel bandwidths associated with some operating bands are limited by the quantity of available spectrum. For example, operating band n51 has only 5 MHz of spectrum so only supports the 5 MHz channel bandwidth

★ Operating bands belonging to Frequency Range 2 are shown in Table 25. These bands support Time Division Duplex (TDD). The bandwidths available from these operating bands are significantly greater than those available from Frequency Range 1

Operating Band	Duplex Mode	Uplink Band (MHz)	Downlink Band (MHz)	Bandwidth (MHz)	Category
n257	TDD	26 500 - 29 500		3 000	New 5G bands
n258		24 250 - 27 500		3 250	
n260		37 000 - 40 000		3 000	
n261		27 500 – 28 350		850	

Table 25 – 5G operating bands for Frequency Range 2 (24.25 to 52.60 GHz)

★ The channel bandwidths supported by each of these operating bands are presented in Table 26. In this case, channel bandwidths up to 400 MHz are supported when using the 120 kHz subcarrier spacing

Operating Band	Bandwidth (MHz)	60 kHz Subcarrier Spacing	120 kHz Subcarrier Spacing
n257	3 000	50,100,200	50,100,200,400
n258	3 250	50,100,200	50,100,200,400
n260	3 000	50,100,200	50,100,200,400
n261	850	50,100,200	50,100,200,400

Table 26 – Channel bandwidths in MHz supported by each operating band (Frequency Range 2)

★ 3GPP specifies the UE radio transmission and reception requirements for the Standalone Base Station architecture using Frequency Range 1 within TS 38.101-1. The equivalent requirements for Frequency Range 2 are specified within TS 38.101-2. Requirements for the Non-Standalone Base Station architecture are specified within TS 38.101-3. Base Station radio transmission and reception requirements for both frequency ranges are specified within TS 38.104

★ 3GPP References: TS 38.101-1, TS 38.101-2, TS 38.101-3, TS 38.104

1.19.3 BAND COMBINATIONS

★ Band Combinations are required for any deployment scenario which allows the UE to be configured with multiple carriers. For example, Carrier Aggregation requires a set of allowed Band Combinations to be specified. A UE signals its supported band combinations as part of its UE capability information

★ 3GPP has specified the Band Combinations for the Non-Standalone Base Station architecture using EUTRA – New Radio Dual Connectivity (EN-DC) within TS 38.101-3. These Band Combinations are categorised as:

- o Intra-band Contiguous EN-DC
- o Intra-band Non-Contiguous EN-DC
- o Inter-band EN-DC within Frequency Range 1 (2, 3, 4, 5 or 6 bands within each combination)
- o Inter-band EN-DC within Frequency Range 2 (2, 3, 4 or 5 bands within each combination)
- o Inter-band EN-DC within Frequency Ranges 1 and 2 (3, 4, 5, 6 bands within each combination)

★ Table 27 presents a small sample of the Band Combinations which have been specified for inter-band EN-DC within Frequency Range 1. These examples illustrate that Band Combinations have been specified to include up to 6 bands. The number of bands belonging to a Band Combination does not necessarily reflect the number of carriers. For example, DC_1-3-7-7_n78 includes 4 bands but 5 carriers, with 2 carriers belonging to E-UTRA Band 7

	EN-DC Band Combination	E-UTRA Band 1	E-UTRA Band 2	E-UTRA Band 3	E-UTRA Band 4	NR Band 1	NR Band 2
2 Bands	DC_1_n28	1	-	-	-	n28	-
	DC_1_n40	1	-	-	-	n40	-
3 Bands	DC_1-3_n28	1	3	-	-	n28	-
	DC_1-3_n77	1	3	-	-	n77	-
	DC_7_n28_n78	7	-	-	-	n28	n78
4 Bands	DC_1-3-5_n78	1	3	5	-	n78	-
	DC_1-3-7_n28	1	3	7	-	n28	-
	DC_1-3-7-7_n78	1	3	7	-	n78	-
5 Bands	DC_1-3-5-7_n78	1	3	5	7	n78	-
	DC_1-3-5-7-7_n78	1	3	5	7	n78	-
6 Bands	DC_1-3-7-20_n28-n78	1	3	7	20	n28	n78

Table 27 – Example band combinations for EN-DC (Inter-Band Frequency Range 1)

★ 3GPP has specified the Band Combinations for Carrier Aggregation within TS 38.101-1 for Standalone Frequency Range 1, TS 38.101-2 for Standalone Frequency Range 2 and TS 38.101-3 for Non-Standalone Frequency Ranges 1 and 2. Both intra-band and inter-band combinations are specified. The release 15 version of the specifications allows inter-band Carrier Aggregation across 2 operating bands. Intra-band Carrier Aggregation assumes that the carriers are contiguous

★ 3GPP has also specified the Band Combinations for Dual Connectivity (DC) between multiple NR operating bands. Inter-band NR-DC between Frequency Range 1 and Frequency Range 2 is specified within TS 38.101-3

★ Band Combinations are also specified for the Supplemental Uplink (SUL) bands because these bands need to be used in combination with other bands. The Supplemental Uplink Band Combinations for Frequency Range 1 are presented in Table 28. The release 15 version of the specifications pairs the Supplemental Uplink bands with either band n78 or n79

Supplemental Uplink Band Combination	TDD Band	Supplemental Uplink Band
SUL_n78-n80	n78	n80
SUL_n78-n81	n78	n81
SUL_n78-n82	n78	n82
SUL_n78-n83	n78	n83
SUL_n78-n84	n78	n84
SUL_n78-n86	n78	n86
SUL_n79-n80	n79	n80
SUL_n79-n81	n79	n81

Table 28 – Band Combinations for Supplemental Uplink (Inter-Band Frequency Range 1)

1.19.4 MILLIMETER WAVE PROPAGATION

★ mm wave spectrum corresponds to frequencies which have wavelengths between 1 mm and 1 cm
  - o corresponds to wavelengths between 30 GHz and 300 GHz
  - o from the perspective of 5G, the range of interest is 30 GHz to 100 GHz

★ mm wave spectrum is of particular interest because it offers the potential for wide channel bandwidths, i.e. the potential for high throughputs. Figure 73 summarises the characteristics associated with propagation within the mm wave band

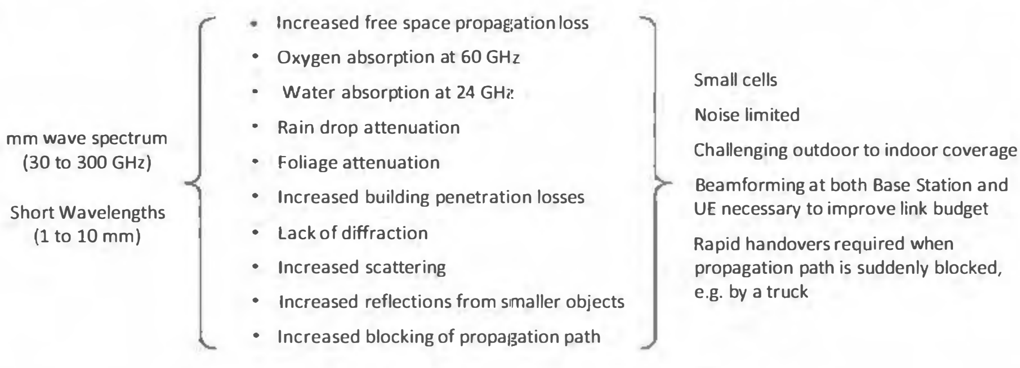


Figure 73 – Characteristics associated with mm wave propagation

★ The fundamental equation for free space path loss between 2 isotropic antennas is given by:

$$Free\ Space\ Loss\ (dB) = 10\ LOG\left(\frac{4\ \pi\ dist}{\lambda}\right)^2 = 20\ LOG\left(\frac{4\ \pi\ dist}{\lambda}\right) = 20\ LOG\left(\frac{4\ \pi\ dist \times freq}{300\ 000\ 000}\right)$$

★ Converting the distance from 'm' to 'km' and the frequency from 'Hz' to 'MHz' leads to:

$$Free\ Space\ Loss\ (dB) = 32.4 + 20\ LOG\ (dist(km)) + 20\ LOG\ (freq(MHz))$$

★ This equation represents the starting point for more sophisticated path loss models. For example, this equation is used as the short distance path loss model for the urban macro line-of-sight scenario within 3GPP TR 38.900 'Study on Channel Model for Frequency Spectrum above 6 GHz'

★ Figure 74 illustrates the free space path loss calculated from this equation for a range of distances and frequencies. Increasing the carrier frequency by a factor of 10, increases the free space path loss by 20 dB

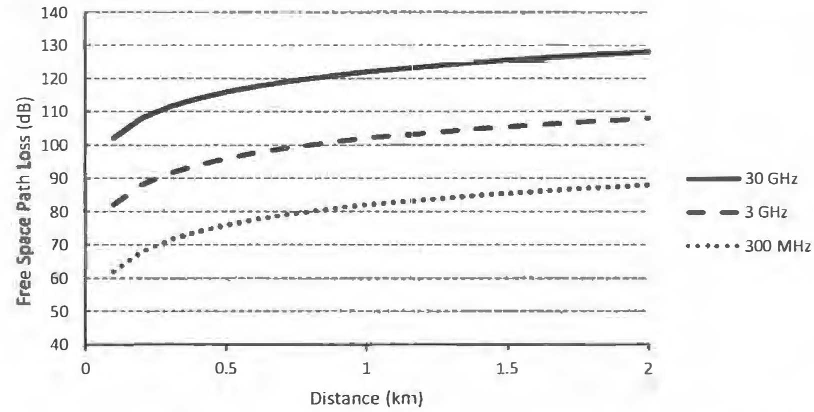


Figure 74 – Free space path loss as a function of distance and frequency

★ Oxygen molecules resonate at a frequency of 60 GHz. This leads to an absorption of radio wave power at 60 GHz and at frequencies close to 60 GHz. 3GPP TR 38.900 quantifies the impact of oxygen absorption when the carrier frequency is between 53 and 67 GHz. Absorption rates are typically quoted in terms of dB/km and the impact is relatively small when considering the distances associated with small cells

★ Water molecules resonate at a frequency of 24 GHz. This leads to an absorption of radio wave power at 24 GHz and at frequencies close to 24 GHz. Absorption rates are typically quoted in terms of dB/km and the impact is relatively small when considering the distances associated with small cells

★ Rain drops can lead to scattering of the radio wave because their size is comparable to the wavelength. This leads to an attenuation which is dependent upon distance, the volume of rainfall and the carrier frequency. As an example, a rainfall of 5 mm per hour can lead to an attenuation of 1 dB per km at 30 GHz, and 2 dB per km at 50 GHz

★ Foliage can lead to significant attenuation within the mm wave frequency range. The attenuation is generally dependent upon the carrier frequency and the depth of foliage. The CCIR (now known as ITU-R) developed the following empirical relationship for foliage depths of less than 400 meters:

$$Foliage\ Loss\ (dB) = 0.2 \times freq^{0.3} \times depth^{0.6}$$

where, the frequency is in MHz and the depth is in meters. As an example, a frequency of 30 GHz and a depth of 10 meters leads to a loss of 17.5 dB. The ITU-R has also published Recommendation ITU-R P.833-9 'Attenuation in Vegetation' which defines more sophisticated models dependent upon tree type and angle of incidence

★ Diffraction is the bending of radio waves around obstacles. Diffraction can be useful in terms of providing coverage because it provides a mechanism for obtaining coverage at locations which do not have line-of-sight. Diffraction effects within the mm wave frequency range are limited because the wavelength is small relative to the majority of obstacles. This leads to increased shadowing behind obstacles.

★ There can be increased scattering within the mm wave frequency range because in general surfaces appear less smooth to the smaller wavelengths. This means that incident waves tend to be scattered in multiple directions rather than reflected in a single direction

★ The smaller wavelengths within the mm wave frequency range mean that smaller objects can lead to reflections. An object which does not act as a significant reflector for the lower operating bands may act as a reflector for the higher operating bands

★ Building penetration losses generally increase with frequency but there is a significant dependence upon the building material. Brick and stone walls can attenuate mm wave signals by more than 20 dB. Double pane windows typically attenuate by less than 10 dB when constructed using standard glass. Energy efficient windows which have reflective coatings can attenuate by more than 30 dB. Building penetration loss is likely to be very scenario specific so a variance should be included when completing link budget calculations

★ Beamforming is necessary within the mm wave band to improve the link budget. The small antenna element size means that it becomes practical to implement antenna arrays at both the Base Station and the UE. Analogue or hybrid beamforming can be used to generate directional transmit and receive beams. There is less scope for high rank spatial multiplexing within the mm wave band so MIMO is likely to be limited to dual stream (rank 2). This allows the antenna array to be used primarily for beamforming purposes

★ mm waves are vulnerable to having their propagation paths blocked by moving objects, e.g. trucks. Beamforming of mm wave transmissions will generate a directional radio link between the transmitter and receiver. If an object intercepts that link then coverage can be lost and it may be necessary to switch to a different beam. This leads to the requirement for rapid handovers between beams or rapid recovery after a beam failure

★ The increased propagation losses within the mm wave band can be beneficial for network deployments at hotspot locations where there is a requirement for a very high site density. The increased propagation losses help to provide isolation between tightly packed sites. This reduces levels of intercell interference and leads to noise limited link budgets rather than interference limited link budgets

1.20 MIMO

★ Multiple Input Multiple Output (MIMO) configurations benefit from multiple antenna elements at the transmitter and multiple antenna elements at the receiver. MIMO contrasts with receive diversity which only requires multiple antenna at the receiver, and transmit diversity which only requires multiple antenna at the transmitter

★ The general concept of MIMO is illustrated in Figure 75. The Multiple Input component refers to multiple transmissions into the propagation channel, whereas the Multiple Output component refers to multiple signals being received out of the propagation channel

★ Similar terminology is used for Single Input Multiple Output (SIMO), Multiple Input Single Output (MISO) and Single Input Single output (SISO)

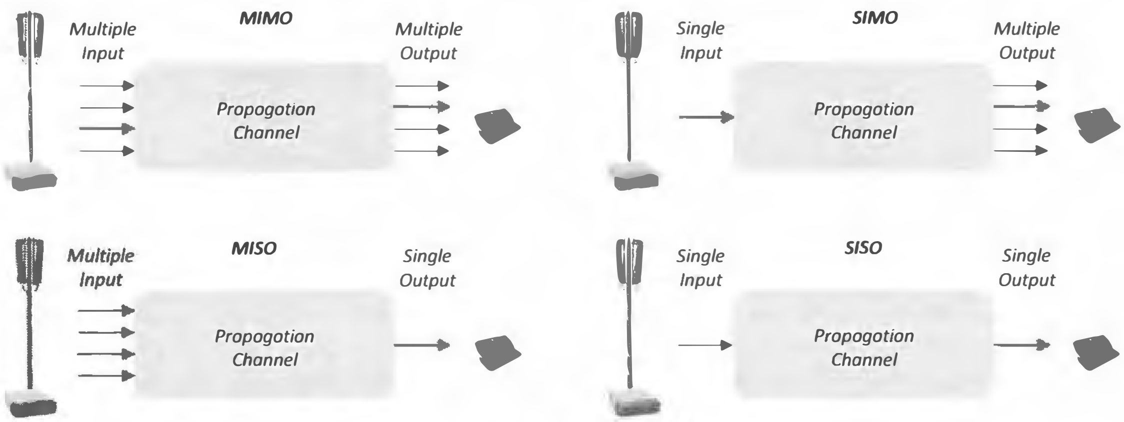


Figure 75 – General concept of MIMO

★ The example of MIMO illustrated in Figure 75 assumes 4 antenna ports used for transmission and 4 antenna ports used for reception. This represents 4×4 MIMO. It is also possible to have an unequal number of antenna ports at the transmitter and receiver. Two examples of this are shown in Figure 76

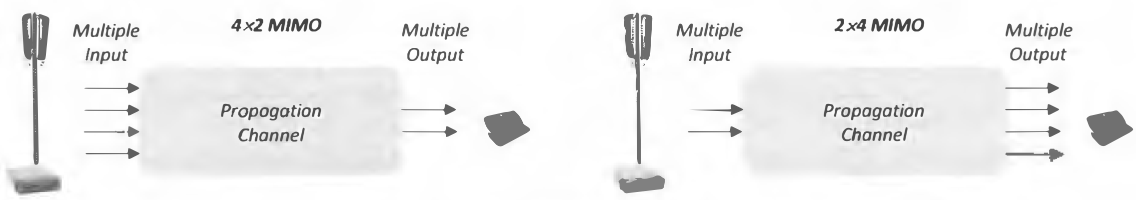


Figure 76 – MIMO with unequal numbers of transmit and receive antenna ports

★ The benefits of MIMO are summarised in Figure 77:

- diversity gain reduces the impact of fading when the fades on each propagation path are uncorrelated, i.e. one path may experience a fade while another path may not experience a fade. The receiver takes advantage of the paths which are not experiencing fades
- array gain is achieved from the beamforming effect which is generated when transmitting from multiple antenna elements. Beamforming directs the transmitted signal towards the UE and improves the received signal to noise ratio
- spatial multiplexing gain increases throughput by transferring multiple streams of data in parallel using the same set of time and frequency domain resources. Uncorrelated transmission paths allow the receiver to differentiate between the data streams

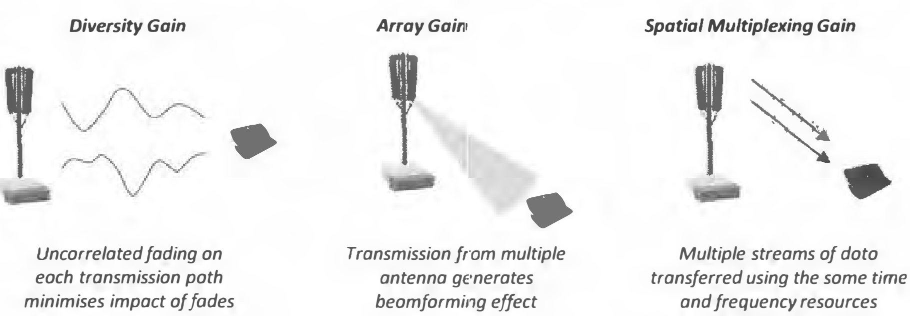


Figure 77 – Benefits of MIMO

- UE experiencing good coverage (with high signal to noise ratios) can take advantage of the spatial multiplexing gain and can receive multiple parallel streams of data. The maximum number of parallel streams is given by the minimum of the number of transmit and receive antenna. For example, 2×2 MIMO, 4×2 MIMO and 2×4 MIMO are all capable of transferring a maximum of 2 parallel streams of data. Maximising throughput also relies upon having uncorrelated propagation paths between the transmit and receive antenna
- UE in poor coverage (with a low signal to noise ratios) can take advantage of the diversity gain to help improve their signal to noise ratio. The magnitude of the diversity gain is dependent upon the number of receive antenna and the level of correlation between each of the propagation paths, i.e. the gain is maximised for a large number of receive antenna and uncorrelated propagation paths
- This dependency upon channel conditions means that MIMO is used to transfer multiple parallel streams of data in good coverage conditions to maximise throughput, and is used to transfer a single stream of data in poor coverage conditions to maximise the diversity gain. These scenarios are illustrated in Figure 78. Both scenarios perform best when the propagation paths between transmit and receive antenna are uncorrelated

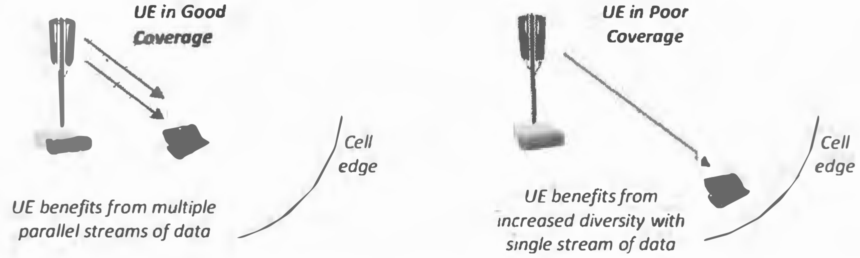
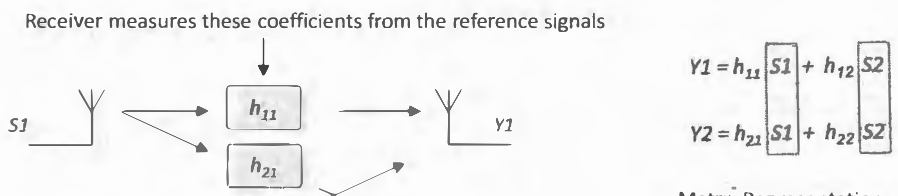


Figure 78 – MIMO scenarios for UE in good and poor coverage

- The drawbacks of MIMO are its increased implementation complexity and increased hardware requirement. MIMO requires additional processing at both the transmitter and receiver. It also requires additional signalling in terms of feedback from the receiver and resource allocation information from the transmitter. MIMO requires additional power amplifiers at the transmitter and additional receive paths at the receiver. It also requires additional antenna elements at both the transmitter and receiver. These antenna elements may already be available if receive diversity is already in use
- A mathematical representation of 2×2 MIMO is illustrated in Figure 79. 'S1' and 'S2' represent the two streams of data transmitted across the air-interface. There are four propagation paths between the pair of transmit antenna and the pair of receive antenna. These propagation paths are represented by the set of 'h_{xx}' coefficients. The received signals are given by 'Y1' and 'Y2' which can be quantified using the pair of equations shown in the figure. The primary task of the receiver is to deduce the values of 'S1' and 'S2' from these equations. Solving these equations requires knowledge of the propagation channel coefficients. If these coefficients are not known then the equations include too many unknowns and cannot be solved. The receiver uses the Demodulation Reference Signal (DMRS) to estimate the propagation channel coefficients. This highlights the fact that it is important for the DMRS to experience the same propagation channel as the data which is being decoded. Once the propagation channel coefficients are known, the two equations include only two unknowns so they can be solved

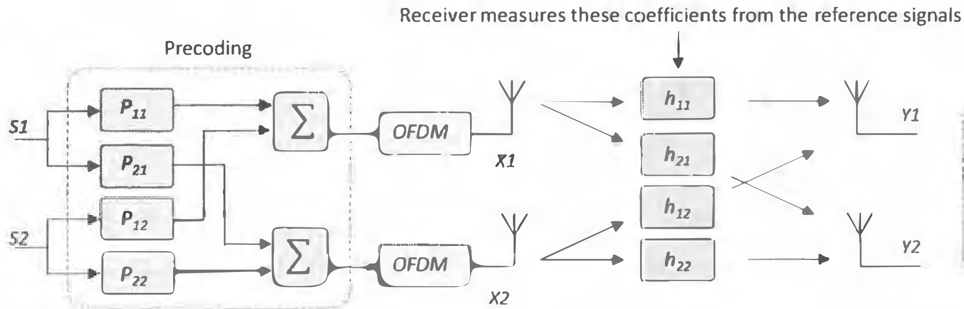


$$\begin{bmatrix} Y1 \\ Y2 \end{bmatrix} = \begin{bmatrix} h_{11} h_{12} \\ h_{21} h_{22} \end{bmatrix} \begin{bmatrix} S1 \\ S2 \end{bmatrix}$$

Figure 79 – Mathematical representation of MIMO

- These equations can be used to highlight the importance of having four independent propagation paths between the transmit and receive antenna. It is possible to solve these equations because there are two equations and two unknowns. Consider the case that the propagation paths are not independent and assume a worst case scenario with $h_{11} = h_{21}$ and $h_{12} = h_{22}$. In this case, Y1 = Y2 and the pair of equations collapse into a single equation. There is then one equation with two unknowns and this is impossible to solve. Thus, MIMO relies upon having independent paths between each transmit antenna and each receive antenna
- Figure 79 also shows a matrix representation of the equations. This representation illustrates that the equations can be solved by identifying the inverse channel coefficient matrix. Multiplication by this inverse matrix will cancel the channel coefficient matrix to leave only the wanted signals. Figure 79 does not include the concept of 'precoding' whereas MIMO and precoding are usually discussed in combination. Figure 79 illustrates that precoding is not an essential part of MIMO when the propagation paths are independent (the propagation paths are said to be orthogonal). In reality, the set of four propagation paths may not be completely orthogonal. Precoding can be used to generate a set of composite propagation paths which have increased orthogonality, i.e. precoding helps to improve the performance of MIMO when using a real propagation channel

★ Figure 80 illustrates a mathematical representation of 2×2 MIMO with the inclusion of precoding. In this case, the matrix representation of the received signals illustrates that the precoding matrix can be multiplied by the channel coefficient matrix to generate a composite channel matrix. This means that the precoding weights can be adjusted to help maximise the orthogonality of the coefficients within the composite matrix, i.e. precoding can be used to improve the performance of MIMO



$$\begin{bmatrix} Y1 \\ Y2 \end{bmatrix} = \underbrace{\begin{bmatrix} h_{11} & h_{12} \\ h_{21} & h_{22} \end{bmatrix} \begin{bmatrix} P_{11} & P_{12} \\ P_{21} & P_{22} \end{bmatrix}}_{\text{Composite Propagation Channel}} \begin{bmatrix} S1 \\ S2 \end{bmatrix}$$

Figure 80 – Mathematical representation of MIMO with Precoding

★ MIMO can be used in either an 'open loop' or 'closed loop' mode. Open loop MIMO requires feedback from the receiver in terms of Rank Indication (RI) and Channel Quality Indicator (CQI). It is categorised as 'open loop' because the receiver is not required to provide feedback in terms of a Precoding Matrix Indicator (PMI). Closed loop MIMO involves feedback from the receiver in terms of RI, CQI and PMI. The receiver selects a PMI to help improve the properties of the composite channel coefficient matrix. Closed loop MIMO provides the transmitter with increased information but generates an increased signalling overhead. Open loop MIMO can be beneficial for high mobility scenarios which would cause a reported PMI to become invalid after only a short period of time

★ MIMO improves spectral efficiency by allowing multiple parallel streams of data transfer. Spectral efficiency can be further improved by using Multi-User MIMO. Multi-User MIMO takes advantage of beamforming to allocate the same set of time and frequency domain resources to multiple UE. These UE are separated in the spatial domain so they are able to re-use Physical Resource Blocks (PRB) without generating significant levels of interference towards each other

★ Figure 81 compares Single User and Multi-User MIMO. Single User MIMO allocates a different subset of PRB to each UE, i.e. the UE are separated in the frequency domain. The UE which are scheduled during a specific time slot do not need to be spatially separated and a relatively high MCS can be allocated because the transmissions to each UE do not interfere with each other. Multi-User MIMO allows the same set of PRB to be allocated to each UE. The UE must be separated in the spatial domain (geographically separated) so beamforming can be used to separate the transmissions towards each UE. In this case, the allocated MCS may be reduced because there may be some level of inter-user interference between the transmissions

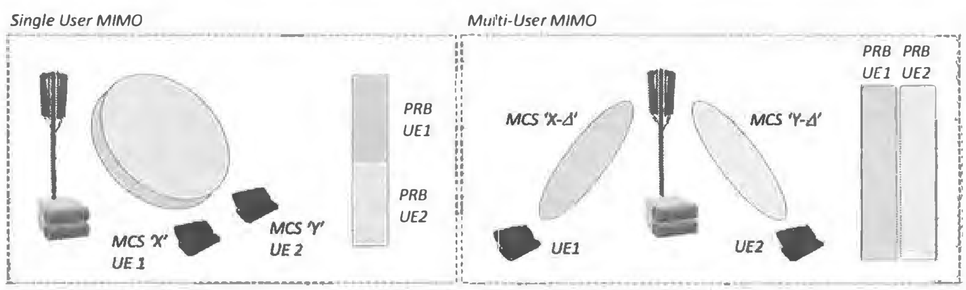


Figure 81 – Comparison between Single User and Multi-User MIMO

★ The release 15 version of the 3GPP specifications for New Radio (NR) supports MIMO in both the uplink and downlink directions. The uplink supports 2×2 MIMO and 4×4 MIMO, whereas the downlink supports 2×2 MIMO, 4×4 MIMO and 8×8 MIMO. The release 15 version of the specifications also supports Multi-User MIMO in both the uplink and downlink directions

★ There may be a trade-off between higher order MIMO and beamforming. 2x2 MIMO requires 2 logical antenna ports which are typically implemented using the +45° and -45° polarisations. Beamforming then generates 2 beams - each beam is generated using all antenna elements with the same polarisation. 4x4 MIMO requires 4 logical antenna ports which may be implemented using 2 subsets of the +45°polarisation and 2 subsets of the -45° polarisation. Beamforming then generates 4 beams where each beam is generated using half of the antenna elements with the same polarisation. This means that the number of antenna elements per beam has halved so the beams becomes less directional. Alternatively, 4x4 MIMO can be implemented by generating a first pair of beams using all antenna elements (+45° and -45° polarisations providing the two beams), and by generating a second pair of beams using the same antenna elements. In this case, the directivity of the beams is maximised because each beam is generated using all antenna elements belonging to a specific polarisation. But the first and second pairs of beams must point in different directions to ensure that they are not completely correlated. This means that the UE relies upon reflections and scattering to receive both pairs of beams (see Figure 399 in section 13.6.3.1)

★ 3GPP References: TS 38.211, TS 38.212, TS 38.214

1.21 BEAMFORMING

★ Beamforming provides benefits in terms of:

- o beamforming improves the uplink and downlink link budgets by increasing the antenna gain. This is particularly important for the higher operating bands which experience greater air-interface attenuation
- o beamforming helps to reduce inter-cell interference by focusing transmissions in a specific direction, i.e. the beamwidth is relatively narrow so the potential for inter-cell interference across a wide range of angles is reduced
- o beamforming provides support for Multi-User MIMO (MU-MIMO). Multiple users can be simultaneously allocated the same Resource Blocks if those users are spatially separated. In this case, multiple simultaneous beams transmit the same Resource Blocks with different payloads in different directions

★ Beamforming requires an antenna array with multiple antenna elements. There are many possible ways for the antenna elements to be arranged and inter-connected. Some examples are illustrated in Figure 82. These examples are based upon 4 columns of cross-polar antenna elements:

- o the first example provides 8 antenna connectors with each connector supporting a column of antenna elements which have equal polarisation. The actual physical antenna has multiple rows of antenna elements but there is only a single row from the perspective of antenna connectivity. This leads to a virtual antenna layout which has 4 columns and 1 row. This is known as a {4,1,2} antenna array, where the 2 refers to 2 polarisations. The product of these 3 indices equals the total number of antenna connectors, i.e. $1\times4\times2 = 8$. This type of array is known as a 1 dimensional array and is able to support beamforming from left to right (the azimuth of the antenna beam can be controlled)
- o the second example provides a second row of antenna connectors by dividing each column into 2 sections. In this case, the virtual antenna layout has 4 columns and 2 rows. This is known as a {4,2,2} antenna array, which provides a total of 16 antenna connectors. This type of array is known as a 2 dimensional array and is able to support beamforming up and down, as well as from left to right (both the elevation and azimuth of the antenna beam can be controlled)
- o the third example provides a third row of antenna connectors by dividing each column into 3 sections. In this case, the virtual antenna layout has 4 columns and 3 rows. This is known as a {4,3,2} antenna array, which provides a total of 24 antenna connectors. Similar to the second example, this type of array is known as a 2 dimensional array and is able to support beamforming in both the azimuth and elevation directions. This third example allows increased control of the beam elevation when compared to the second example

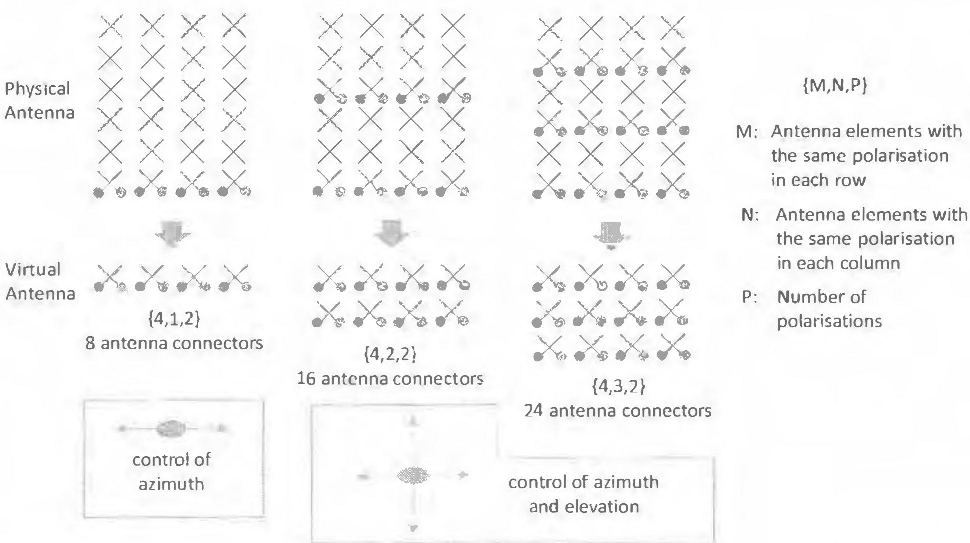


Figure 82 – Example antenna array layouts

★ The physical size of an antenna array depends upon the carrier frequency. Antenna arrays are typically designed using half-wave dipoles. This means that the length of each antenna element is half a wavelength. At 3 GHz this corresponds to 5 cm, whereas at 30 GHz it corresponds to 5 mm. The reduced size means that antenna panels with a large number of antenna elements are more practical at the higher operating bands. A typical antenna panel at 3 GHz which includes 128 antenna elements (64 cross polar pairs, arranged as 8 × 8) has dimensions of 50 cm × 65 cm. The same antenna panel operating at 30 GHz can be expected to have dimensions of 5 cm × 6.5 cm. The reduced size at the high operating bands means that it becomes practical to include antenna arrays within a UE. The antenna panels within a UE may have fewer antenna elements than the Base Station and this will further reduce the size. For example, a UE antenna panel operating at 30 GHz with 32 antenna elements (16 cross polar pairs, arranged as 4 × 4) could have dimensions of 2.5 cm × 3.3 cm. UE may include multiple antenna panels to allow switching dependent upon the orientation of the device and the position of the end-user's hand which could be shielding at least one of the antenna panels

- ★ At the transmitter, beamforming relies upon constructive interference between the signals transmitted by each antenna element. Adjusting the phase (delay) between the transmitted signals allows the angle at which the constructive interference occurs to be controlled. Similarly, at the receiver, adjusting the phase (delay) between the received signals allows the constructive interference to be achieved from the signals received at a specific angle
- ★ Figure 83 illustrates an example of 8 antenna elements transmitting duplicated versions of a signal. Each antenna transmits the signal without any phase shift. This means that the signals sum constructively at locations directly in front of the antenna array

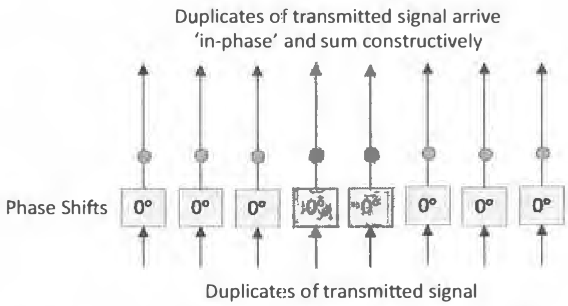


Figure 83 – Antenna elements transmitting duplicate signals <u>without</u> phase shifts

- ★ Figure 84 illustrates the same example but with phase shifts applied to the set of antenna elements. This figure illustrates that the propagation distance to the receiver is different for each antenna element when the receiver is not directly in front of the antenna array. The set of phase shifts adjust the timings of the transmitted signals to ensure that they all sum constructively at the receiver. The antenna element with the longest path does not require any delay. The adjacent antenna element is given a delay defined by phase shift θ, while the next antenna element is given a delay defined by phase shift 2θ, and so on. The set of phase shifts are multiples of the first phase shift because the antenna elements are evenly spaced

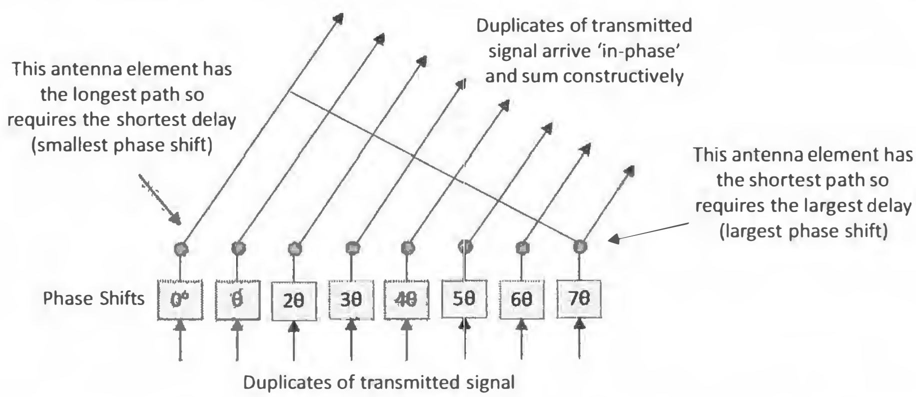


Figure 84 – Antenna elements transmitting duplicate signals <u>with</u> phase shifts

- ★ Increasing the number of antenna elements decreases the beamwidth and increases the gain, i.e. the beam becomes more directional. Figure 85 presents the antenna gain pattern when using 4 antenna elements, whereas Figure 86 presents the antenna gain pattern when using 8 antenna elements. Doubling the number of antenna elements doubles antenna gain because twice as many signals are being summed. This corresponds to a 3 dB increase in antenna gain. Doubling the number of antenna elements halves the beamwidth, i.e. the 3 dB beamwidth when using 4 antenna elements is 20°, whereas the 3 dB beamwidth when using 8 antenna elements is 10°

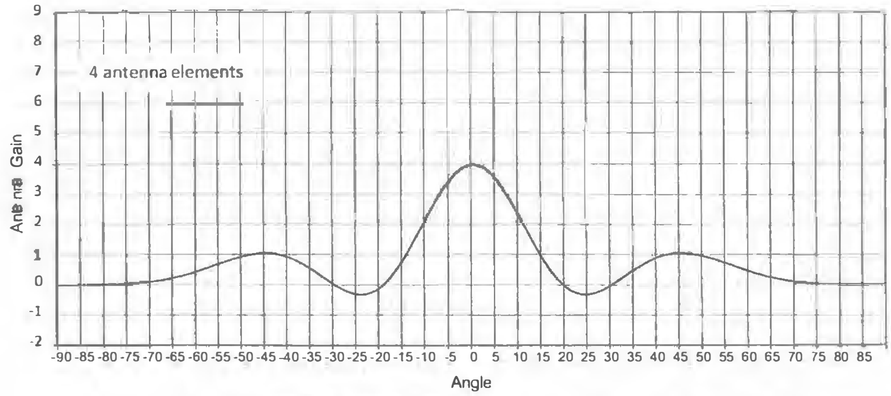


Figure 85 – Horizontal antenna gain pattern when using 4 antenna elements

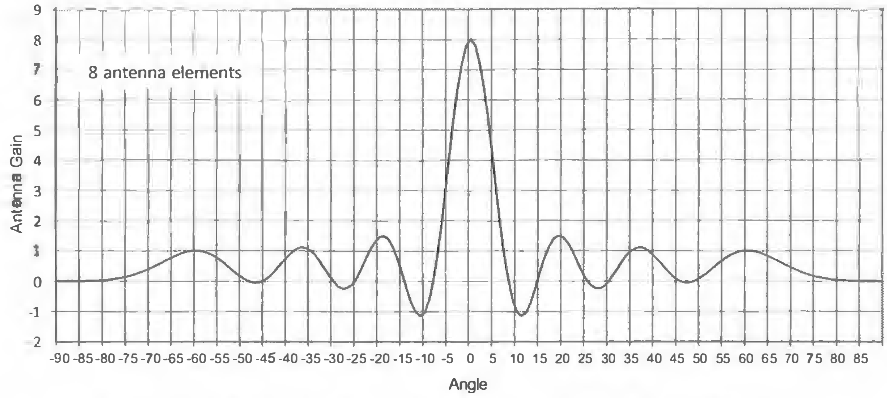


Figure 86 – Horizontal antenna gain pattern when using 8 antenna elements

★ Reducing the beamwidth by increasing the number of antenna elements means that a larger number of beams (or a larger number of beam positions) are required to cover the cell area. The 3 dB beamwidth reduces by a factor of 2 when the number of antenna elements is doubled. This implies that 2 columns of cross polar antenna elements require 2 beams to provide coverage across a similar range of azimuths. Similarly, 4 columns of cross polar antenna elements require 4 beams to provide coverage across a similar range of azimuths, and so on

★ 3GPP TS 38.214 assumes a specific set of antenna element layouts for the purposes of Precoding Matrix Indicator (PMI) reporting. These layouts (presented in Table 29) support up to 32 antenna ports for the CSI Reference Signal. Within this context, PMI reporting corresponds to beam selection, i.e. the set of PMI codebook entries corresponds to a set of beams. The UE uses the CSI Reference Signal transmissions to evaluate each codebook entry and to identify the entry which provides the best beam. Table 29 specifies a set of 'Over-Sampling' factors which are used to increase the number of beams available for selection. For example, the second entry within the table is based upon 2 rows and 2 columns of cross polar antenna elements. This implies that 2 beams in the horizontal direction and 2 beams in the vertical direction would 'normally' be sufficient to provide coverage across the cell area, i.e. a total of 4 beams. 'Over-Sampling' increases the number of beams to improve the resolution of beam selection for PMI reporting. In this example, an 'Over-Sampling' factor of 4 is specified for both the horizontal and vertical directions so PMI reporting involves beam selection from a grid of 8 × 8 beams rather than a grid of 2 × 2 beams

Number of CSI Reference Signal Antenna Ports	{M,N,P}	Over-Sampling
4	{2,1,2}	{4,1}
8	{2,2,2}	{4,4}
	{4,1,2}	{4,1}
12	{3,2,2}	{4,4}
	{6,1,2}	{4,1}
16	{4,2,2}	{4,4}
	{8,1,2}	{4,1}
24	{4,3,2}	{4,4}
	{6,2,2}	{4,4}
	{12,1,2}	{4,1}
32	{4,4,2}	{4,4}
	{8,2,2}	{4,4}
	{16,1,2}	{4,1}

Table 29 – Antenna array dimensions for Type I single panel PMI reporting

★ CSI Reference Signals are used for a range of different purposes, e.g. PMI reporting and beam selection refinement. The precoding applied to CSI Reference Signals depends upon the use-case and the network implementation. When CSI Reference Signals are transmitted for PMI reporting, it is not necessary to apply any precoding and the CSI Reference Signals can be transmitted directly from the set of physical antenna elements. In this case, there is a one-to-one mapping between CSI Reference Signal and antenna element. The lack of precoding means that the CSI Reference Signals are not beamformed and so they radiate across the cell area with a wide beamwidth. This scenario is illustrated in Figure 87

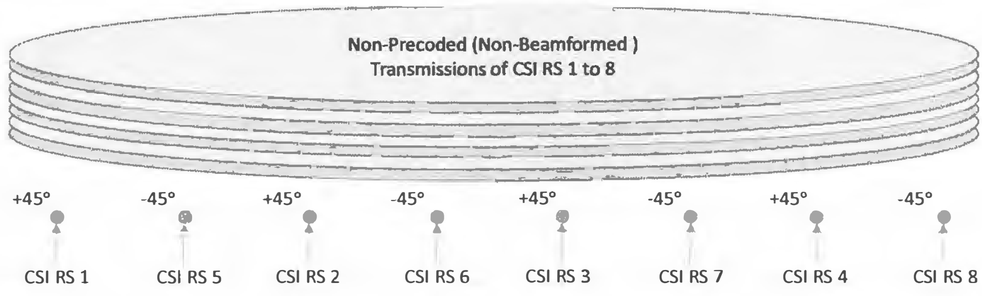


Figure 87 – Transmission of 8 CSI RS from 8 antenna elements without precoding

- The UE is responsible for evaluating each entry within the PMI Codebook and determining which entry, if applied to the CSI Reference Signal transmissions, would generate the best beam towards the UE
- When CSI Reference Signals are transmitted for beam selection refinement, the CSI Reference Signals are precoded to generate directional beams. The UE is responsible for identifying the best directional beam and providing feedback to the Base Station using a CSI Reference Signal Resource Indicator (CRI). Figure 88 illustrates the transmission of 8 CSI Reference Signals using 8 antenna elements with precoding applied to generate directional beams. The first 4 CSI Reference Signals are transmitted using the antenna elements with +45° polarisation while the second 4 CSI Reference Signals are transmitted using the antenna elements with -45° polarisation, i.e. each beam is generated by transmitting the CSI Reference Signal using 4 antenna elements

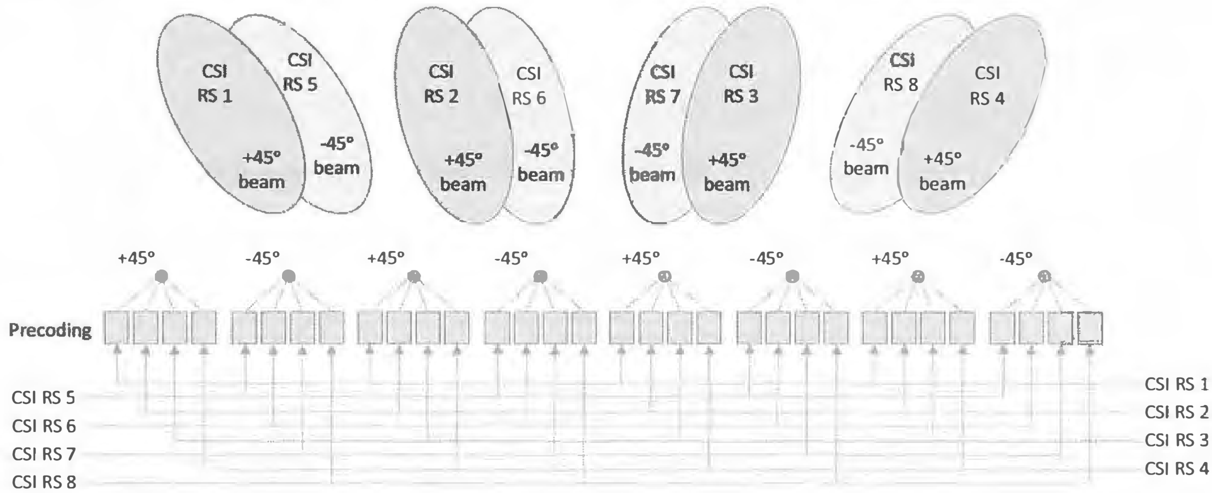


Figure 88 – Transmission of 8 CSI RS from 8 antenna elements with precoding

- In general, antenna elements can be used for beamforming, MIMO or a combination of both beamforming and MIMO. Using MIMO in combination with beamforming can reduce the number of antenna elements available for beamforming (depending upon the implementation). Some examples of beamforming and MIMO based upon a 64 element antenna array are shown in Figure 89
  - all 64 antenna elements can be used to generate a single beam to maximise the antenna gain and coverage. In this case, MIMO is not possible because it is necessary to co-ordinate all precoding weights to generate the single high gain beam
  - the set of 64 antenna elements can be divided into 2 groups of 32 elements (+45 degree and -45 degree elements) and then used to provide 2x2 MIMO using 32 elements for each stream of data. In this case, each group of 32 antenna elements is used to generate a beam so there are 2 beams but each beam has lower gain relative to the single beam generated from all 64 antenna elements
  - the set of 64 antenna elements can be divided into 4 groups of 16 elements and then used to provide 4x4 MIMO using 16 elements for each stream of data. In this case, each group of 16 antenna elements is used to generate a beam so there are 4 beams but each beam has lower gain relative to the single beam generated from all 64 antenna elements

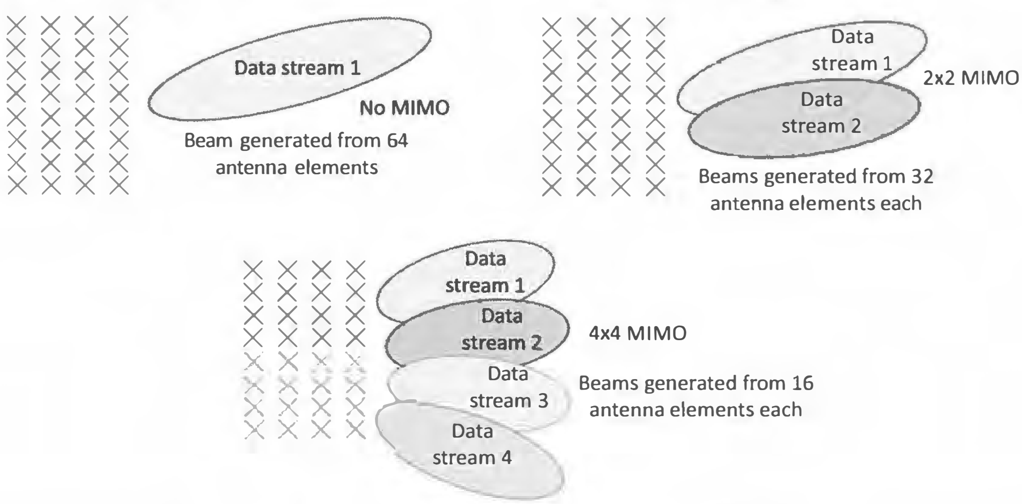


Figure 89 – Use of antenna elements for beamforming and MIMO

- Note that the above is one example implementation of 4x4 MIMO but as mentioned earlier in this section, it is also possible to implement 4x4 MIMO using 2,pairs of beams, where each pair of beams transmits in a different direction and thus experiences a different propagation path. In this case, each beam can be generated using all of the antenna elements with a specific polarisation. The UE relies upon reflections and scattering to receive transmissions from all four beams

★ Beamforming can be implemented in the digital domain, in the analogue domain, or in a combination of both the digital and analogue domains. There are benefits and drawbacks associated with each approach. In general, digital beamforming is applicable to Frequency Range 1 (450 MHz to 6 GHz), while analogue beamforming is applicable to Frequency Range 2 (24.25 GHz to 52.60 GHz)

★ Figure 90 illustrates digital beamforming towards a single UE. In the case of digital beamforming, the precoding is applied in the digital domain and there is a requirement to have multiple parallel RF chains. This is a significant drawback for digital beamforming when the number of controllable antenna elements is high because each RF chain is expensive and consumes high quantities of power. It becomes less practical to have an RF chain for each controllable antenna element when the number of antenna elements is high, e.g. when implementing beamforming for the mm wave band

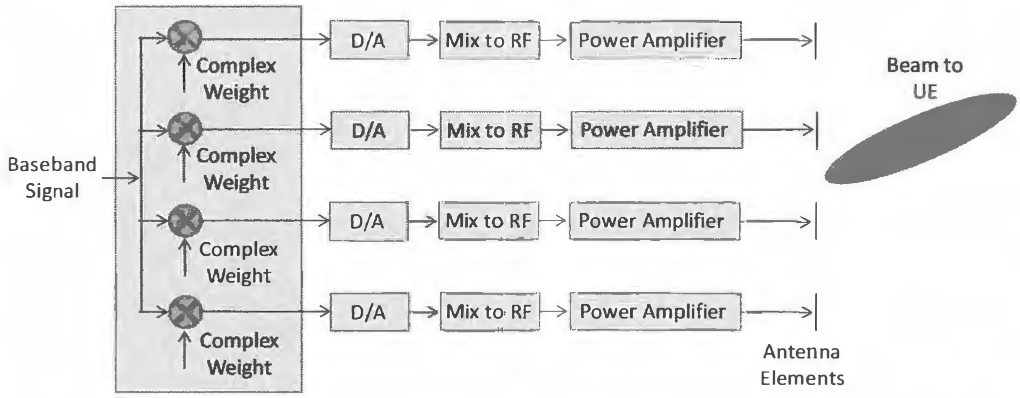


Figure 90 – Digital beamforming towards a single UE

★ The primary benefit of digital beamforming is its flexibility. Figure 91 illustrates how digital beamforming can be used to simultaneously serve 2 UE which are located in different parts of the cell. Digital beamforming allows multiple beams to be generated simultaneously and so separate beams can be directed towards each UE. This is possible because the signals for each UE can be separated in the digital domain and different beamforming weights can be applied to each signal. Figure 91 is based upon 2 UE but there is no theoretical upper limit on the number of UE which can be served and the number of beams which can be generated

★ If the UE have sufficient spatial separation then they can be allocated the same set of Resource Blocks to improve both spectral efficiency and end-user experience (each UE is allocated 'X' Resource Blocks rather than 'X/2' Resource Blocks). This corresponds to Multi-User MIMO (MU-MIMO) which relies upon spatial separation rather than time or frequency domain separation. If the UE do not have sufficient spatial separation then they can be allocated dedicated sets of Resource Blocks. This corresponds to Single User MIMO (SU-MIMO) which relies upon frequency domain (or time domain) separation

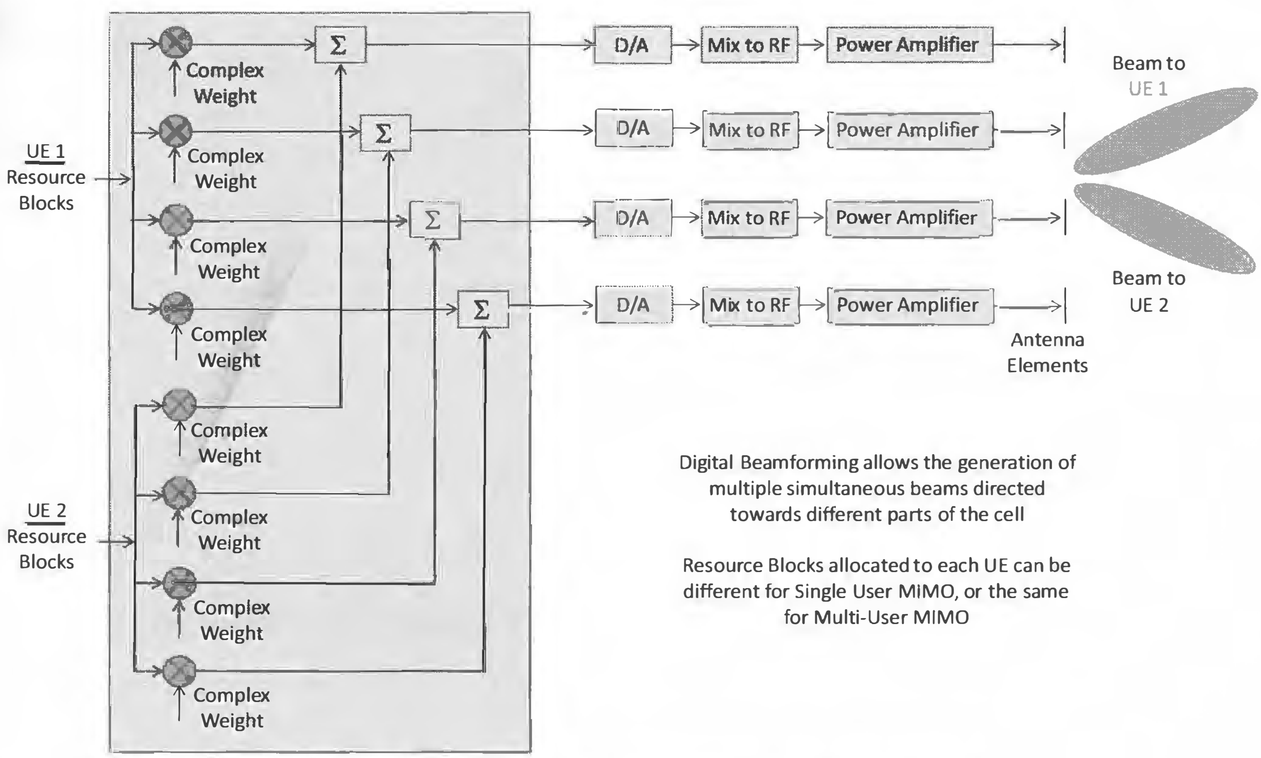


Figure 91 – Digital beamforming towards multiple UE using multiple simultaneous beams

★ Figure 92 illustrates the general architecture used for analogue beamforming. In this case, the beamforming weights (phase shifts) are applied in the analogue domain after the signal has been mixed to RF. This approach does not allow different beamforming weights to be applied to different Resource Blocks nor does it allow different beamforming weights to be applied for different users. All Resource Blocks and user transmissions are combined into a single signal once the Inverse Fast Fourier Transform (IFFT) has been used to generate the CP-OFDM waveform prior to D/A conversion. Applying the set of beamforming weights to the RF signal generates a single beam which can be directed towards the UE being served at that point in time. Multiple UE can be served simultaneously but those UE must be located in the same direction

★ The primary benefit of analogue beamforming is the reduced requirement for RF chains, i.e. it is only necessary to have one RF chain 'per beam'. Practical deployments are likely to support at least 2 RF chains and 2 beams to provide support for 2×2 MIMO. A first RF chain and a first beam can use the +45° antenna elements, while a second RF chain and a second beam can use the -45° antenna elements

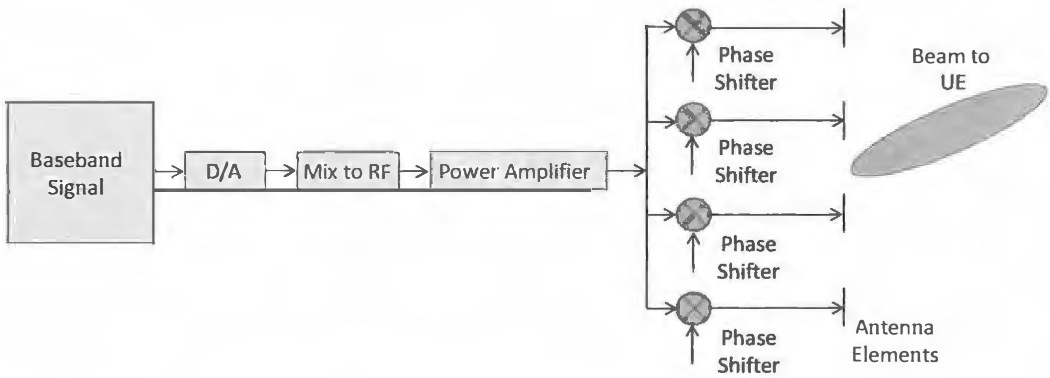


Figure 92 – Analogue beamforming used to generate a single beam

★ Figure 93 illustrates the use of time multiplexing with analogue beamforming when users are located in different directions. The Packet Scheduler is responsible for selecting the UE to be served during each time slot. The appropriate set of beamforming weights is applied to ensure that the beam is directed towards the UE being served during that time slot

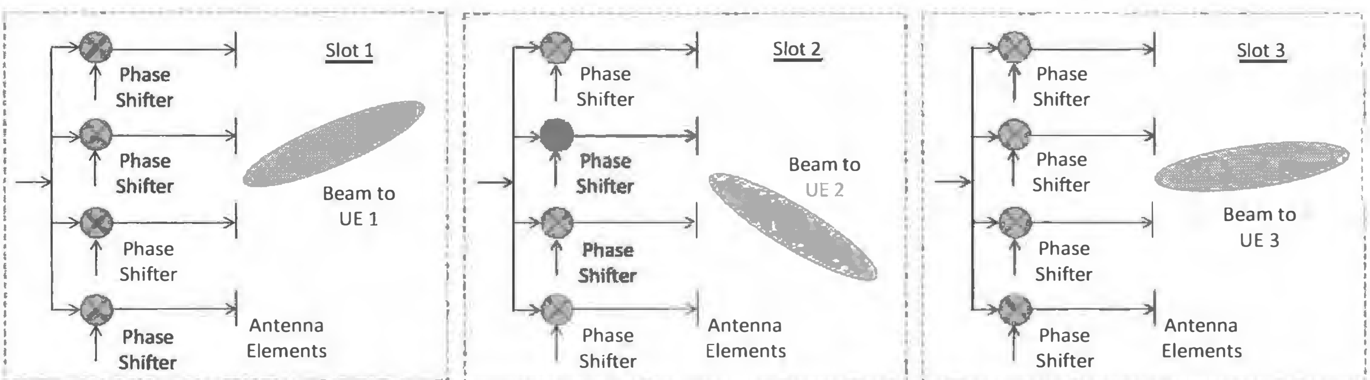


Figure 93 – Time multiplexing of beam positions for analogue beamforming

1.22 3GPP SPECIFICATIONS

- The '38' series of 3GPP Technical Specifications focuses upon New Radio (NR) radio technology
- Many of the specifications have similar titles to the equivalent '25' series for UMTS and '36' series for LTE
- Other series of specifications also include relevant information, e.g. TS 24.501 specifies the Non-Access Stratum (NAS) protocol
- The '29' series includes a specification of the services offered by each Network Function within the 5G Core Network
- A sample of the 3GPP specifications applicable to NR and the 5G System is presented in Table 30
- These specifications are available to download from the 3GPP internet site: www.3gpp.org

Number	Title
TS 38.101-1	NR, UE Radio Transmission and Reception, Part 1: Range 1 Standalone
TS 38.101-2	NR, UE Radio Transmission and Reception, Part 2: Range 2 Standalone
TS 38.101-3	NR, UE Radio Transmission and Reception, Part 3: Range 1 and Range 2 Interworking with other Radios
TS 38.104	NR, Base Station Radio Transmission and Reception
TS 38.133	NR, Requirements for support of Radio Resource Management
TS 38.211	NR, Physical Channels and Modulation
TS 38.212	NR, Multiplexing and Channel Coding
TS 38.213	NR, Physical Layer Procedures for Control
TS 38.214	NR, Physical Layer Procedures for Data
TS 38.215	NR, Physical Layer Measurements
TS 38.300	NR, Overall Description; Stage-2
TS 38.304	NR, UE Procedures in Idle Mode and in RRC Inactive State
TS 38.306	NR, UE Radio Access Capabilities
TS 38.321	NR, Medium Access Control (MAC) Protocol Specification
TS 38.322	NR, Radio Link Control (RLC) Protocol Specification
TS 38.323	NR, Packet Data Convergence Protocol (PDCP) Specification
TS 38.331	NR, Radio Resource Control (RRC) Protocol Specification
TS 38.401	NG-RAN, Architecture Description
TS 38.413	NG-RAN, NG Application Protocol (NGAP)
TS 38.415	NG-RAN, PDU Session User Plane Protocol
TS 38.423	NG-RAN, Xn Application Protocol (XnAP)
TS 38.425	NG-RAN, NR User Plane Protocol
TS 38.463	NG-RAN, E1 Application Protocol (E1AP)
TS 38.473	NG-RAN, F1 Application Protocol (F1AP)
TS 37.340	NR, Multi-Connectivity, Overall description
TS 37.324	E-UTRA and NR, Service Data Adaptation Protocol (SDAP) specification
TS 24.501	Non-Access-Stratum (NAS) protocol for 5G System (5GS)
TS 23.003	Numbering, Addressing and Identification
TS 23.501	System Architecture for the 5G System
TS 23.502	Procedures for the 5G System
TS 29.500	5G System, Technical Realization of Service Based Architecture
TS 29.502	5G System, Session Management Services
TS 29.503	5G System, Unified Data Management Services
TS 29.510	5G System, Network function repository services
TS 29.518	5G System, Access and Mobility Management Services

Table 30 – 3GPP specifications applicable to the 5G System

2 AIR INTERFACE

2.1 NUMEROLOGY

★ The numerology defines the frequency domain subcarrier spacing. 3GPP TS 38.211 specifies subcarrier spacings of 15, 30, 60, 120 and 240 kHz, i.e. a set of 5 different numerologies. The subcarrier spacing determines the frequency domain bandwidth and the time domain duration of a single Resource Element. A Resource Element has dimensions of 1 subcarrier in the frequency domain and 1 symbol in the time domain

★ Figure 94 illustrates the dimensions of a Resource Element for subcarrier spacings of 15 kHz and 30 kHz. The frequency domain bandwidth of a Resource Element is equal to the subcarrier spacing, i.e. increasing the subcarrier spacing by a factor of 2, increases the Resource Element bandwidth by a factor of 2. The time domain duration of a Resource Element (excluding the cyclic prefix) is equal to 1 cycle of a sine wave with a frequency equal to the subcarrier spacing, e.g. the duration of a Resource Element (excluding the cyclic prefix) is equal to 1 / 15 = 0.067 ms when using the 15 kHz subcarrier spacing. Increasing the subcarrier spacing by a factor of 2, decreases the Resource Element duration by a factor of 2

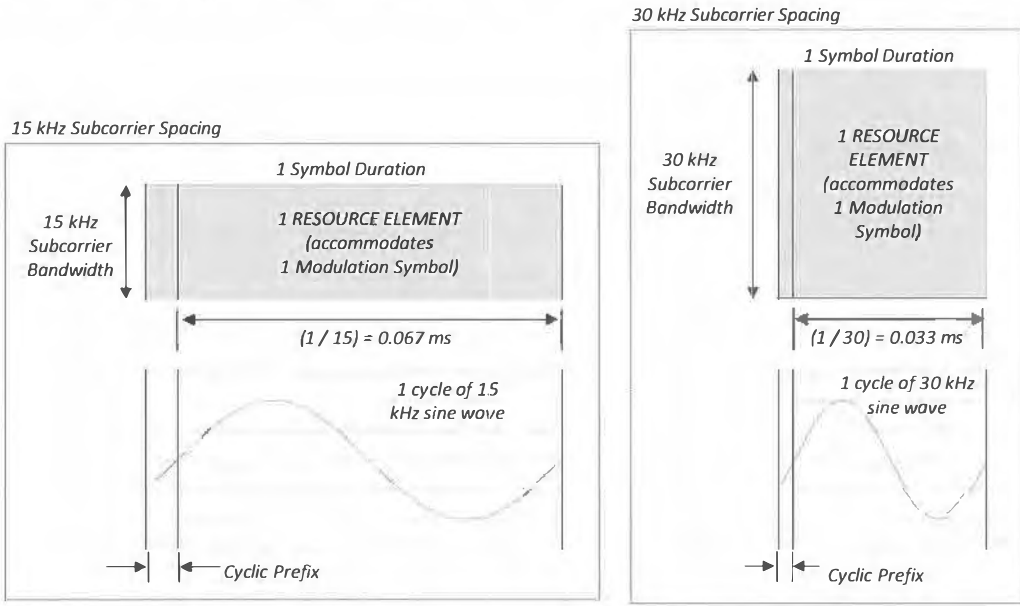


Figure 94 – Resource Element dimensions for 15 kHz and 30 kHz subcarrier spacings

★ A single Resource Element can accommodate a single modulation symbol, e.g. a single Resource Element could be used to transmit a single QPSK, 16QAM, 64QAM or 256QAM modulation symbol. A QPSK symbol represents 2 bits of information so the capacity of a Resource Element corresponds to 2 bits when transferring a QPSK symbol. A 256QAM symbol represents 8 bits of information so the capacity of a Resource Element corresponds to 8 bits when transferring a 256QAM symbol

★ The use of multiple subcarriers in the frequency domain and multiple symbols in the time domain generates a grid of Resource Elements. Figure 95 illustrates the Resource Element grid for the 15 kHz subcarrier spacing

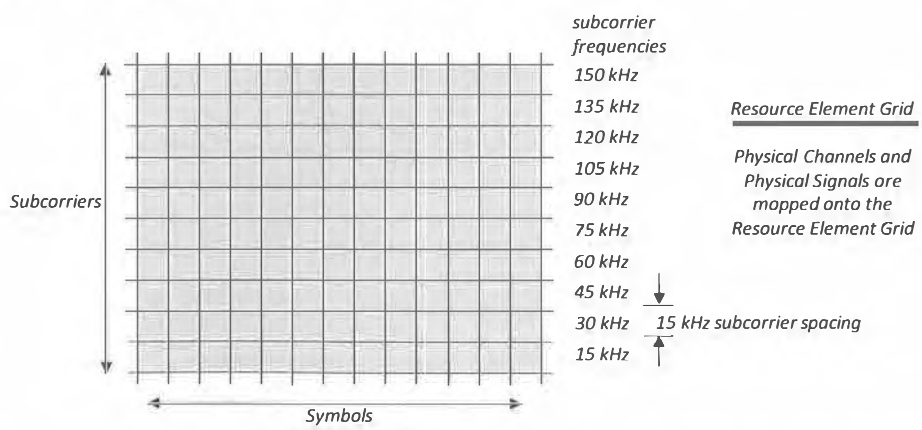


Figure 95 – Resource Element grid generated by frequency domain subcarriers and time domain symbols

★ The lowest row of Resource Elements within Figure 95 uses a subcarrier frequency of 15 kHz, while the row above uses a subcarrier frequency of 30 kHz, and the row above that uses a subcarrier frequency of 45 kHz, i.e. the subcarrier spacing is 15 kHz. These subcarriers are modulated and summed at the transmitter when generating the air-interface waveform. The modulation and summing of subcarriers corresponds to an Inverse Fast Fourier Transform (IFFT). Figure 96 illustrates the set of subcarriers before they are modulated and summed

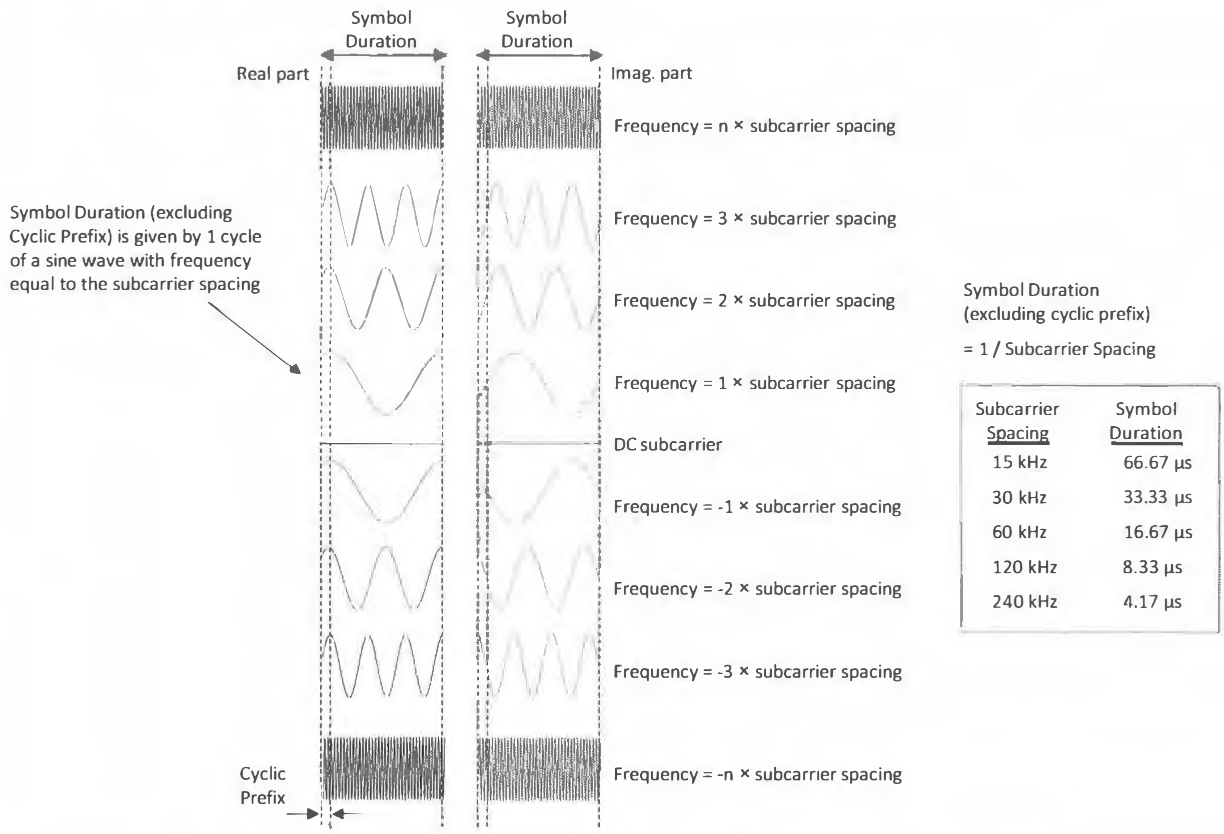


Figure 96 – Subcarriers which are modulated and summed to generate the CP-OFDM waveform

★ Figure 96 illustrates that a subcarrier can have a frequency of 0 Hz, i.e. the DC subcarrier, and that subcarriers can have negative frequencies. This results from the baseband signal having a 'center' frequency of 0 Hz. Digital signal processing within the Base Station is completed using the baseband signal. The baseband signal is mixed to an RF signal at the transmitter before it is radiated across the air-interface, i.e. the center frequency of 0 Hz is increased to the center frequency of the appropriate RF channel. Waveform generation and the DC subcarrier are described in greater detail within section 2.9

★ A combination of numerologies can be used within the duration of a single symbol, e.g. the subcarrier spacings of 15 and 30 kHz can be combined when generating the air-interface waveform. The concept of combining multiple numerologies is illustrated in Figure 97. 3GPP has specified which numerologies can be used within each operating band. This means that only specific numerology combinations are permitted, e.g. the 15 and 30 kHz subcarrier spacings can be combined, but the 15 and 120 kHz subcarrier spacings cannot be combined

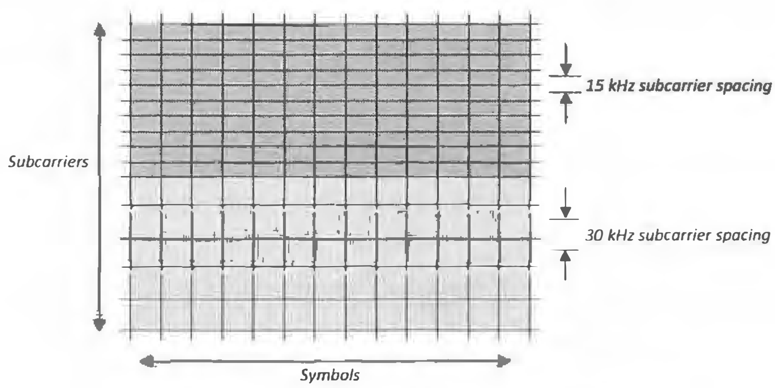


Figure 97 – Combination of different numerologies

- ★ The range of numerologies allows 5G to support diverse deployment scenarios and diverse end-user applications, i.e. the subcarrier spacing can be selected to suit the deployment scenario and the end-user application requirements:
  - o deployment scenarios with larger propagation channel delay spread use lower subcarrier spacings to benefit from longer symbol and longer cyclic prefix durations. Longer cyclic prefix durations are able to accommodate larger delay spreads. Delay spreads are typically larger for macro cell deployments with relatively large cell ranges. This means that the lower operating bands with their lower air-interface propagation losses and larger cell ranges benefit from using the lower subcarrier spacings. The higher operating bands with their higher air-interface propagation losses and smaller cell ranges can use the higher subcarrier spacings
  - o deployments using the higher operating bands suffer from increased oscillator phase noise which causes a random jitter in the phase of the received signal. Higher subcarrier spacings are more robust against this jitter because the magnitude of the jitter is relatively small when compared to the magnitude of the subcarrier spacing
  - o deployment scenarios with high mobility, e.g. high speed train scenarios, experience high Doppler frequency offsets. Higher subcarrier spacings are more robust against these offsets because the magnitude of the offset is relatively small when compared to the magnitude of the subcarrier spacing
  - o end-user applications with low latency requirements benefit from short symbol durations, i.e. high subcarrier spacings. The short symbol durations allow data to be transmitted and acknowledged with minimal delay
- ★ The complete set of numerologies are available when using the normal cyclic prefix (the normal and extended cyclic prefix are described in section 2.8). There are always 14 symbols per slot when using the normal cyclic prefix, and 12 symbols per slot when using the extended cyclic prefix. The reduction in the number of symbols is caused by the longer (extended) cyclic prefix duration
- ★ Table 31 presents the key characteristics belonging to each numerology when using the normal cyclic prefix. The 5G radio frame has a fixed duration of 10 ms, and the 5G subframe has a fixed duration of 1 ms. The symbol duration and slot duration vary according to the subcarrier spacing so the number of slots per radio frame and slots per subframe also vary according to the subcarrier spacing. The variable 'μ' is used to index the subcarrier spacing such that the subcarrier spacing = 15 kHz × 2^{μ}
- ★ In the case of 4G, when using the 15 kHz subcarrier spacing there are 20 slots per radio frame and 2 slots per subframe, i.e. the slot duration is 0.5 ms rather than 1 ms. The 4G radio frame and subframe durations are the same as those used by 5G, i.e. 10 ms and 1 ms respectively

μ	Subcarrier Spacing	Slots per 10 ms Radio Frame	Slots per 1 ms Subframe	Symbols per Slot	Symbol Duration (μs)	Slot Duration (μs)	Operating Bands	Expected Use Case
0	15 kHz	10	1	14	Symbols 0 & 7 = 71.875 Other symbols = 71.354	All slots = 1000	Frequency Range 1	eMBB
1	30 kHz	20	2	14	Symbols 0 & 14 = 36.198 Other symbols = 35.677	All slots = 500	Frequency Range 1	eMBB, URLLC
2	60 kHz	40	4	14	Symbols 0 & 28 = 18.359 Other symbols = 17.839	Slots 0, 2 = 250.260 Other slots = 249.740	Frequency Ranges 1 & 2	eMBB, URLLC
3	120 kHz	80	8	14	Symbols 0 & 56 = 9.440 Other symbols = 8.919	Slots 0, 4 = 125.391 Other slots = 124.870	Frequency Range 2	eMBB, URLLC
4*	240 kHz	160	16	14	Symbols 0 & 112 = 4.980 Other symbols = 4.460	Slots 0, 8 = 62.956 Other slots = 62.435	Frequency Range 2	-

* subcarrier spacing of 240 kHz is only applicable to the Synchronisation Signal / PBCH Blocks (it is not used to transfer application data)

Table 31 – Range of numerologies for the Normal Cyclic Prefix

- ★ The symbol durations presented in Table 31 differ from those presented in Figure 96 because they include the impact of the cyclic prefix. The precise cyclic prefix duration depends upon the symbol number. There are two symbols within each subframe which have a longer cyclic prefix. This approach has been adopted to ensure that a slot and symbol boundary always coincides with a subframe boundary, i.e. there is an integer number of slots and symbols within a subframe. The variation in symbol duration causes a variation in slot duration (when the number of slots per subframe is greater than 2)
- ★ 3GPP has specified that subcarrier spacings of 15, 30 and 60 kHz can be applied to Frequency Range 1 (450 MHz to 6 GHz), while subcarrier spacings of 60, 120 and 240 kHz can be applied to Frequency Range 2 (24.25 GHz to 52.60 GHz). The subcarrier spacing of 240 kHz is only applicable to the transmission of Synchronisation Signal / PBCH Blocks. It cannot be used to transfer application data
- ★ 3GPP has only specified the 60 kHz subcarrier spacing for the extended cyclic prefix. Table 32 presents the key characteristics belonging to the 60 kHz subcarrier spacing when using the extended cyclic prefix. In the case of the extended cyclic prefix, all symbols and slots have equal duration

μ	Subcarrier Spacing	Slots per 10 ms Radio Frame	Slots per 1 ms Subframe	Symbols per Slot	Symbol Duration (μs)	Slot Duration (μs)	Operating Bands	Expected Use Case
2	60 kHz	40	4	12	20.833	250	Frequency Ranges 1 & 2	eMBB, URLLC

Table 32 – Numerology for Extended Cyclic Prefix

- A receiver samples the analogue waveform to generate the set of digital samples which are subsequently processed to determine the received bit stream. The sampling frequency is dependent upon both the numerology and the size of the Fast Fourier Transform (FFT). For example, a channel bandwidth which includes 100 Resource Blocks has 1200 subcarriers so requires an FFT size > 1200, e.g. an FFT size of 2048 can be used. This means that there would be 2048 samples within the payload of each CP-OFDM symbol. If the subcarrier spacing is 15 kHz then the time interval between samples would be 1 / (15 000 × 2048) seconds, i.e. the sampling frequency would be 2048 × 15 000 samples per second
- 3GPP TS 38.211 specifies a unit of time referred to as T_c which represents the time interval between samples for an FFT size of 4096 with a subcarrier spacing of 480 kHz, i.e. $T_c = 1 / (\Delta f_{max} \times N_f)$, where $\Delta f_{max} = 480$ kHz and $N_f = 4096$
  - an FFT size of 4096 with a subcarrier spacing of 480 kHz corresponds to a channel bandwidth of 1.97 GHz
  - the maximum channel bandwidth within the release 15 version of the 3GPP specification is 800 MHz. The value of T_c has been selected to future-proof the specifications against potential increases in the maximum channel bandwidth
- The value of T_c does not define the sampling interval used by a specific implementation but the sampling interval is expected to be a multiple of T_c. For example, a subcarrier spacing of 15 kHz with an FFT size of 2048 generates a sampling interval of 1 / (15 000 × 2048) seconds, which is $64 \times T_c$
- 3GPP TS 38.211 uses the 15 kHz subcarrier spacing with the FFT size of 2048 as a reference. The sampling interval generated by this reference is known as $T_s = 1 / (\Delta f_{ref} \times N_{f,ref})$, where $\Delta f_{ref} = 15$ kHz and $N_{f,ref} = 2048$, i.e. $T_s = 32.55$ ns
- 3GPP References: TS 38.211

2.2 RADIO FRAMES AND SLOTS

★ The 5G radio frame has a fixed duration of 10 ms. Radio frames are indexed using the System Frame Number (SFN) which ranges from 0 to 1023, i.e. the SFN cycles every 10.24 seconds

★ The SFN is acquired from the Physical Broadcast Channel (PBCH) when accessing a cell. A set of 10 bits is used to represent the SFN. The 6 Most Significant Bits (MSB) of the SFN are included within the layer 3 payload of the PBCH, i.e. they are provided by the RRC signalling protocol. The 4 Least Significant Bits (LSB) of the SFN are added by the Physical layer, i.e. they are included within the payload of layer 1. The Least Significant Bits are the bits which are changing most frequently, e.g. the 1st LSB changes every 10 ms, while the 2nd LSB changes every 20 ms. Allowing the Physical layer to add these bits reduces the rate at which the RRC layer needs to generate new content for the PBCH

★ The 5G subframe has a fixed duration of 1 ms so there are always 10 subframes within each radio frame

★ The 5G slot duration and the 5G symbol duration depend upon the numerology, as presented in Table 31 and Table 32 (section 2.1). This means that the number of slots per subframe and the number of symbols per subframe also depends upon the numerology. The number of symbols per slot is always 14 when using the normal cyclic prefix and is always 12 when using the extended cyclic prefix

★ Figure 98 illustrates the symbols belonging to a 1 ms subframe for each numerology. The 2 symbols with longer cyclic prefix duration are visible at the start and middle of the subframe. In the case of the 15 kHz subcarrier spacing, all slots have equal duration because all slots include 2 symbols with a longer cyclic prefix. Similarly, in the case of the 30 kHz subcarrier spacing, all slots have equal duration because all slots include 1 symbol with a longer cyclic prefix. The higher subcarrier spacings have some slots which include 1 symbol with a longer cyclic prefix and other slots which do not include any symbols with the longer cyclic prefix, i.e. the set of slots do not all have equal duration

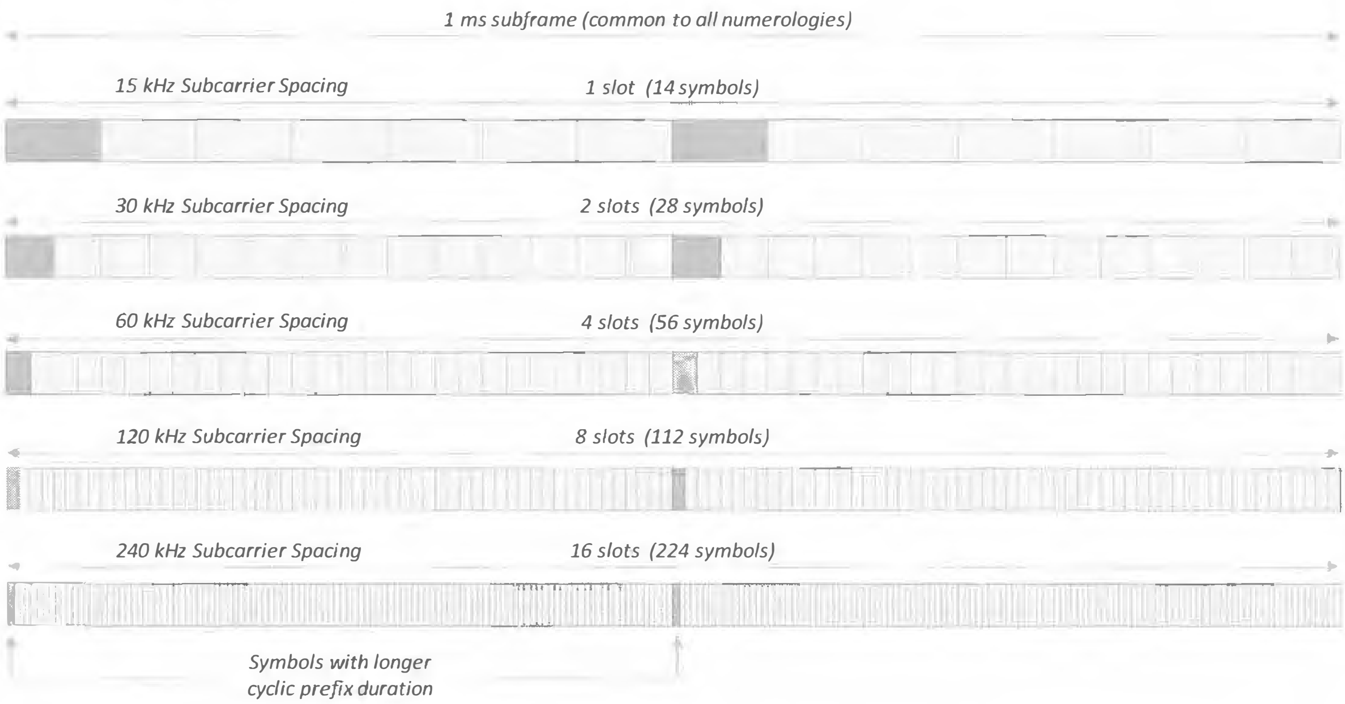


Figure 98 – Symbols per 1 ms Subframe for each numerology

★ When using Frequency Division Duplex (FDD), the symbols belonging to the downlink carrier are used for Base Station transmissions, while the symbols belonging to the uplink carrier are used for UE transmissions

★ When using a Supplemental Downlink (SDL) carrier, all symbols are used for Base Station transmissions. Similarly, when using a Supplemental Uplink (SUL) carrier, all symbols are used for UE transmissions

★ When using Time Division Duplex (TDD), one subset of symbols is used for Base Station transmissions, while another subset is used for UE transmissions. A third subset is used for transceiver switching and guarding against the impact of air-interface propagation delay. The 'slot format' determines which symbols are used for each purpose

★ In the case of 4G, 3GPP TS 36.211 specifies a set of 7 uplink-downlink configurations. Each configuration defines a pattern of uplink, downlink and special subframes. The set of configurations support both 5 ms and 10 ms transceiver switching periods. The release 15 version of the 3GPP specifications includes 11 different formats for the special subframes which are used for transceiver switching and guarding against propagation delay. Each of these special subframe formats defines a pattern of uplink, downlink and guard symbols. SIB1 is used to broadcast both the uplink-downlink configuration and the special subframe configuration

★ In the case of 5G, SIB1 is also used to broadcast an uplink-downlink configuration, but in this case the configuration is not constrained to a pattern specified by 3GPP. Instead, the Base Station is able to specify its own pattern with an uplink-downlink switching period which can be as short as 0.5 ms. 5G also provides scope for dynamically adjusting the uplink-downlink configuration broadcast in SIB1 using either RRC signalling or layer 1 signalling on the PDCCH. The PDCCH signalling is based upon a set of 56 standardised slot formats within 3GPP TS 38.213. These concepts are described in greater detail later in this section. A general example of an uplink-downlink configuration is illustrated in Figure 99

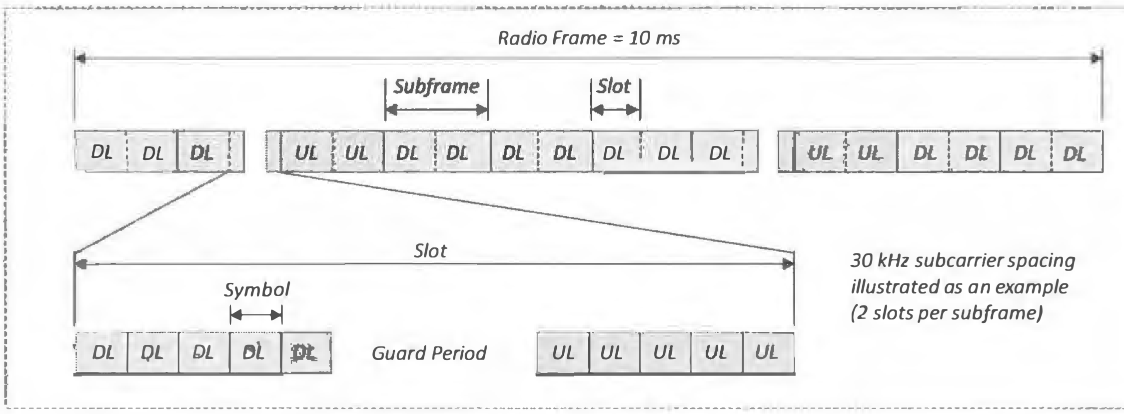


Figure 99 – Example uplink-downlink configuration for TDD

★ The precise time resolution for 5G depends upon the numerology because the symbol duration depends upon the subcarrier spacing. In the case of the 120 kHz subcarrier spacing, symbols have durations of either 8.9 or 9.4 μs. When using such a high time resolution, it is likely that multiple symbols must be allocated to the guard period to accommodate transceiver switching and the impact of the propagation delay

★ TDD slot formats are normally illustrated with a guard period when switching from downlink to uplink, but without a guard period when switching from uplink to downlink. This principle is illustrated in Figure 100

Figure 100 – Guard period when switching from downlink to uplink

★ In reality, neither the UE nor the Base Station experience the timing pattern illustrated in Figure 100. The combination of propagation delay and Timing Advance lead to different timing patterns at the UE and Base Station. The timing experienced by the UE and Base Station is illustrated in Figure 101. This figure illustrates that the guard period must be long enough to accommodate the round trip propagation delay, plus the UE transceiver switching delay, plus the Base Station transceiver switching delay

★ The downlink transmissions are received by the UE after the propagation channel delay. The maximum propagation channel delay depends upon the cell range. The UE then takes some time to switch its transceiver from receive to transmit. This switching delay is typically assumed to be 20 μs. The UE subsequently starts its uplink transmissions according to the Timing Advance instructions received from the Base Station. The Base Station provides Timing Advance commands to each UE to ensure that all uplink transmissions are received with equal timing. UE which are close to the Base Station will have a small Timing Advance, while UE which are far from the Base Station will have a large Timing Advance (section 13.2 describes Timing Advance in greater detail). Uplink transmissions are received by the Base Station after the propagation channel delay. The Base Station also requires some transceiver switching time between reception on the uplink and transmission on the downlink. Similar to the UE, this switching time is typically assumed to be 20 μs

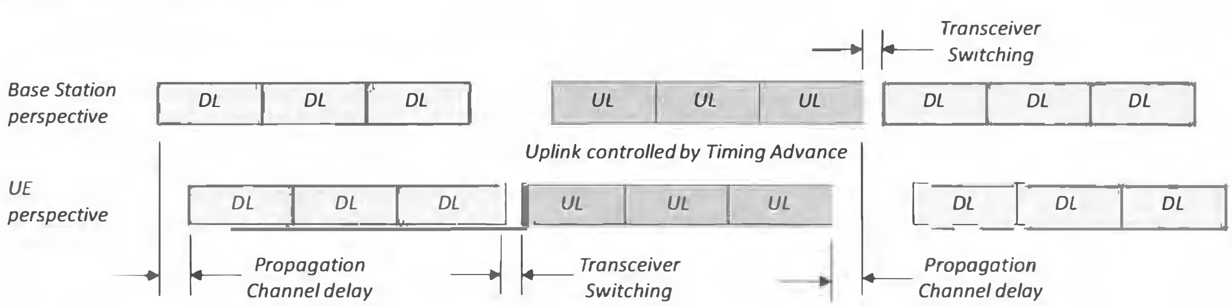


Figure 101 – TDD timing experienced by Base Station and UE

★ 5G supports dynamic TDD which allows a rapid reconfiguration of symbols between the uplink and downlink. This allows the Base Station to adjust the uplink and downlink resources according to short term requirements. Neighbouring cells can reconfigure their symbols between uplink and downlink without co-ordination. This means that one cell may be transmitting in the downlink while a neighbouring cell may be receiving in the uplink. This scenario may lead to cross link interference:

- o the uplink of one cell causing interference to the downlink of a neighbouring cell (UE to UE interference)
- o the downlink of one cell causing interference to the uplink of a neighbouring cell (BTS to BTS interference)

★ Figure 102 illustrates the general concept of cross link interference for a relatively worst case scenario, i.e. one cell is configured to use a downlink centric slot while a neighbouring cell is configured to use an uplink centric slot

★ In the case of 4G TDD networks, all cells sharing the same carrier are typically synchronised and configured with the same uplink/downlink subframe configuration. This means that all cells transmit in the downlink direction at the same time, and receive in the uplink direction at the same time. This type of solution is less flexible but avoids the potential for cross link interference

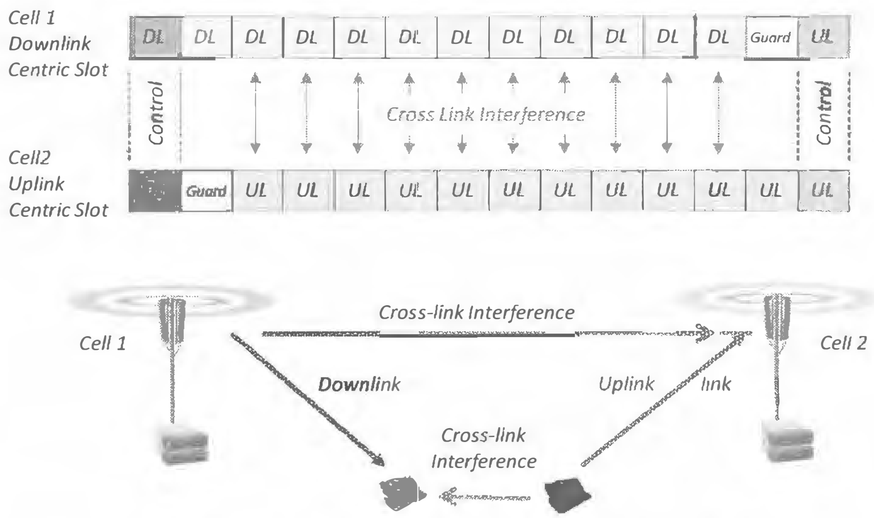


Figure 102 – Cross Link Interference between neighbouring TDD cells

★ The 3GPP specifications for 5G allow the timing of the uplink and downlink control regions to be configured to avoid any impact from cross link interference, i.e. all cells transmit downlink control information at the start of a slot, while all cells receive uplink control information at the end of a slot (as shown in Figure 102). In this context, control information refers to Downlink Control Information (DCI) on the Physical Downlink Control Channel (PDCCH), and Uplink Control Information (UCI) on the Physical Uplink Control Channel (PUCCH). The PDCCH and PUCCH do not benefit from re-transmissions so avoiding the impact of cross link interference is important to help ensure reliable reception

★ Signalling Radio Bearer (SRB) transmissions are transmitted on the Physical Downlink Shared Channel (PDSCH) and Physical Uplink Shared Channel (PUSCH). These transmissions also have high importance but they may experience cross link interference, i.e. SRB messages are transmitted within the central region of the slot. The impact of cross link interference can be mitigated using increased channel coding redundancy and re-transmissions. Application data is also transmitted on the PDSCH and PUSCH within the central region of the slot. Similar to the set of SRB, application data can benefit from channel coding redundancy and re-transmissions

★ Cross link interference is likely to be less of an issue when using small cells in the higher operating bands, i.e. mm wave bands, because the high air-interface attenuation will limit the interference power between neighbouring cells. Cells operating in the mm wave band are likely to be noise limited rather than interference limited. Cross link interference may also be manageable for indoor solutions which are isolated from the outdoor macrocell network. Macrocells are more likely to be configured with a common uplink-downlink transmission timing pattern to avoid cross link interference

★ Figure 103 illustrates the two main options for configuring the timing of uplink and downlink transmissions. The first option does not provide the UE with a specific uplink/downlink transmission pattern. Instead, the UE monitors the PDCCH for uplink and downlink resource allocations and simply transmits or receives according to those allocations, i.e. the Packet Scheduler is in control of the uplink/downlink transmission timing

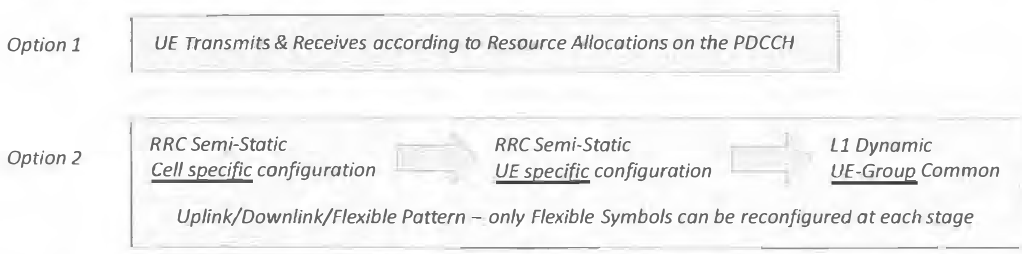


Figure 103 – High level options for configuring the timing of uplink/downlink transmissions

★ The second option relies upon the Base Station providing the UE with a specific uplink-downlink transmission pattern. This pattern can be signalled using a combination of RRC and Layer 1 signalling, or it can be configured using only RRC signalling, or only Layer 1 signalling. RRC signalling provides a semi-static configuration which remains valid unless reconfigured by subsequent RRC signalling. Layer 1 signalling provides a dynamic configuration which is valid for a relatively short time window and requires continuous updating

★ The *tdd-UL-DL-ConfigurationCommon* parameter structure presented in Table 33 can be broadcast as part of SIB1. It can also be provided to the UE using dedicated signalling, e.g. when using the EN-DC Non-Standalone Base Station architecture. The parameter structure defines a default uplink-downlink configuration for a cell. The *referenceSubcarrierSpacing* is specified to define the duration of the symbols and slots belonging to the uplink/downlink configuration. For example, each slot has a duration of 1 ms if the 15 kHz subcarrier spacing is specified, or 0.5 ms if the 30 kHz subcarrier spacing is specified

★ The parameter structure can include either 1 or 2 patterns. If only 1 pattern is included then that pattern repeats periodically based upon the configured *dl-UL-TransmissionPeriodicity.* If 2 patterns are included then the second pattern follows the first pattern and the pair of patterns repeat with a period equal to *dl-UL-TransmissionPeriodicity* (pattern1) + *dl-UL-TransmissionPeriodicity* (pattern2). 3GPP specifies that the sum of the 2 pattern periods must divide into 20 ms, e.g. periods of 2 + 2 ms are permitted but periods of 1 + 2 ms are not permitted. Periods are initialised at the start of every even numbered radio frame

★ Each transmission period includes a specific number of slots for the specified reference subcarrier spacing. The period of 0.625 ms is only permitted when using a reference subcarrier spacing of 120 kHz. In this case, the period includes 5 slots of 0.125 ms. The period of 1.25 ms is only permitted when using reference subcarrier spacings of 60 or 120 kHz. Similarly, the period of 2.5 ms is only permitted when using reference subcarrier spacings of 30, 60 or 120 kHz. The *dl-UL-TransmissionPeriodicity-v1530* information element was added by the release 15.3 version of the specifications to extend the range of the original *dl-UL-TransmissionPeriodicity* information element. The UE ignores the original information element if this new version is included

tdd-UL-DL-ConfigurationCommon		
referenceSubcarrierSpacing	15, 30, 60, 120 kHz	
pattern1	dl-UL-TransmissionPeriodicity	0.5, 0.625, 1, 1.25, 2, 2.5, 5, 10 ms
	nrofDownlinkSlots	0 to 320 (current max is 80)
	nrofDownlinkSymbols	0 to 13
	nrofUplinkSlots	0 to 320 (current max is 80)
	nrofUplinkSymbols	0 to 13
	dl-UL-TransmissionPeriodicity-v1530	3, 4 ms
pattern2	dl-UL-TransmissionPeriodicity	0.5, 0.625, 1, 1.25, 2, 2.5, 5, 10 ms
	nrofDownlinkSlots	0 to 320 (current max is 80)
	nrofDownlinkSymbols	0 to 13
	nrofUplinkSlots	0 to 320 (current max is 80)
	nrofUplinkSymbols	0 to 13
	dl-UL-TransmissionPeriodicity-v1530	3, 4 ms

Table 33 – *tdd-UL-DL-ConfigurationCommon* parameter structure

★ Within each pattern period, *nrofDownlinkSlots* defines the number of downlink slots at the start of the period, while *nrofUplinkSlots* defines the number of uplink slots at the end of the period. A range from 0 to 320 has been specified for these information elements although the release 15 version of the specifications limits the upper value to 80 slots. This corresponds to the maximum number of slots within a 10 ms period when using the 120 kHz subcarrier spacing

★ The *nrofDownlinkSymbols* defines the number of downlink symbols within the slot which follows the downlink slots. Similarly, the *nrofUplinkSymbols* defines the number of uplink symbols within the slot which precedes the uplink slots. Figure 104 illustrates the general uplink/downlink pattern generated by the parameter structure. Symbols and slots which remain unallocated at the center of the pattern are treated as 'Flexible' and can be subsequently allocated to either the uplink or downlink

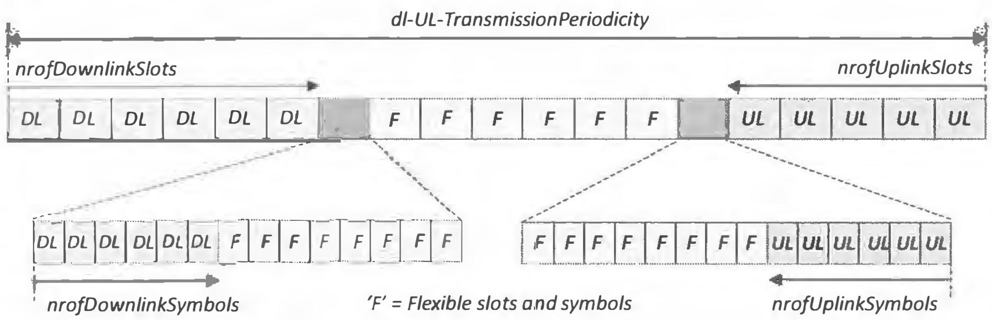


Figure 104 – Uplink/Downlink Slot and Symbol pattern configured using *tdd-UL-DL-ConfigurationCommon*

★ The *tdd-UL-DL-ConfigurationDedicated* parameter structure presented in Table 34 can be provided to the UE using dedicated signalling. This parameter structure can be used to refine the uplink/downlink transmission pattern provided by *tdd-UL-DL-ConfigurationCommon*. Refining the transmission pattern means that 'Flexible' slots and symbols can be reconfigured as uplink or downlink slots and symbols. It is not possible to change slots and symbols which have already been configured as uplink or downlink

tdd-UL-DL-ConfigurationDedicated					
slotSpecificConfigurationsToAddModList	SEQUENCE (1 to 320 instances)				
	slotIndex	0 to 319			
	symbols	CHOICE			
		allDownlink	allUplink	explicit	
				nrofDownlinkSymbols	1 to 13
				nrofUplinkSymbols	1 to 13
slotSpecificConfigurationsToreleaseList	SEQUENCE (1 to 320 instances)				
	slotIndex	0 to 319			

Table 34 – *tdd-UL-DL-ConfigurationDedicated* parameter structure

★ The dedicated parameter structure provides a list of configurations for individual slots. Each slot can be configured as downlink, uplink, partially downlink, partially uplink or a combination of both uplink and downlink. Figure 105 illustrates an example of the dedicated parameter set being used to reconfigure the Flexible symbols defined by the common parameter set

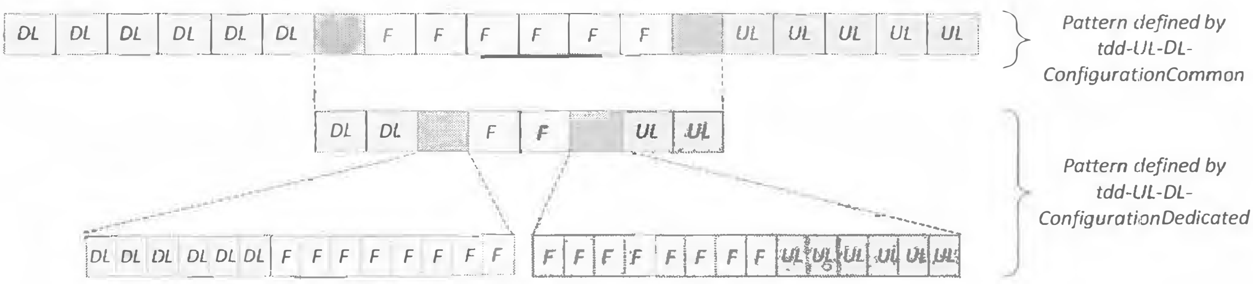


Figure 105 – Uplink/Downlink Slot and Symbol pattern configured using *tdd-UL-DL-ConfigurationDedicated*

★ Any remaining Flexible symbols can be dynamically reconfigured using Downlink Control Information (DCI) Format 2_0. This allows rapid reconfiguration using Layer 1 signalling. A UE must be allocated a Slot Format Indicator RNTI (SFI-RNTI) before it can receive information on DCI Format 2_0. An SFI-RNTI is allocated to the UE using the *SlotFormatIndicator* parameter structure shown in Table 35. DCI Format 2_0 provides 'UE Group' common signalling so multiple UE will be allocated the same SFI-RNTI and will decode the same PDCCH transmissions. The *PositionInDCI* information element specifies the location of the relevant Slot Format Indicator (SFI) within the payload. Different UE can be configured with different *PositionInDCI* values and so extract different information from the payload. The *SlotFormatIndicator* parameter structure also specifies the size of the PDCCH payload belonging to DCI Format 2_0. This information helps the UE to complete the decoding process

SlotFormatIndicator			
sfi-RNTI	0 to 65535		
dci-PayloadSize	1 to 128 bits		
slotFormatCombToAddModList	SEQUENCE (1 to 16 instances)		
	servingCellId	0 to 31	
	subcarrierSpacing	15, 30, 60, 120 kHz	
	subcarrierSpacing2	15, 30, 60, 120 kHz	
	slotFormatCombinations	SEQUENCE (1 to 512 instances)	
		slotFormatCombinationId	0 to 511
		slotFormats	SEQUENCE (1 to 256 instances)
			INTEGER (0 to 255)
	PositionInDCI	0 to 127	
slotFormatCombToReleaseList	SEQUENCE (1 to 16 instances)		
	servingCellId	0 to 31	

Table 35 – *SlotFormatIndicator* parameter structure

★ The Slot Format Indicator (SFI) provided by the payload of DCI Format 2_0 defines a pointer towards a specific Slot Format Combination. Each Slot Format Combination is generated using a series of Slot Formats standardised by 3GPP. These standardised Slot Formats are presented in Table 36. The release 15 version of the 3GPP specifications defines 56 standardised Slot Formats

★ The majority of standardised Slot Formats are based upon a cycle of 14 symbols (1 slot). Slot Formats 46 to 53 are based upon a cycle of 7 symbols (half a slot). These Slot Formats can be used for low latency applications which require more frequent switching between the uplink and downlink, i.e. to return acknowledgements with less delay. Slot Format 0 provides only downlink symbols, while Slot Format 1 provides only uplink symbols. These Slot Formats may be used for FDD scenarios. In general, full duplex devices using FDD do not require specific Slot Format Combinations because those devices can transmit continuously and simultaneously receive continuously. Half duplex FDD devices can be configured with specific Slot Format Combinations to indicate when to transmit and when to receive (IoT devices could be half duplex to help reduce hardware cost)

★ Slot Format 255 can be used as a 'wildcard' Slot Format which means that the uplink/downlink transmission pattern for that slot is not determined by the Slot Format Combination. Instead, the UE uses the transmission pattern which has been configured by RRC signalling or the transmission pattern determined by uplink/downlink resource allocations on the PDCCH

	0	1	2	3	4	5	6	7	8	9	10	11	12	13
0	D	D	D	D	D	D	D	D	D	D	D	D	D	D
1	U	U	U	U	U	U	U	U	U	U	U	U	U	U
2	F	F	F	F	F	F	F	F	F	F	F	F	F	F
3	D	D	D	D	D	D	D	D	D	D	D	D	D	F
4	D	D	D	D	D	D	D	D	D	D	D	D	F	F
5	D	D	D	D	D	D	D	D	D	D	D	F	F	F
6	D	D	D	D	D	D	D	D	D	D	F	F	F	F
7	D	D	D	D	D	D	D	D	D	F	F	F	F	F
8	F	F	F	F	F	F	F	F	F	F	F	F	F	U
9	F	F	F	F	F	F	F	F	F	F	F	F	U	U
10	F	U	U	U	U	U	U	U	U	U	U	U	U	U
11	F	F	U	U	U	U	U	U	U	U	U	U	U	U
12	F	F	F	U	U	U	U	U	U	U	U	U	U	U
13	F	F	F	F	U	U	U	U	U	U	U	U	U	U
14	F	F	F	F	F	U	U	U	U	U	U	U	U	U
15	F	F	F	F	F	F	U	U	U	U	U	U	U	U
16	D	F	F	F	F	F	F	F	F	F	F	F	F	F
17	D	D	F	F	F	F	F	F	F	F	F	F	F	F
18	D	D	D	F	F	F	F	F	F	F	F	F	F	F
19	D	F	F	F	F	F	F	F	F	F	F	F	F	U
20	D	D	F	F	F	F	F	F	F	F	F	F	F	U
21	D	D	D	F	F	F	F	F	F	F	F	F	F	U
22	D	F	F	F	F	F	F	F	F	F	F	F	U	U
23	D	D	F	F	F	F	F	F	F	F	F	F	U	U
24	D	D	D	F	F	F	F	F	F	F	F	F	U	U
25	D	F	F	F	F	F	F	F	F	F	F	U	U	U
26	D	D	F	F	F	F	F	F	F	F	F	U	U	U
27	D	D	D	F	F	F	F	F	F	F	F	U	U	U
28	D	D	D	D	D	D	D	D	D	D	D	D	F	U
29	D	D	D	D	D	D	D	D	D	D	D	F	F	U
30	D	D	D	D	D	D	D	D	D	D	F	F	F	U
31	D	D	D	D	D	D	D	D	D	D	D	F	U	U
32	D	D	D	D	D	D	D	D	D	D	F	F	U	U
33	D	D	D	D	D	D	D	D	D	F	F	F	U	U
34	D	F	U	U	U	U	U	U	U	U	U	U	U	U
35	D	D	F	U	U	U	U	U	U	U	U	U	U	U
36	D	D	D	F	U	U	U	U	U	U	U	U	U	U
37	D	F	F	U	U	U	U	U	U	U	U	U	U	U
38	D	D	F	F	U	U	U	U	U	U	U	U	U	U
39	D	D	D	F	F	U	U	U	U	U	U	U	U	U
40	D	F	F	F	U	U	U	U	U	U	U	U	U	U
41	D	D	F	F	F	U	U	U	U	U	U	U	U	U
42	D	D	D	F	F	F	U	U	U	U	U	U	U	U
43	D	D	D	D	D	D	D	D	D	F	F	F	F	U
44	D	D	D	D	D	D	F	F	F	F	F	F	U	U
45	D	D	D	D	D	D	F	F	U	U	U	U	U	U
46	D	D	D	D	D	F	U	D	D	D	D	D	F	U
47	D	D	F	U	U	U	U	D	D	F	U	U	U	U
48	D	F	U	U	U	U	U	D	F	U	U	U	U	U
49	D	D	D	D	F	F	U	D	D	D	D	F	F	U
50	D	D	F	F	U	U	U	D	D	F	F	U	U	U
51	D	F	F	U	U	U	U	D	F	F	U	U	U	U
52	D	F	F	F	F	F	U	D	F	F	F	F	F	U
53	D	D	F	F	F	F	U	D	D	F	F	F	F	U
54	F	F	F	F	F	F	F	D	D	D	D	D	D	D
55	D	D	F	F	F	U	U	U	D	D	D	D	D	D
56 to 254	Reserved													
255	Slot format determined from RRC configuration or DCI on the PDCCH													

Table 36 – Slot Formats standardised by 3GPP for inclusion within Slot Format Combinations

★ Each Slot Format Combination is linked to a specific Serving Cell and has a specific position within the payload of DCI Format 2_0. The size of the Slot Format Indicator (SFI) within DCI Format 2_0 depends upon the set of *slotFormatCombinationId* values which have been configured. The number of bits is given by Max[LOG_2(Max(*slotFormatCombinationId* + 1)), 1]. For example, if the maximum configured value of *slotFormatCombinationId* is 7 then 3 bits are required within the payload of DCI Format 2_0. This means that different UE can extract different numbers of bits from the payload

★ Figure 106 illustrates an example of 3 Slot Format Combinations, where each Slot Format Combination is based upon 3 Slot Formats. This example assumes that the payload of DCI Format 2_0 includes 7 SFI and that the *PositionInDCI* value points to a bit position which corresponds to the 6th SFI

★ The Slot Format Combination starts during the slot which includes the DCI Format 2_0 transmission. The duration of the Slot Format Combination is defined by the number of Slot Formats included within the Combination. The duration should be at least as long as the monitoring period for DCI Format 2_0 to avoid any gaps in the dynamic uplink/downlink configuration pattern

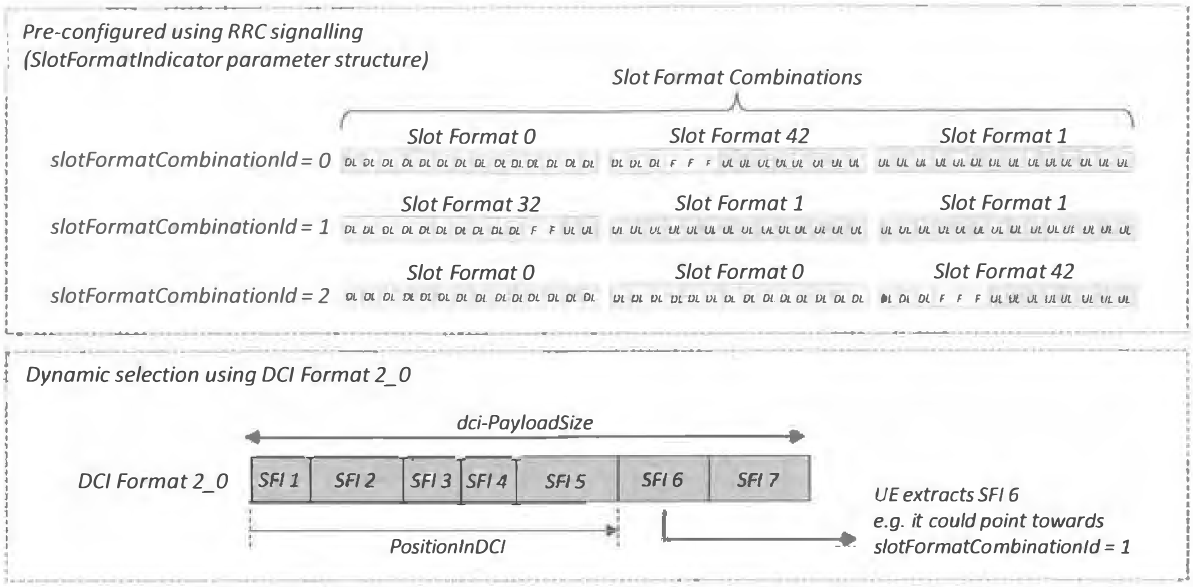


Figure 106 – Example Slot Format Combinations and Slot Format Indicator (SFI) within DCI Format 2_0

- ★ Returning to the content of Table 35, each Slot Format Combination can be associated with one or two subcarrier spacings. Configuring the uplink-downlink transmission pattern for a TDD serving cell requires the definition of only a single subcarrier spacing. In contrast, configuring the uplink-downlink transmission pattern for an FDD serving cell requires the definition of two subcarrier spacings – a first subcarrier spacing (*subcarrierSpacing*) which is applicable to the downlink, and a second subcarrier spacing (*subcarrierSpacing2*) which is applicable to the uplink. In this case, the Slot Format Combination interleaves both downlink and uplink Slot Formats
- ★ Figure 107 illustrates the interleaving of uplink and downlink Slot Formats within a Slot Format Combination when configuring an FDD cell. If the uplink and downlink use the same subcarrier spacing then the Slot Formats alternate. Otherwise, the transmission direction with the higher subcarrier spacing has a proportionally higher number of Slot Formats within the combination

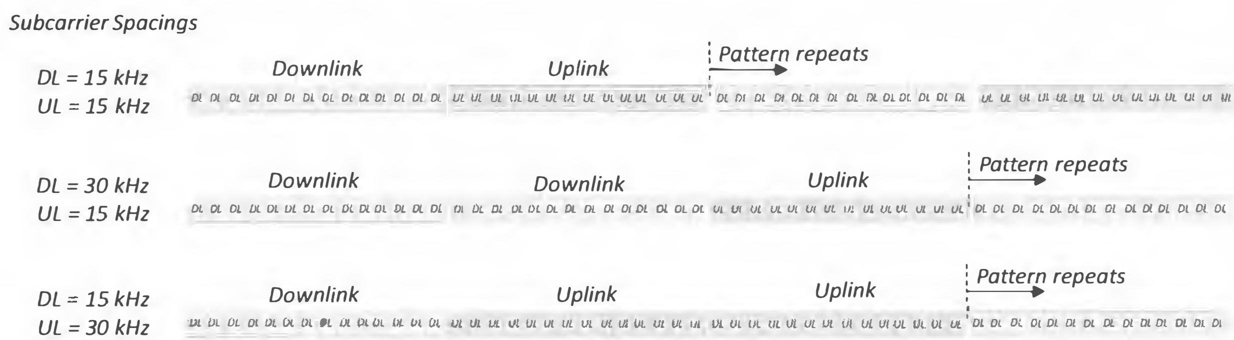


Figure 107 – Interleaving of Slot Formats applicable to the Downlink and Uplink when configuring an FDD cell

- ★ The second subcarrier spacing can also be used when a Supplemental Uplink carrier is configured. In that case, the value of *subcarrierSpacing* is applicable to the Normal Uplink (NUL) carrier, and the value of *subcarrierSpacing2* is applicable to the Supplemental Uplink (SUL) carrier. The patterns illustrated in Figure 107 can then be applied to the NUL and SUL carriers
- ★ The UE monitors the PDCCH for uplink and downlink resource allocations during any Flexible symbols/slots that have been configured using the semi-static parameter structures. However, the UE does not monitor the PDCCH for resource allocations during any Flexible symbols/slots that have been configured using DCI Format 2_0. In this case, the Flexible symbols/slots can be used to generate 'reserved' periods during which the UE does not transmit nor receive. For example, reserved periods could be used when the same RF carrier is being shared between LTE and NR. The NR carrier could be configured with DCI Format 2_0 Flexible symbols/slots during periods when the LTE Packet Scheduler is allocating resources and is thus using the air-interface
- ★ Dynamic uplink/downlink configuration using DCI Format 2_0 can also be used to block specific periodic transmissions. For example, if a UE is periodically transmitting the Sounding Reference Signal (SRS) but the Base Station would like to temporarily change the transmission direction to downlink then DCI Format 2_0 can be used to reconfigure the transmission direction to downlink and prevent the UE from transmitting its periodic SRS. This assumes that the relevant symbols have not been configured as uplink using semi-static signalling in which case the transmission direction cannot be changed by DCI Format 2_0
- ★ 3GPP References: TS 38.213, TS 38.212, TS 38.331

2.3 RESOURCE BLOCKS AND BANDWIDTH PARTS

★ 4G Resource Blocks are defined in both the frequency and time domains. When using the normal cyclic prefix, a 4G Resource Block occupies 12 subcarriers in the frequency domain and 7 symbols in the time domain. When using the extended cyclic prefix, a 4G Resource Block occupies 12 subcarriers in the frequency domain and 6 symbols in the time domain

★ 5G Resource Blocks are only defined in the frequency domain. This means that a 5G resource allocation must specify both the number of Resource Blocks and the number of symbols. A 5G Resource Block always occupies 12 consecutive subcarriers in the frequency domain. The bandwidth occupied by a Resource Block depends upon the subcarrier spacing. Table 37 presents the bandwidth occupied by a single Resource Block for each subcarrier spacing

μ	Subcarrier Spacing	Resource Block Bandwidth
0	15 kHz	180 kHz
1	30 kHz	360 kHz
2	60 kHz	720 kHz
3	120 kHz	1.44 MHz
4	240 kHz	2.88 MHz

Table 37 – Bandwidth occupied by a single Resource Block

2.3.1 COMMON RESOURCE BLOCKS

★ Common Resource Blocks are the set of Resource Blocks which occupy the channel bandwidth. There is a set of Common Resource Blocks for each subcarrier spacing

★ Common Resource Blocks are numbered from 0 upwards, where Common Resource Block 0 is the Resource Block located at the lower side of the channel bandwidth. The Common Resource Blocks associated with each subcarrier spacing are aligned at 'Point A'

★ 'Point A' corresponds to the center of subcarrier 0 belonging to Common Resource Block 0 (CRB 0). The location of 'Point A' is illustrated in Figure 108. The use of 'Point A' as a reference means that the Common Resource Block edges are not aligned

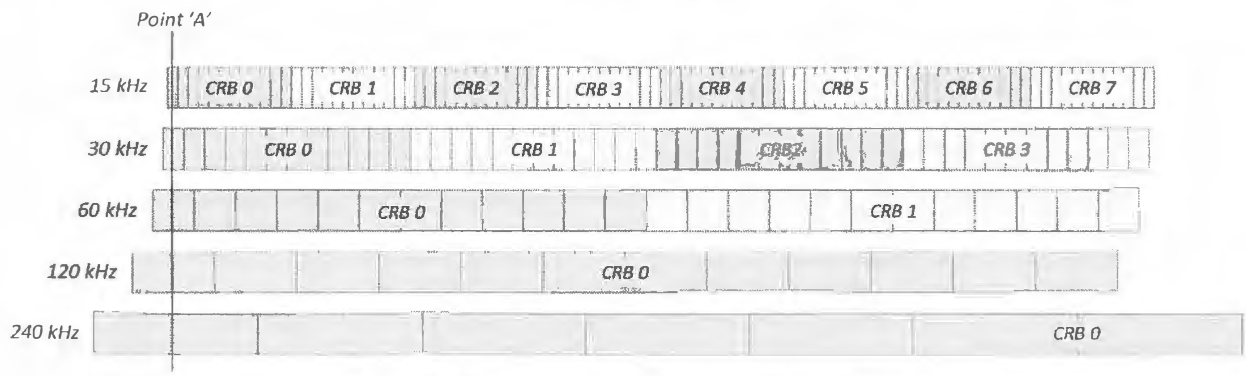


Figure 108 – Reference 'Point A' for each subcarrier spacing

★ A UE does not immediately know the position of 'Point A' after completing a band scan. A UE which completes a band scan will identify the frequency domain location of a Synchronisation Signal / Physical Broadcast Channel (SS/PBCH) Block. However, the UE will not know the position of the channel bandwidth relative to that SS/PBCH Block, i.e. the SS/PBCH Block is not at a single standardised location within the channel bandwidth. The UE can proceed to decode SIB1 without knowing the location of 'Point A' because the air-interface resources allocated to SIB1 are signalled relative to the position of the SS/PBCH

★ A UE determines the position of 'Point A' using either a frequency offset relative to the SS/PBCH, or an Absolute Radio Frequency Channel Number (ARFCN). The frequency offset approach uses a combination of information from the MIB and SIB1. In the case of TDD, this information is applicable to both the uplink and downlink. In the case of FDD, this information is applicable to the downlink and SIB1 includes an ARFCN to specify the position of 'Point A' for the uplink. SIB1 can also include an ARFCN to specify the position of 'Point A' for a Supplemental Uplink

★ Both the uplink and downlink ARFCN for 'Point A' can be provided to the UE using dedicated signalling. For example, this approach could be used during an incoming handover procedure or when using the EN-DC Non-Standalone Base Station architecture. The use of dedicated signalling avoids the requirement to extract information from SIB1

★ The Frequency Offset approach requires both a Resource Block offset and a subcarrier offset:

- SIB1 provides *offsetToPointA* to specify the Resource Block offset between Common Resource Block 0 and the Common Resource Block which overlaps with the start of the SS/PBCH. The numerology used for the Common Resource Block numbering is set equal to the value of *subCarrierSpacingCommon* provided by the MIB
- the MIB provides *ssb-SubcarrierOffset* which defines the 4 Least Significant Bits of the subcarrier offset (k_{SSB}). In the case of Frequency Range 2 (24.25 GHz to 52.60 GHz), the subcarrier offset requires a range from 0 to 11 and these 4 bits are sufficient. In the case of Frequency Range 1 (450 MHz to 6 GHz), the subcarrier offset requires a range from 0 to 23 so a 5th bit is required. This 5th bit (the Most Significant Bit) is included within the Physical layer payload of the PBCH and is transmitted in combination with the MIB
- the subcarrier offset (k_{SSB}) represents an offset from subcarrier 0 of the Common Resource Block identified by *offsetToPointA* to subcarrier 0 of the SS/PBCH. In the case of Frequency Range 1, k_{SSB} is based upon a 15 kHz subcarrier spacing while the SS/PBCH can use subcarrier spacings of 15 or 30 kHz, and *subCarrierSpacingCommon* can be set to either 15 or 30 kHz
- Figure 109 illustrates two examples of the Resource Block and subcarrier offsets for Frequency Range 1. The first example is based upon *subCarrierSpacingCommon* = 15 kHz, and in this case the subcarrier offset can range from 0 to 11. The second example is based upon *subCarrierSpacingCommon* = 30 kHz, and in this case the subcarrier offset can range from 0 to 23

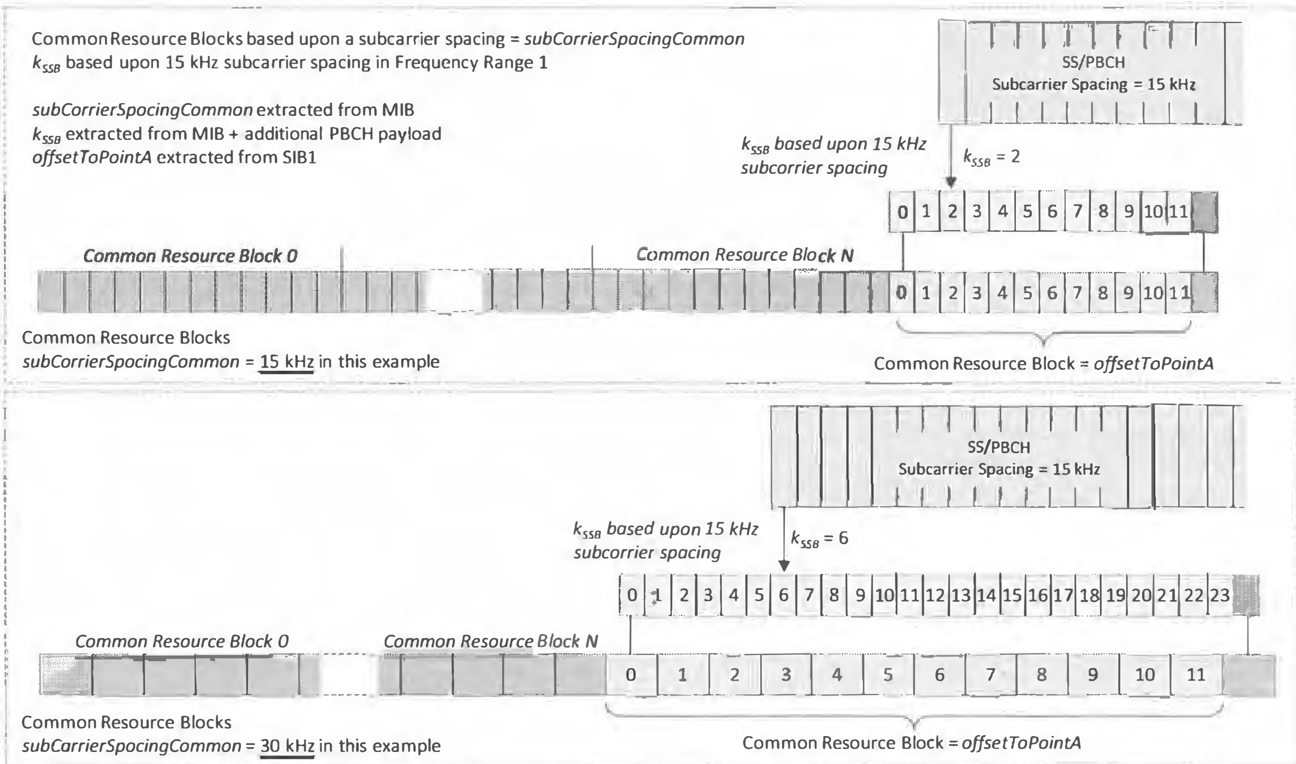


Figure 109 – Examples of Resource Block and Subcarrier Offsets for Frequency Range 1

- In the case of Frequency Range 2, k_{SSB} is based upon a subcarrier spacing which is set equal to *subCarrierSpacingCommon*. Within Frequency Range 2, *subCarrierSpacingCommon* can be set to either 60 or 120 kHz, while the SS/PBCH can use subcarrier spacings of 120 or 240 kHz
- Figure 110 illustrates two examples of the Resource Block and subcarrier offsets for Frequency Range 2. The first example is based upon *subCarrierSpacingCommon* = 60 kHz, while the second example is based upon *subCarrierSpacingCommon* = 120 kHz. In both cases, the subcarrier offset has a range from 0 to 11

★ The ARFCN approach to specifying the position of 'Point A' requires the Base Station to signal an integer within the range 0 to 3279165. This requires 22 bits so is too large to be accommodated by the MIB but can be provided by SIB1 or by dedicated signalling. In this case, the ARFCN is being used to identify a frequency at the lower side of the channel bandwidth rather than a frequency at the center of the channel bandwidth

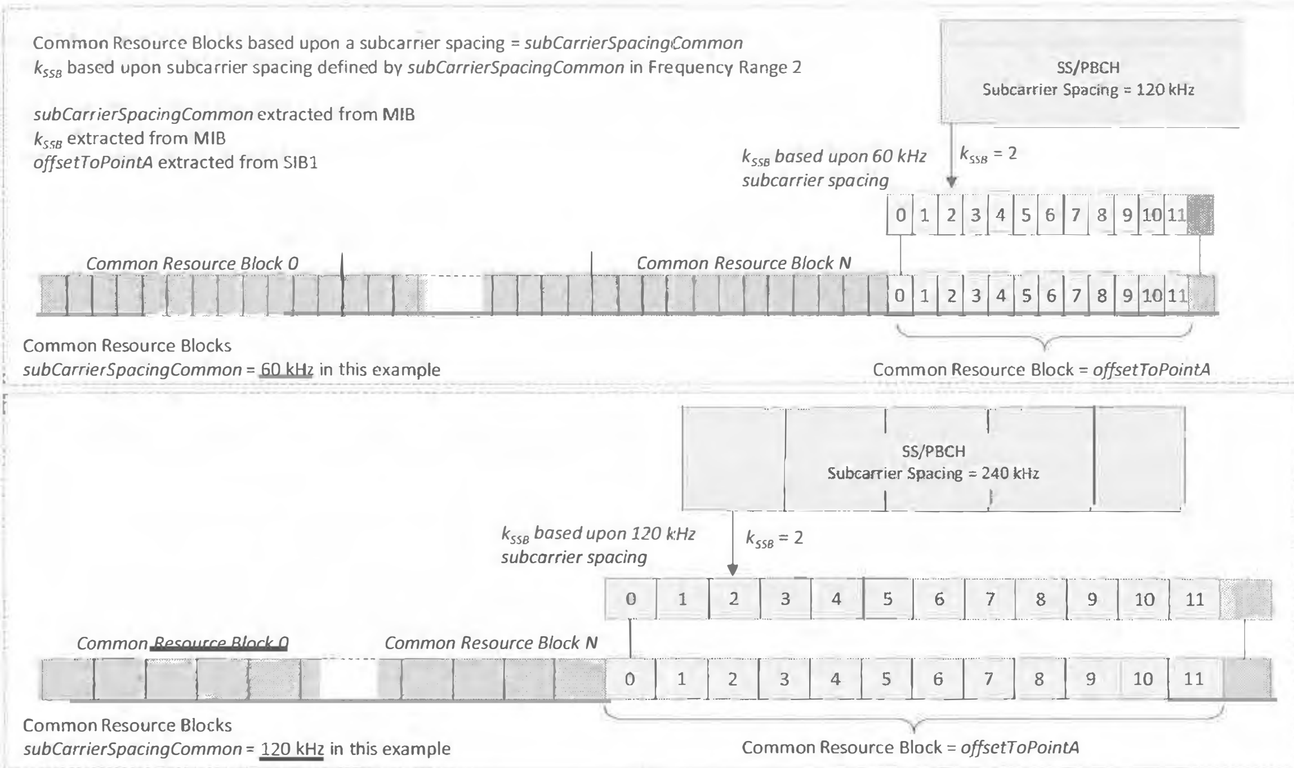


Figure 110 – Examples of Resource Block and Subcarrier Offsets for Frequency Range 2

★ The complete set of Common Resource Blocks may not be used for transmission. Consider an example of the 20 MHz channel bandwidth which accommodates 106 Common Resource Blocks when using the 15 kHz subcarrier spacing (illustrated in Figure 111). These 106 Common Resource Blocks are equivalent to 53 Common Resource Blocks when using the 30 kHz subcarrier spacing. However, 3GPP TS 38.104 specifies that the 20 MHz channel bandwidth can accommodate up to 51 Resource Blocks when using the 30 kHz subcarrier spacing. This means that Common Resource Blocks 0 and 52 remain unused. Similarly, 3GPP TS 38.104 specifies that the 20 MHz channel bandwidth can accommodate up to 24 Resource Blocks when using the 60 kHz subcarrier spacing. This means that Common Resource Blocks 0 and 25 remain unused

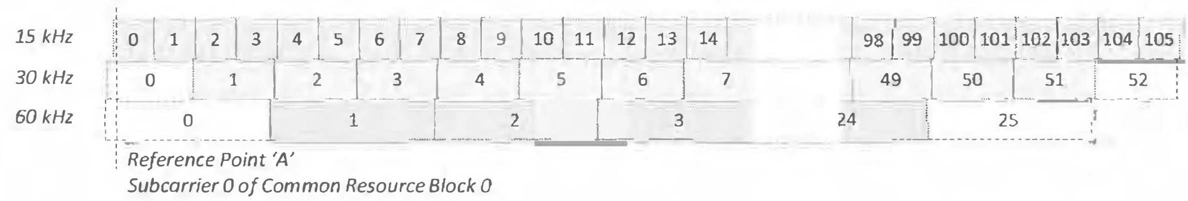


Figure 111 – Example of unused Common Resource Blocks

★ SIB1 provides the *FrequencyInfoDL-SIB* parameter structure presented in Table 38. This parameter structure includes an instance of *scs-SpecificCarrierList* for each of the supported numerologies. The *offsetToCarrier* value specifies the number of Resource Blocks between Point A and subcarrier 0 within the lowest usable Resource Block. The *carrierBandwidth* value specifies the number of Resource Blocks which are available for that numerology

FrequencyInfoDL-SIB		
offsetToPointA	0 to 2199	
scs-SpecificCarrierList	SEQUENCE (1 to 5 instances)	
	offsetToCarrier	0 to 2199
	subcarrierSpacing	15, 30, 60, 120 kHz
	carrierBandwidth	1 to 275

Table 38 – Parameter structure used to specify the set of usable Resource Blocks for each numerology

★ Similar information is provided within SIB1 for the uplink. Alternatively, both the uplink and downlink information can be provided using dedicated signalling

★ 3GPP References: TS 38.211, TS 38.212, TS 38.331

2.3.2 BANDWIDTH PARTS

★ A Bandwidth Part is a set of contiguous Common Resource Blocks. A Bandwidth Part may include all Common Resource Blocks within the channel bandwidth, or a subset of Common Resource Blocks

★ Bandwidth Parts are an important aspect of 5G because they can be used to provide services to UE which do not support the full channel bandwidth, i.e. the Base Station and UE channel bandwidth capabilities do not need to match. For example, a Base Station could be configured with a 400 MHz channel bandwidth, while a UE may only support a 200 MHz channel bandwidth. In this case, the UE can be configured with a 200 MHz Bandwidth Part and can then receive services using a subset of the total channel bandwidth

★ A UE can be configured with up to 4 downlink Bandwidth Parts per carrier and up to 4 uplink Bandwidth Parts per carrier. Only a single Bandwidth Part per carrier can be active in each direction. A UE receives the PDCCH and PDSCH only within an active downlink Bandwidth Part. A UE transmits the PUCCH and PUSCH only within an active uplink Bandwidth Part. A UE can complete measurements outside the active bandwidth part but this can require the use of Measurement Gaps

★ Figure 112 illustrates some example Bandwidth Part allocations for an operator using 2 × 400 MHz RF carriers. These examples illustrate the flexibility which Bandwidth Parts allow when configuring frequency domain resources

- o the first UE is assumed to support the complete 400 MHz channel bandwidth and inter-band Carrier Aggregation
- o the second UE is assumed to support inter-band Carrier Aggregation but a maximum channel bandwidth of 200 MHz
- o the third UE is assumed to support both inter and intra-band Carrier Aggregation with a maximum channel bandwidth of 200 MHz. This combination allows the UE to use all 800 MHz of spectrum simultaneously, i.e. a single active Bandwidth Part per Component Carrier
- o the fourth UE is also assumed to support both inter and intra-band Carrier Aggregation. However, this UE is assumed to support a maximum channel bandwidth of 100 MHz and is configured with multiple Bandwidth Parts per Component Carrier
- o the fifth UE is assumed to support only one of the two operating bands and a maximum channel bandwidth of 200 MHz. For the purposes of this example, the UE is allocated only a single Bandwidth Part to illustrate that the set of allocated Bandwidth Parts do not have to cover the complete channel bandwidth

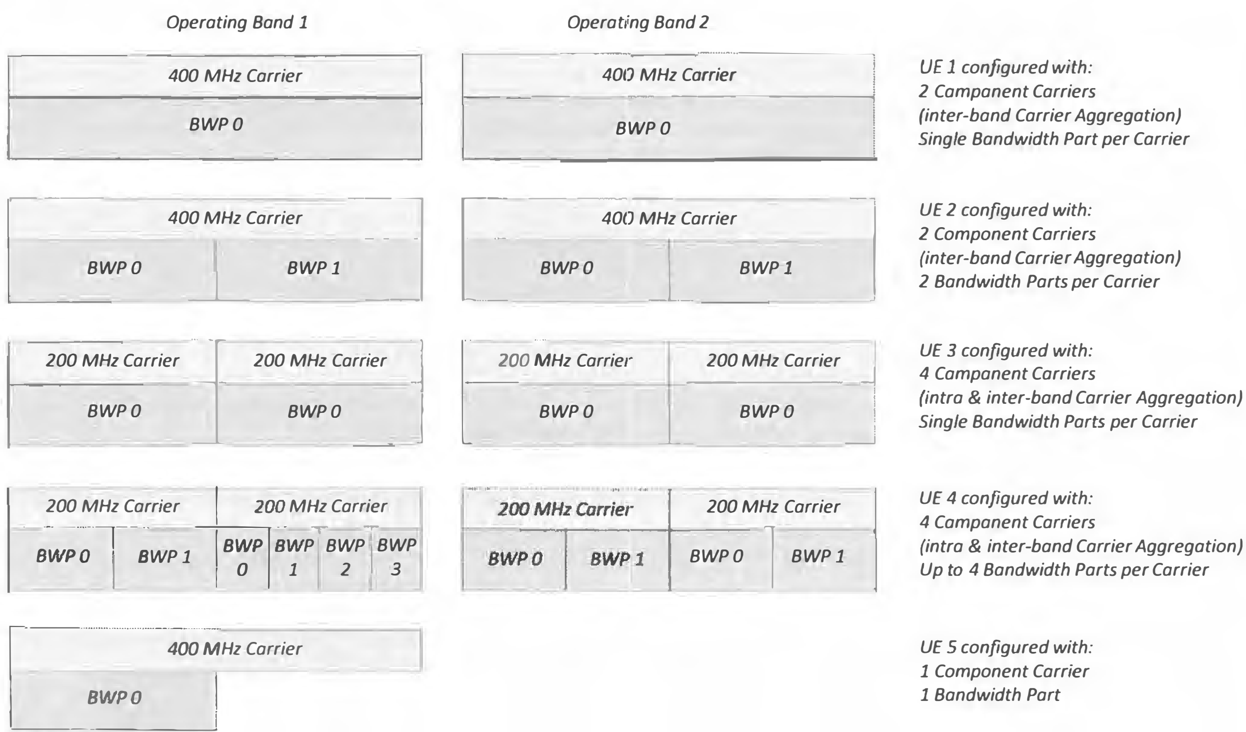


Figure 112 – Example allocation of Component Carriers and Bandwidth Parts

★ Within Figure 112, the second and third UE appear to have very similar configurations, i.e. both UE are configured with 2 × 200 MHz Bandwidth Parts within each operating band. The second UE is configured with 2 Component Carriers and 2 Bandwidth Parts per carrier, whereas the third UE is configured with 4 Component Carriers and 1 Bandwidth Part per Carrier. This difference in configuration has implications upon some lower level procedures and also the RF performance requirements

- o at the MAC layer there is a HARQ entity for each serving cell. The second UE which is configured with 2 Component Carriers would have 2 HARQ entities and HARQ re-transmissions can be switched between Bandwidth Parts by dynamically changing the active Bandwidth Part (field within the PDCCH DCI can be used to change the active Bandwidth Part). The third UE which is configured with 4 Component Carriers would have 4 HARQ entities and HARQ re-transmissions cannot be switched between Component Carriers

- o RF performance requirements such as out-of-band emissions are specified per carrier rather than per Bandwidth Part. This means that the second UE has to achieve its RF requirements at the edge of each 400 MHz carrier, while the third UE has to achieve its RF requirements at the edge of each 200 MHz carrier

★ A UE uses an 'Initial' Bandwidth Part when first accessing a cell. The Initial Downlink Bandwidth Part can be signalled within SIB1 using the *initialDownlinkBWP* parameter structure presented in Table 39. This parameter structure uses the *locationAndBandwidth* information element to specify the set of contiguous Common Resource Blocks belonging to the Initial Downlink Bandwidth Part. The value is coded using Resource Indication Value (RIV) rules with $N_{BWP}^{size} = 275$ (these rules are described in section 3.6.4.2.2 within the context of allocating Resource Blocks for the PDSCH). The RB_{start} value which is derived from the *locationAndBandwidth* value is added to the *offsetToCarrier* value presented in Table 38, i.e. the starting position of the Bandwidth Part is relative to the first usable Resource Block. The *initialDownlinkBWP* parameter structure also specifies the subcarrier spacing to be used for the Bandwidth Part and provides the UE with cell level information for receiving the PDCCH and PDSCH

initialDownlinkBWP			
bwp-Common	genericParameters	locationAndBandwidth	0 to 37949
		subcarrierSpacing	15, 30, 60, 120 kHz
		cyclicPrefix	extended
	pdcch-ConfigCommon	SetupRelease {PDCCH-ConfigCommon}	
	pdsch-ConfigCommon	SetupRelease {PDSCH-ConfigCommon}	

Table 39 – Parameter structure used to configure an Initial Downlink Bandwidth Part

★ The *initialDownlinkBWP* parameter structure can also be provided to the UE using dedicated signalling. If the parameter structure is not provided to a UE then the Initial Downlink Bandwidth Part is defined by the set of Resource Blocks belonging to the Control Resource Set (CORESET) for the Type 0 PDCCH Common Search Space. These Resource Blocks can be deduced from information within the MIB

★ Information regarding the Initial Uplink Bandwidth Part can also be signalled within SIB1 or by using dedicated signalling

★ The Base Station can use dedicated signalling to configure up to 4 Downlink Bandwidth Parts per cell and up to 4 Uplink Bandwidth Parts per cell. The parameter structure used to configure a Downlink Bandwidth Part is presented in Table 40. The Initial Bandwidth Part is referenced using an identity of 0, whereas other Bandwidth Parts are allocated an identity within the range 1 to 4

BWP-Downlink			
bwp-Id	0 to 4		
bwp-Common	genericParameters	locationAndBandiwidth	0 to 37949
		subcarrierSpacing	15, 30, 60, 120 kHz
		cyclicPrefix	extended
	pdcch-ConfigCommon	SetupRelease {PDCCH-ConfigCommon}	
	pdsch-ConfigCommon	SetupRelease {PDSCH-ConfigCommon}	
bwp-Dedicated	pdcch-Config	SetupRelease {PDCCH-Config}	
	pdsch-Config	SetupRelease {PDSCH-Config}	
	sps-Config	SetupRelease {SPS-Config}	
	radioLinkMonitoringConfig	SetupRelease {RadioLinkMonitoringConfig}	

Table 40 – Parameter structure used to configure downlink Bandwidth Part

★ In the case of TDD, an Uplink and Downlink Bandwidth Part with the same *bwp-Id* share the same center frequency

★ The Base Station can dynamically switch the Active Bandwidth Part using the *Bandwidth Part Indicator* field within DCI Formats 0_1 and 1_1. The switching procedure is not instantaneous so the Base Station cannot allocate resources immediately after changing the Active Bandwidth Part. The switching delay is specified within 3GPP TS 38.133

★ A UE can also be configured with a Default Downlink Bandwidth Part (identified using *defaultDownlinkBWP-Id* which points to one of the configured *bwp-id* values). If a UE is not explicitly provided with a Default Downlink Bandwidth Part then it is assumed to be the Initial Downlink Bandwidth Part

★ If a UE is configured with a *bwp-InactivityTimer* then the UE switches back to the Default Downlink Bandwidth part after the inactivity timer has expired while using a non-Default Downlink Bandwidth Part

★ 3GPP References: TS 38.211, TS 38.213, TS 38.331, TS 38.133

2.3.3 PHYSICAL RESOURCE BLOCKS

★ Physical Resource Blocks (PRB) are the Resource Blocks belonging to a Bandwidth Part. They are numbered from 0 upwards, starting from the lower side of the Bandwidth Part. Each Bandwidth Part has its own set of Physical Resource Blocks. The Physical Resource Block number is related to the Common Resource Block number using the expression:

$$n_{CRB} = n_{PRB} + N_{BWP,i}^{start}$$

where, n_{CRB} is the Common Resource Block number, n_{PRB} is the Physical Resource Block number and $N_{BWP,i}^{start}$ is the Common Resource Block where the Bandwidth Part starts

★ Figure 113 illustrates the Physical Resource Blocks belonging to some example Bandwidth Parts. This example assumes that each Common Resource Block 0 belongs to a Bandwidth Part, i.e. each Common Resource Block 0 coincides with a Physical Resource Block 0. As stated in section 2.3.1, Common Resource Block 0 is not always used and may not be associated with a Bandwidth Part nor a Physical Resource Block

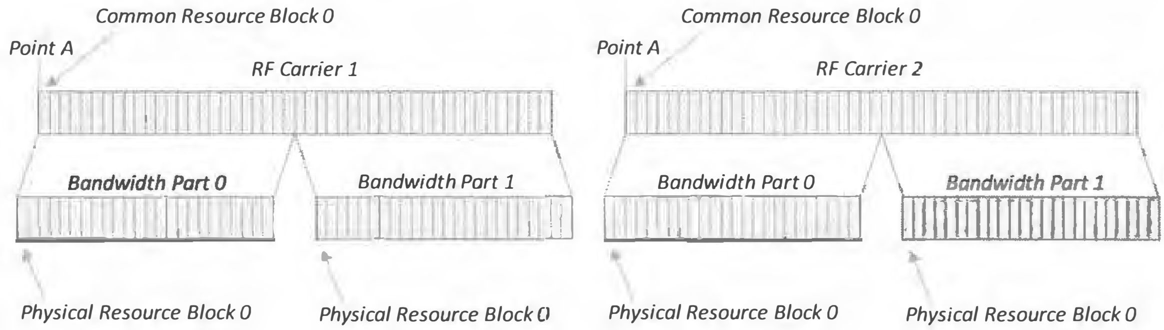


Figure 113 – Physical Resource Blocks belonging to Bandwidth Parts

★ 3GPP References: TS 38.211

2.3.4 VIRTUAL RESOURCE BLOCKS

★ UE are allocated Virtual Resource Blocks (VRB) when receiving PDSCH or PUSCH resource allocations on the PDCCH. These Virtual Resource Blocks are subsequently mapped onto Physical Resource Blocks

★ In the uplink direction, a 'non-interleaved' mapping is always used between the allocated Virtual Resource Blocks and the actual Physical Resource Blocks on the PUSCH. This means that Virtual Resource Block 'n' maps onto Physical Resource Block 'n', i.e. Virtual Resource Blocks are the same as Physical Resource Blocks

★ In the downlink direction, a 'non-interleaved' mapping is always applied if Resource Allocation Type 0 is used to signal the allocation of Virtual Resource Blocks on the PDCCH (Resource Allocation Type 0 is described in section 3.6.4.2.1). If Resource Allocation Type 1 is used then the mapping from Virtual Resource Blocks to Physical Resource Blocks can be either 'non-interleaved' or 'interleaved'

★ The 'interleaved' mapping must be configured by the RRC layer before it can be used. Once it has been configured, the 'VRB to PRB Mapping' field within DCI Formats 1_0 and 1_1 can be used to indicate whether or not the 'interleaved' mapping should be applied. Section 3.6.4.2.2 describes the interleaving function used to map Virtual Resource Blocks onto Physical Resource Blocks

★ 3GPP References: TS 38.211, TS 38.212, TS 38.331

2.4 CHANNEL BANDWIDTHS

★ The Base Station channel bandwidth supports a single RF carrier at the Base Station. The UE channel bandwidth can be equal to, or less than the Base Station channel bandwidth

★ The channel bandwidths for Frequency Range 1 (450 MHz to 6 GHz) are presented in Table 41. Channel bandwidths range from 5 MHz to 100 MHz. The 5 MHz channel bandwidth is only applicable to the 15 and 30 kHz subcarrier spacings, whereas channel bandwidths greater than 50 MHz are only applicable to the 30 and 60 kHz subcarrier spacings

★ Table 41 presents the number of Physical Resource Blocks associated with each channel bandwidth and the corresponding spectrum utilisation. In general, the spectrum utilisation is higher than 4G when making a like-for-like comparison. For example, in the case of 4G, the 20 MHz channel bandwidth supports 100 Resource Blocks with a 15 kHz subcarrier spacing. These 100 Resource Blocks occupy 18 MHz of spectrum which results in a 90% utilisation. The equivalent figure for 5G is visible in Table 41 as 95.4 %. In the case of the 5 MHz channel bandwidth and the 15 kHz subcarrier spacing, 4G and 5G have equal spectrum utilisation, i.e. both technologies support 25 Resource Blocks. 5G supports particularly high spectrum utilisation for the higher channel bandwidths, i.e. exceeding 98 %

★ The high spectrum utilisation means that Physical Resource Blocks are positioned relatively close to the edge of the channel bandwidth. Filters are required to ensure that the vast majority of transmit power remains within the channel bandwidth, i.e. the high spectrum utilisation does not mean that increased levels of unwanted emissions are permitted outside the channel bandwidth

Subcarrier Spacing	Metric	Base Station Channel Bandwidth (MHz)												
		5	10	15	20	25	30	40	50	60	70	80	90	100
15 kHz	PRB	25	52	79	106	133	160	216	270	-	-	-	-	-
	MHz	4.50	9.36	14.22	19.08	23.94	28.80	38.88	48.60					
	% Util.	90.0	93.6	94.8	95.4	95.8	96.0	97.2	97.2					
	Guard (kHz)	242.5	312.5	382.5	452.5	522.5	592.5	552.5	692.5					
30 kHz	PRB	11	24	38	51	65	78	106	133	162	189	217	245	273
	MHz	3.96	8.64	13.68	18.36	23.40	28.08	38.16	47.88	58.32	68.04	78.12	88.2	98.28
	% Util.	79.2	86.4	91.2	91.8	93.6	93.6	95.4	95.8	97.2	97.2	97.7	98.0	98.3
	Guard (kHz)	505	665	645	805	785	945	905	1045	825	965	925	885	845
60 kHz	PRB	-	11	18	24	31	38	51	65	79	93	107	121	135
	MHz		7.92	12.96	17.28	22.32	27.36	36.72	46.80	56.88	66.96	77.04	87.12	97.20
	% Util.		79.2	86.4	86.4	89.3	91.2	91.8	93.6	94.8	95.7	96.3	96.8	97.2
	Guard (kHz)		1010	990	1330	1310	1290	1610	1570	1530	1490	1450	1410	1370

Table 41 – Channel Bandwidths for Frequency Range 1 (450 MHz to 6 GHz)

★ The channel bandwidths for Frequency Range 2 (24.25 GHz to 52.60 GHz) are presented in Table 42. Channel bandwidths range from 50 MHz to 400 MHz. The 400 MHz channel bandwidth is only applicable to the 120 kHz subcarrier spacing. It is expected that 3GPP will add larger channel bandwidths after the release 15 version of the specifications. In the case of Frequency Range 2, the spectrum utilisation is 95 % for all channel bandwidths and subcarrier spacings

Subcarrier Spacing	Metric	Base Station Channel Bandwidth (MHz)			
		50	100	200	400
60 kHz	PRB	66	132	264	-
	MHz	47.52	95.04	190.08	
	%	95.0	95.0	95.0	
	Guard (kHz)	1210	2450	4930	
120 kHz	PRB	32	66	132	264
	MHz	46.08	95.04	190.08	380.16
	%	95.0	95.0	95.0	95.0
	Guard (kHz)	1900	2420	4900	9860

Table 42 – Channel Bandwidths for Frequency Range 2 (24.25 GHz to 52.60 GHz)

★ Table 41 and Table 42 present the guard band requirements associated with each channel bandwidth. These guard band requirements have been calculated using the following equation:

$$Guard\ Band\ (kHz) = \frac{[Channel\ Bandwidth\ (kHz) - (12 \times PRB \times SCS)]}{2} - \frac{SCS}{2}$$

where, 'PRB' is the number of Physical Resource Blocks within the Channel Bandwidth and 'SCS' is the subcarrier spacing. The value of SCS/2 is subtracted because all channel bandwidths have an even number of subcarriers. An even number of subcarriers means that the central point is between two subcarriers, whereas in reality the center frequency of the channel corresponds to the center frequency of a specific subcarrier. This means that there are 'N-1' subcarriers to one side of the central subcarrier and 'N' subcarriers to the other side of the central subcarrier. The resultant pattern is illustrated in Figure 114 (section 2.5.1)

★ Table 41 and Table 42 indicate which channel bandwidths can be used within each Frequency Range. 3GPP also specifies a specific set of channel bandwidths for each operating band. These channel bandwidths are presented in Table 24 and Table 26 within section 1.19.2

★ An initial and optimistic view of throughput can be quantified based upon the Resource Block allocations presented in Table 41 and Table 42. These figures are not realistic but indicate the absolute upper limit for maximum throughput. Table 43 presents a set of results for Frequency Range 1 assuming a single MIMO layer, the normal cyclic prefix, a coding rate of 1 and zero overhead from the control channels and reference signals. These figures can be scaled upwards by factors of 2, 4 and 8 for 2×2, 4×4 and 8×8 MIMO respectively

Subcarrier Spacing	Modulation	Base Station Channel Bandwidth (MHz)												
		5	10	15	20	25	30	40	50	60	70	80	90	100
15 kHz	QPSK	8.4	17.5	26.5	35.6	44.7	53.8	72.6	90.7	-	-	-	-	-
	16QAM	16.8	34.9	53.1	71.2	89.4	107.5	145.2	181.4					
	64QAM	25.2	52.4	79.6	106.8	134.1	161.3	217.7	272.2					
	256QAM	33.6	69.9	106.2	142.5	178.8	215.0	290.3	362.9					
30 kHz	QPSK	7.4	16.1	25.5	34.3	43.7	52.4	71.2	89.4	108.9	127.0	145.8	164.6	183.5
	16QAM	14.8	32.3	51.1	68.5	87.4	104.8	142.5	178.8	217.7	254.0	291.6	329.3	366.9
	64QAM	22.2	48.4	76.6	102.8	131.0	157.2	213.7	268.1	326.6	381.0	437.5	493.9	550.4
	256QAM	29.6	64.5	102.1	137.1	174.7	209.7	284.9	357.5	435.5	508.0	583.3	658.6	733.8
60 kHz	QPSK	-	14.8	24.2	32.3	41.7	51.1	68.5	87.4	106.2	125.0	143.8	162.6	181.4
	16QAM		29.6	48.4	64.5	83.3	102.1	137.1	174.7	212.4	250.0	287.6	325.2	362.9
	64QAM		44.4	72.6	96.8	125.0	153.2	205.6	262.1	318.5	375.0	431.4	487.9	544.3
	256QAM		59.1	96.8	129.0	166.7	204.3	274.2	349.4	424.7	500.0	575.2	650.5	725.8

Table 43 – Upper limits for Physical Layer Throughput per MIMO layer (Mbps)
(normal cyclic prefix, all Resource Elements transfer data, coding rate 1, Frequency Range 1)

★ Similarly, Table 44 presents a set of results for Frequency Range 2 assuming a single MIMO layer, the normal cyclic prefix, a coding rate of 1 and zero overhead from the control channels and reference signals. These figures can be scaled upwards for multi-layer MIMO transmission

Subcarrier Spacing	Metric	Base Station Channel Bandwidth (MHz)			
		50	100	200	400
60 kHz	QPSK	88.7	177.4	354.8	-
	16QAM	177.4	354.8	709.6	
	64QAM	266.1	532.2	1064.4	
	256QAM	354.8	709.6	1419.3	
120 kHz	QPSK	86.0	177.4	354.8	709.6
	16QAM	172.0	354.8	709.6	1419.3
	64QAM	258.0	532.2	1064.4	2128.9
	256QAM	344.1	709.6	1419.3	2838.5

Table 44 – Upper limits for Physical Layer Throughput per MIMO layer (Mbps)
(normal cyclic prefix, all Resource Elements transfer data, coding rate 1, Frequency Range 2)

★ None of the tables in this section include the 240 kHz subcarrier spacing. The 240 kHz subcarrier spacing is only applicable to the Synchronisation Signals / Physical Broadcast Channel (SS/PBCH) Block so is not directly associated with a specific channel bandwidth. The 240 kHz subcarrier spacing is specified for the SS/PBCH belonging to Frequency Range 2 so is indirectly linked to the larger channel bandwidths

★ 3GPP References: TS 38.211, TS 38.212, TS 38.331

2.5 FREQUENCY RASTER

★ The frequency raster defines the spacing between the allowed center frequencies of a transmission. For example, a frequency raster of 100 kHz would allow signals to be transmitted using center frequencies of 1940.1 MHz, 1940.2 MHz, 1940.3 MHz, etc

★ 4G uses a single frequency raster for the channel bandwidth, the Synchronisation Signals and the PBCH. This is possible because the Synchronisation Signals and PBCH are always positioned at the center of the channel bandwidth, i.e. there is a one-to-one relationship between the position of the channel bandwidth and the position of the Synchronisation Signals and PBCH. The frequency raster used by 4G is 100 kHz and is known as the channel raster

★ In the case of 5G, separate frequency rasters have been specified for the channel bandwidth and the Synchronisation Signals / Physical Broadcast Channel (SS/PBCH) Block. The channel raster has relatively high resolution to allow flexibility when configuring the position of the channel within the allocated spectrum. The SS/PBCH Block raster (known as the synchronisation raster) has relatively low resolution to reduce the number of positions which a UE must check when completing a band scan, i.e. the band scan procedure becomes faster and more efficient

★ Having separate channel and synchronisation rasters means that the position of the SS/PBCH Block within the channel bandwidth is not fixed. With the exception of the smaller channel bandwidths there is a choice of SS/PBCH Block positions within the channel bandwidth. Cells using larger channel bandwidths can transmit multiple SS/PBCH Blocks distributed across the channel bandwidth

2.5.1 CHANNEL RASTER

★ The channel raster defines the spacing between the allowed center frequencies of a channel. The center frequency defines the frequency of a specific subcarrier, i.e. one subcarrier is selected to be the 'central' subcarrier. All channel bandwidths have an even number of subcarriers (12 × number of Resource Blocks) so it is not possible to have an equal number of subcarriers either side of the 'central' subcarrier. Instead, the 'central' subcarrier has 'N' subcarriers to one side, and 'N – 1' subcarriers to the other side. This concept is illustrated in Figure 114

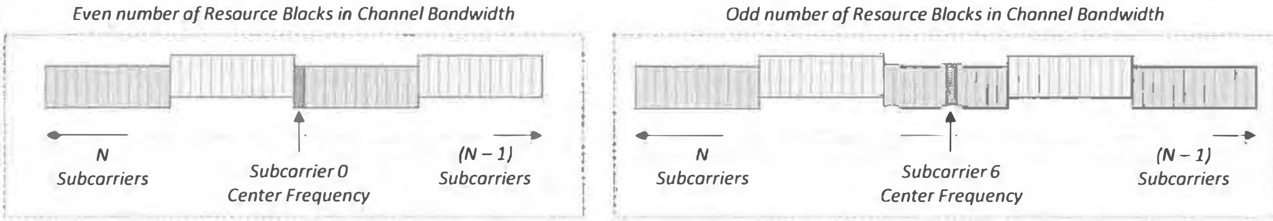


Figure 114 – Central subcarrier for even and odd number of Resource Blocks within Channel Bandwidth

★ 3GPP has specified a global frequency raster which is used as a foundation for the actual channel rasters. A channel raster can include all frequencies belonging to the global frequency raster, or a subset of the frequencies belonging to the global frequency raster. The global frequency raster and the set of channel rasters are illustrated in Figure 115

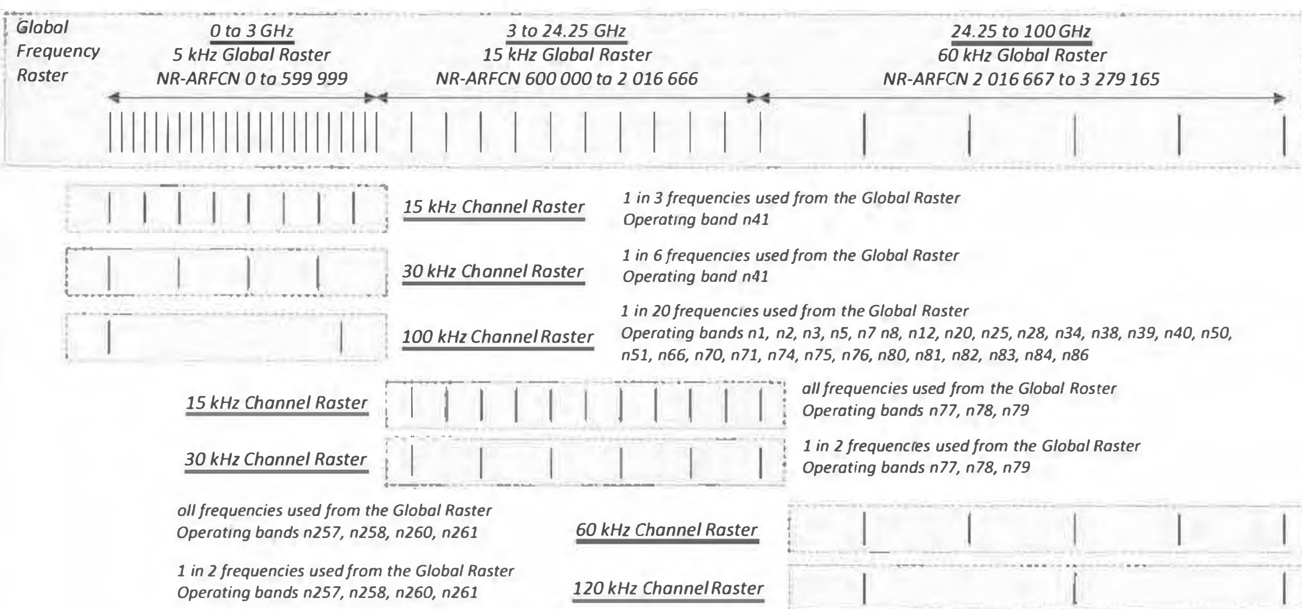


Figure 115 – Channel rasters based upon the Global Frequency Raster

★ The global frequency raster is defined in 3 sections to allow the spacing between raster entries to increase for the higher operating bands. This helps to prevent the range of New Radio Absolute Radio Frequency Channel Numbers (NR-ARFCN) becoming too large. Every entry within the global frequency raster has an associated NR-ARFCN

★ Figure 115 illustrates that the global frequency raster uses spacings of 5, 15 and 60 kHz, while the channel rasters use spacings of 15, 30, 60, 100 and 120 kHz. With the exception of operating band n41, the 100 kHz raster has been allocated to all operating bands below 3 GHz. The benefit of this raster is improved coexistence with 4G. 4G uses a 100 kHz raster and specifying the same raster for both technologies allows them to share the same set of center frequencies

★ The 15, 30, 60 and 120 kHz channel rasters are known as subcarrier based rasters. These rasters provide the benefit of improved compatibility with the subcarrier spacing. In particular, when using intra-band Carrier Aggregation, they allow a 0 Hz guard band between Component Carriers

★ The global frequency raster is used to calculate the NR-ARFCN according to the following equation and the set of parameters presented in Table 45 (all frequency based parameters are in MHz within the equation):

$$\text{NR-ARFCN} = N_{REF\text{-}Offs} + (\text{Center Frequency} - F_{REF\text{-}Offs}) \,/\, \Delta F_{Global}$$

Frequency Range	ΔF_{Global}	$F_{REF\text{-}Offs}$ (MHz)	$N_{REF\text{-}Offs}$	Range of NR-ARFCN
0 to 3 GHz	5 kHz	0	0	0 to 599 000
3 to 24.25 GHz	15 kHz	3 000	600 000	600 000 to 2 016 666
24.25 to 100 GHz	60 kHz	24 250.08	2 016 667	2 016 667 to 3 279 165

Table 45 – Parameters used to calculate the NR-ARFCN

★ The channel raster will not use all NR-ARFCN values if it only includes a subset of the frequencies belonging to the global frequency raster, e.g. if the global frequency raster is 5 kHz while the channel raster is 100 kHz, the NR-ARFCN will have a step size of 20

★ The channel raster and the associated set of NR-ARFCN are presented in Table 46 for a subset of operating bands

Operating Band	ΔF_{Global}	ΔF_{Raster}	Uplink Band (MHz)	Downlink Band (MHz)
n1	5 kHz	100 kHz	384 000 to 396 000, step 20	422 000 to 434 000, step 20
n2		100 kHz	370 000 to 382 000, step 20	386 000 to 398 000, step 20
n3		100 kHz	342 000 to 357 000, step 20	361 000 to 376 000, step 20
n5		100 kHz	164 800 to 169 800, step 20	173 800 to 178 800, step 20
n8		100 kHz	176 000 to 183 000, step 20	185 000 to 192 000, step 20
n20		100 kHz	166 400 to 172 400, step 20	158 200 to 164 200, step 20
n38		100 kHz	514 000 to 524 000, step 20	
n41		15 kHz	499 200 to 537 999, step 3	
		30 kHz	499 200 to 537 996, step 6	
n66		100 kHz	342 000 to 356 000, step 20	422 000 to 440 000, step 20
n70		100 kHz	339 000 to 342 000, step 20	399 000 to 404 000, step 20
n75		100 kHz	Not Applicable	286 400 to 303 400, step 20
n76		100 kHz		285 400 to 286 400, step 20
n77	15 kHz	15 kHz	620 000, to 680 000, step 1	
		30 kHz	620 000, to 680 000, step 2	
n78		15 kHz	620 000 to 653 333, step 1	
		30 kHz	620 000 to 653 332, step 2	
n80	5 kHz	100 kHz	342 000 to 357 000, step 20	Not Applicable
n81		100 kHz	176 000 to 183 000, step 20	
n257	60 kHz	60 kHz	2 054 167 to 2 104 166, step 1	
		120 kHz	2 054 167 to 2 104 165, step 2	
n258		60 kHz	2 016 667 to 2 070 833, step 1	
		120 kHz	2 016 667 to 2 070 831, step 2	

Table 46 – Channel raster and range of NR-ARFCN for a subset of operating bands

★ 3GPP allows a special case for the Supplemental Uplink (SUL) and the uplink of FDD operating bands - center frequencies can be increased by 7.5 kHz. This is an optional offset which can be applied depending upon the deployment scenario. The objective of this 7.5 kHz offset is to allow coexistence with legacy 4G uplink transmissions. The uplink of 4G applies a 7.5 kHz offset when generating the SC-FDMA waveform to avoid having a 0 Hz subcarrier (also known as the DC subcarrier, or null subcarrier). The uplink of 5G does not apply this offset when generating its waveform so a 7.5 kHz frequency shift is required to achieve subcarrier alignment with 4G (assuming that 5G uses the 15 kHz subcarrier spacing). Dynamic Spectrum Sharing with 4G is described in section 17

★ 3GPP Reference: TS 38.104

2.5.2 SYNCHRONISATION RASTER

★ The synchronisation raster defines the set of allowed center frequencies for the Synchronisation Signal / Physical Broadcast Channel (SS/PBCH) Block. The SS/PBCH Block has a bandwidth of 20 Resource Blocks and must be contained within the bandwidth of the downlink channel. The SS/PBCH does not need to be Resource Block aligned with the downlink channel but must be subcarrier aligned to maintain orthogonality

★ The center frequency of the SS/PBCH Block is defined as the frequency of subcarrier 0 belonging to Resource Block 10. This definition is illustrated in Figure 116. The SS/PBCH Block occupies a total of 240 subcarriers in the frequency domain so there are 120 subcarriers below the central subcarrier and 119 subcarriers above the central subcarrier

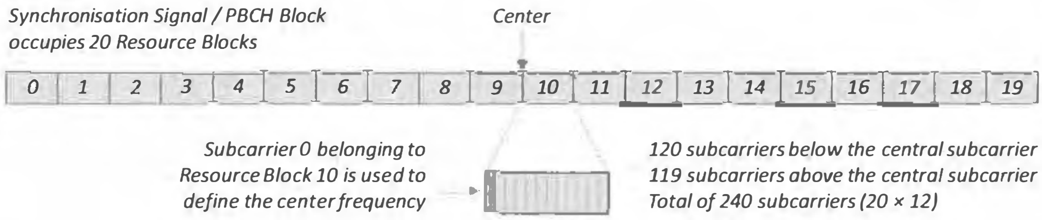


Figure 116 – Central subcarrier belonging to Synchronisation Signal (SS) / PBCH Block

★ The SS/PBCH Block is used by the UE during the initial cell search procedure. A key requirement for the initial cell search procedure is to minimise delay. This can be achieved by defining a sparse synchronisation raster to limit the number of frequency domain positions that a UE must search for the SS/PBCH Block

★ Consider the example of a 5 MHz channel bandwidth occupying 25 Resource Blocks with a 15 kHz subcarrier spacing and using the 100 kHz channel raster. Figure 117 illustrates two consecutive channel positions on the 100 kHz channel raster. It must be possible to configure an SS/PBCH transmission within both channels. The maximum possible spacing is achieved when the SS/PBCH block is located at the lower end of the first channel position, and the upper end of the second channel position. This leads to a maximum possible spacing of 1 MHz

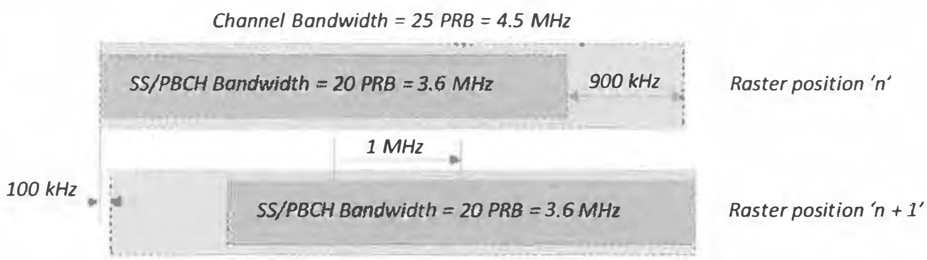


Figure 117 – Central subcarrier belonging to Synchronisation Signal (SS) / PBCH Block

★ The solution adopted by 3GPP is presented in Table 47. A center frequency belonging to the synchronisation raster is identified by its Global Synchronisation Channel Number (GSCN), i.e. the GSCN is equivalent to the NR-ARFCN used by the channel raster. The synchronisation raster is defined in 3 sections to allow the spacing between raster entries to increase for the higher operating bands

★ Figure 117 illustrates that the synchronisation raster should not have a spacing greater than 1 MHz when considering the 5 MHz channel bandwidth. The 5 MHz channel bandwidth is only supported within operating bands below 3 GHz so it is only necessary to consider the first frequency range. This frequency range supports raster entries which are spaced by 50 kHz, 150 kHz and 250 kHz so the requirement for a maximum spacing of 1 MHz is satisfied

★ The first frequency range uses both 'N' and 'M' variables to calculate the set of raster entries and the corresponding GSCN. The calculations for this frequency range are relatively complex because there is a requirement to support the 100 kHz channel raster. This channel raster poses an additional challenge in terms of maintaining subcarrier alignment between the main channel and the SS/PBCH because 100 kHz is not a multiple of 15 kHz. Operating bands above 3 GHz do not use the 100 kHz channel raster and so this additional challenge does not exist

Frequency Range	SS/PBCH Block Frequency Position	Range of N	Range of M	GSCN	Range of GSCN
0 to 3 GHz	N × 1.2 MHz + M × 50 kHz	1 to 2944	1, 3, 5	3N + (M-3)/2	2 to 7498
3 to 24.25 GHz	2400 MHz + N × 1.44 MHz	0 to 14756	-	7499 + N	7499 to 22255
24.25 to 100 GHz	24250.08 MHz + N × 17.28 MHz	0 to 4383	-	22256 + N	22256 to 26639

Table 47 – Parameters used to calculate the Global Synchronisation Channel Number (GSCN)

★ Figure 118 illustrates the use of the 'N' and 'M' variables to maintain subcarrier alignment between the main channel and the SS-PBCH when using the 100 kHz channel raster. This example is based upon the 5 MHz channel bandwidth which accommodates 25 Resource Blocks occupying 4.5 MHz. The first channel raster entry has the SS/PBCH positioned to the far right of the 4.5 MHz. In this case the frequency offset between the center of the channel and the center of the SS/PBCH is (4.5 – 3.6 MHz) / 2 = 450 kHz. This is a multiple of 15 kHz so subcarrier alignment is achieved

★ The second channel raster entry shifts the channel by 100 kHz. If the first SS/PBCH position is re-used then the frequency offset between the center of the channel and the center of the SS/PBCH would be 350 kHz. This is not a multiple of 15 kHz and so subcarrier alignment would be lost. Instead, the value of 'M' is increased from '1' to '3' to shift the SS/PBCH by 100 kHz and thus maintain the 450 kHz frequency offset. Similarly, for the third channel raster entry the value of 'M' is increased from '3' to '5' to maintain the 450 kHz frequency offset

★ The fourth channel raster entry shifts the channel by 300 kHz. 'M' cannot be increased from '5' to '7' but the original value of '1' can be re-used. In this case the frequency offset between the center of the channel and the center of the SS/PBCH is 150 kHz. This is a multiple of 15 kHz so subcarrier alignment is achieved

★ This pattern continues until the channel raster has introduced frequency shifts of 900, 1000 and 1100 kHz. In these cases, the SS/PBCH is aligned with the lower edge of the channel bandwidth. This means that the next channel raster position (1200 kHz frequency shift) requires the value of 'N' to be incremented. Once 'N' has been incremented, the pattern repeats for the next 12 channel raster entries

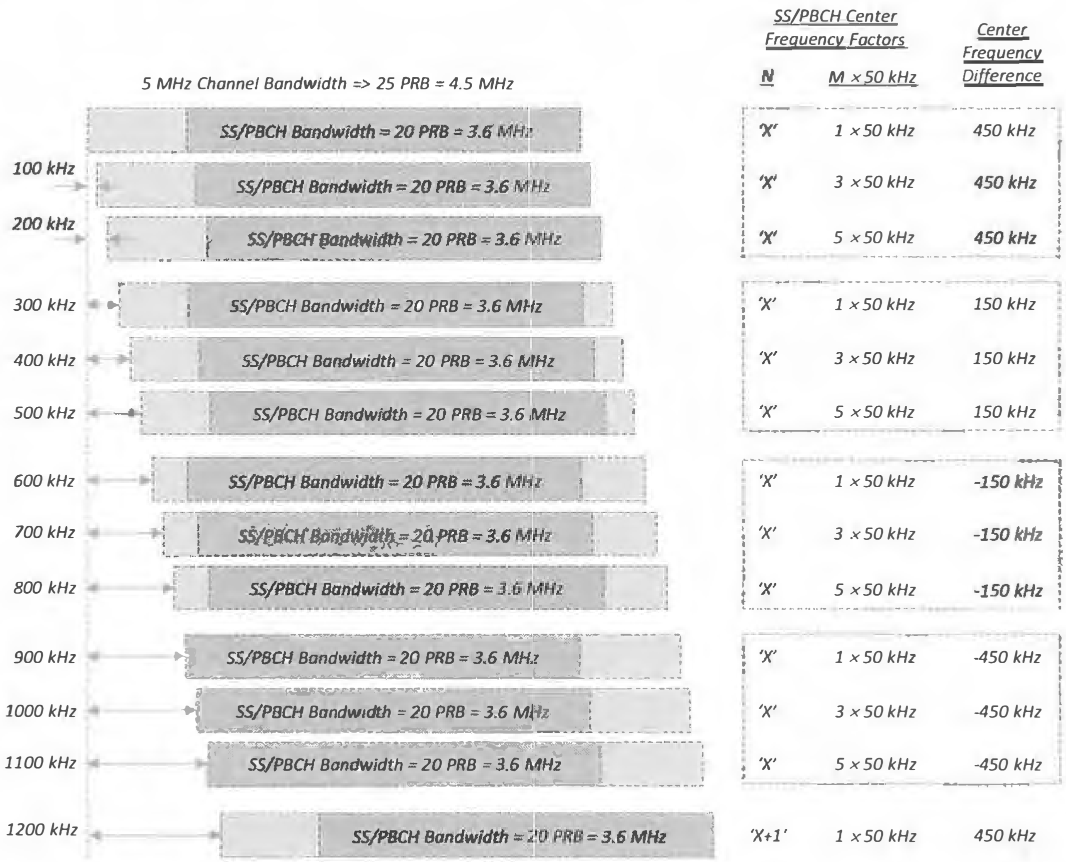


Figure 118 – Synchronisation raster entries which maintain subcarrier alignment with 100 kHz channel raster

★ This example helps to highlight the planning requirements for the GSCN. The GSCN should be selected to ensure that:

- o the bandwidth of the SS/PBCH is within the transmission bandwidth belonging to the channel bandwidth
- o subcarrier alignment is achieved between the SS/PBCH and the Resource Blocks belonging to the channel

★ Returning to Table 47, the second frequency range uses a synchronisation raster spacing of 1.44 MHz. The operating bands within this frequency range use a 30 kHz subcarrier spacing for the SS/PBCH. This means that the SS/PBCH occupies 7.2 MHz, while there are 24 Resource Blocks spanning 8.64 MHz within a 10 MHz channel (the operating bands within the second frequency range have a minimum channel bandwidth of 10 MHz rather than 5 MHz). The 1.44 MHz raster spacing is then calculated as 8.64 – 7.2 = 1.44 MHz

★ A similar calculation can be completed for the third frequency range based upon an SS/PBCH subcarrier spacing of 120 kHz generating an SS/PBCH bandwidth of 28.8 MHz. The minimum channel bandwidth within this frequency range is 50 MHz which includes 32 Resource Blocks spanning 46.08 MHz when assuming the 120 kHz subcarrier spacing. The synchronisation raster spacing is then calculated as 46.08 – 28.8 = 17.28 MHz

★ Table 48 presents the SS/PBCH subcarrier spacings which are used for each operating band within Frequency Range 1 (450 MHz to 6 GHz). Operating bands n77, n78 and n79 belong to the second frequency range within Table 47. The remaining operating bands belong to the first frequency range

★ Table 49 presents the SS/PBCH subcarrier spacings which are used for each operating band within Frequency Range 2 (24.25 GHz to 52.60 GHz). In this case, all operating bands can use SS/PBCH subcarrier spacings of either 120 or 240 kHz

Operating Band	Duplex Mode	Uplink Band (MHz)	Downlink Band (MHz)	SS/PBCH Subcarrier Spacing	Range of GSCN
n1	FDD	1920 - 1980	2110 - 2170	15 kHz	5279 to 5419, step 1
n2	FDD	1850 - 1910	1930 - 1990	15 kHz	4829 to 4969, step 1
n3	FDD	1710 - 1785	1805 - 1880	15 kHz	4517 to 4693, step 1
n5	FDD	824 - 849	869 - 894	15 kHz	2177 to 2230, step 1
				30 kHz	2183 to 2224, step 1
n7	FDD	2500 - 2570	2620 - 2690	15 kHz	6554 to 6718, step 1
n8	FDD	880 - 915	925 - 960	15 kHz	2318 to 2395, step 1
n12	FDD	699 - 716	729 - 746	15 kHz	1828 to 1858, step 1
n20	FDD	832 - 862	791 - 821	15 kHz	1982 to 2047, step 1
n25	FDD	1850 - 1915	1930 - 1995	15 kHz	4829 to 4981, step 1
n28	FDD	703 - 748	758 - 803	15 kHz	1901 to 2002, step 1
n34	TDD	2010 - 2025		15 kHz	5030 to 5056, step 1
n38	TDD	2570 - 2620		15 kHz	6431 to 6544, step 1
n39	TDD	1880 - 1920		15 kHz	4706 to 4795, step 1
n40	TDD	2300 - 2400		15 kHz	5756 to 5995, step 1
n41	TDD	2496 - 2690		15 kHz	6246 to 6717, step 3
				30 kHz	6252 to 6714, step 3
n50	TDD	1432 - 1517		15 kHz	3584 to 3787, step 1
n51	TDD	1427 - 1432		15 kHz	3572 to 3574, step 1
n66	FDD	1710 - 1780	2110 - 2200	15 kHz	5279 to 5494, step 1
				30 kHz	5285 to 5488, step 1
n70	FDD	1695 - 1710	1995 - 2020	15 kHz	4993 to 5044, step 1
n71	FDD	663 - 698	617 - 652	15 kHz	1547 to 1624, step 1
n74	FDD	1427 - 1470	1475 - 1518	15 kHz	3692 to 3790, step 1
n75	SDL	Not Applicable	1432 - 1517	15 kHz	3584 to 3787, step 1
n76	SDL	Not Applicable	1427 - 1432	15 kHz	3572 to 3574, step 1
n77	TDD	3300 - 4200		30 kHz	7711 to 8329, step 1
n78	TDD	3300 - 3800		30 kHz	7711 to 8051, step 1
n79	TDD	4400 - 5000		30 kHz	8480 to 8880, step 16

Table 48 – SS/PBCH subcarrier spacings and GSCN ranges for Frequency Range 1 (450 MHz to 6 GHz)

Operating Band	Duplex Mode	Uplink Band (MHz)	Downlink Band (MHz)	SS/PBCH Subcarrier Spacing	Range of GSCN
n257	TDD	26 500 - 29 500		120 kHz	22388 to 22558, step 1
				240 kHz	22390 to 22556, step 2
n258	TDD	24 250 - 27 500		120 kHz	22257 to 22443, step 1
				240 kHz	22258 to 22442, step 2
n260	TDD	37 000 - 40 000		120 kHz	22995 to 23166, step 1
				240 kHz	22996 to 23164, step 2
n261	TDD	27 500 – 28 350		120 kHz	22446 to 22492, step 1
				240 kHz	22446 to 22490, step 2

Table 49 – SS/PBCH subcarrier spacings and GSCN ranges for Frequency Range 2 (24.25 GHz to 52.60 GHz)

- ★ It should be noted that operating band n41 uses a GSCN step size of 3 rather than 1. This results from operating band n41 having a minimum channel bandwidth of 10 MHz rather than 5 MHz. Similarly, operating band n79 uses a GSCN step size of 16 rather than 1. This results from operating band n79 having a minimum channel bandwidth of 40 MHz rather than 10 MHz
- ★ The Supplemental Uplink (SUL) bands are not included within Table 48 because these bands are only used for uplink transmissions and do not include any SS/PBCH
- ★ A single channel can include multiple SS/PBCH transmissions distributed across the channel bandwidth. This could be applied when the channel bandwidth is divided into multiple Bandwidth Parts. In that case, it is useful to have an SS/PBCH within each Bandwidth Part because the UE uses the SS/PBCH for downlink measurements such as RSRP and RSRQ. The inclusion of multiple SS/PBCH transmissions could also help to reduce the cell search time
- ★ The SS/PBCH transmissions used for the cell search procedure are always positioned using the synchronisation raster, i.e. the synchronisation raster defines the set of positions that a UE will check when completing a band scan. However, the SS/PBCH can also be transmitted at positions away from the synchronisation raster. These additional transmissions can be used for other purposes. For example, a UE can be provided with information regarding the location of additional SS/PBCH when configuring a Measurement Object for RRC Connected Mode measurements. These additional SS/PBCH can then be used to trigger mobility procedures. The location of the additional SS/PBCH is signalled used an NR-ARFCN so the position follows the pattern of the global channel raster and is not restricted to the GSCN frequency raster
- ★ 3GPP Reference: TS 38.104, TR 38.817

2.6 ANTENNA PORTS AND QUASI CO-LOCATION

★ Transmissions sharing the same antenna port experience the same propagation channel. In some cases, it is important that transmissions share the same antenna port. In other cases, it is important that transmissions use different antenna ports. Examples include:

- o the PDSCH physical channel and its Demodulation Reference Signal (DMRS) share the same antenna port. This allows the UE to deduce the propagation channel from the DMRS and use that information to help decode the information content from the PDSCH
- o MIMO is able to transmit multiple parallel streams of data using the same time and frequency resources. This is made possible by transmitting each stream on a different antenna port to ensure that each stream experiences a different propagation channel. The receiver is then able to differentiate each stream and complete decoding

★ It is important to differentiate between logical 'antenna ports' and physical 'antenna elements'. Specific transmissions use specific antenna ports and then those antenna ports are mapped onto one or more physical antenna elements. For example, the Synchronisation Signals, the PBCH and the PBCH Demodulation Reference Signal use antenna port 4000, i.e. all three transmissions share the same antenna port and so are transmitted such that they experience the same propagation channel. Antenna port 4000 is mapped onto a specific set of physical antenna elements which radiate across the air-interface

★ In some cases, there is a one-to-one mapping between antenna port and physical antenna element. This may be done when using the lower operating bands which do not require beamforming (beamforming requires multiple physical antenna elements). As an example, consider the case of a single cross-polar antenna used for downlink 2x2 MIMO. In this case, the PDSCH and its Demodulation Reference Signals (DMRS) can use antenna ports 1000 and 1001. Antenna port 1000 is mapped onto one physical antenna element, while antenna port 1001 is mapped onto the other physical antenna element. This example is illustrated in Figure 119

★ From the UE perspective, there are two downlink transmissions – one PDSCH and its DMRS associated with antenna port 1000, and another PDSCH and its DMRS associated with antenna port 1001. The UE does not require knowledge of which physical antenna elements were used for the two transmissions

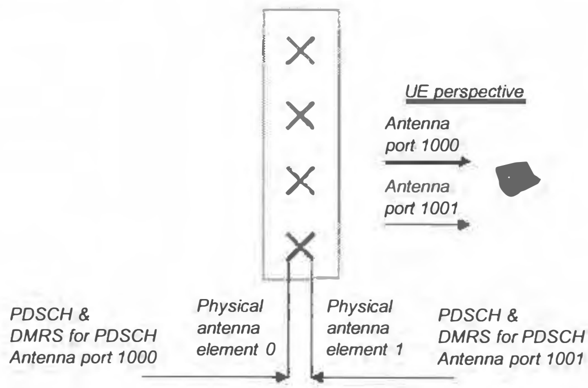


Figure 119 – Example of one-to-one mapping between antenna port and physical antenna element

★ In other cases, there is a one-to-many mapping between antenna port and physical antenna element. This may be done when using the higher operating bands which require beamforming. Beamforming uses multiple physical antenna elements to direct the downlink transmissions towards a specific UE. This is typically achieved using an antenna array consisting of multiple columns of cross-polar antenna elements. This scenario is illustrated in Figure 120. Beamforming principles are described in section 1.21.

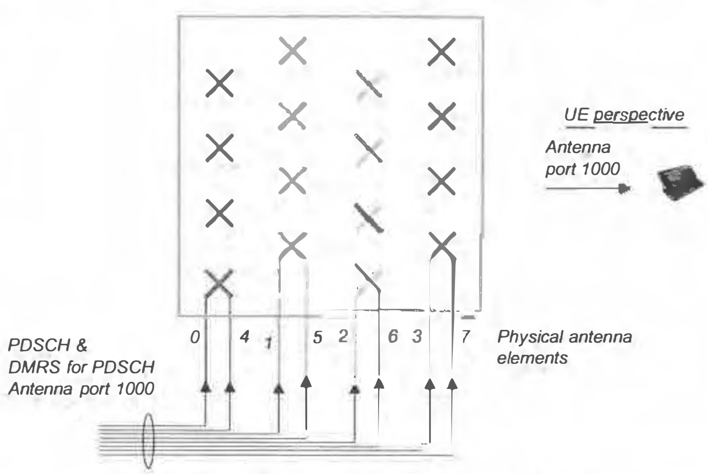


Figure 120 – Example of one-to-many mapping between antenna port and physical antenna elements

★ The example shown in Figure 120 illustrates an antenna array with 8 physical antenna elements (4 columns of cross-polar pairs). The PDSCH and its DMRS are using antenna port 1000 which is mapped onto all 8 of the physical antenna elements. Using a relatively large number of physical antenna elements per antenna port increases the beamforming gain and directivity. From the UE perspective, there is a single downlink transmission originating from antenna port 1000

★ Antenna ports can be viewed as being virtual because they represent the downlink transmission from the UE perspective rather than the actual downlink transmission from physical antenna elements at the Base Station

★ Another example of the mapping between antenna ports and physical antenna elements is illustrated in Figure 121. This example is based upon an antenna array being used for downlink 2×2 MIMO. In this case, antenna ports 1000 and 1001 are each mapped onto multiple physical antenna elements. This provides beamforming but with less gain and directivity than the example in Figure 120 because there are fewer physical antenna elements per antenna port

★ From the UE perspective, the examples in Figure 119 and Figure 121 are the same, i.e. in both cases, the UE receives antenna ports 1000 and 1001. The beamforming helps to improve the link budget but is transparent to the UE, i.e. the UE does not require any explicit knowledge of the beamforming at the Base Station

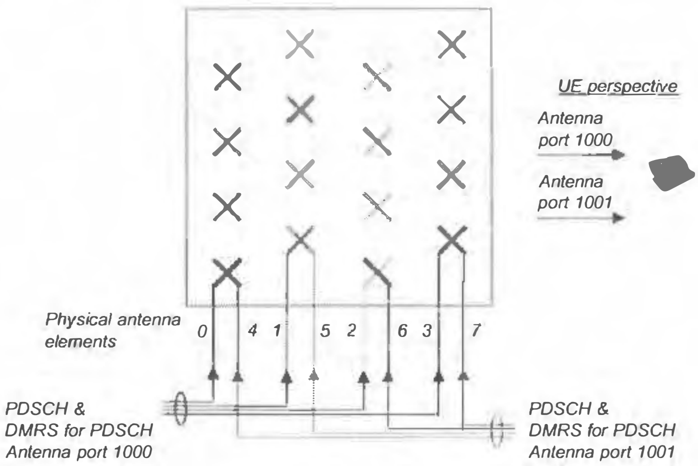


Figure 121 – Example of mapping two antenna ports onto multiple physical antenna elements

★ So far this section has explained that transmissions sharing the same antenna port experience the same radio channel, whereas transmissions using different antenna ports experience different radio channels. There are also scenarios where transmissions using different antenna ports experience radio channels which share some common characteristics. In this case, the antenna ports are said to be Quasi Co-Located (QCL)

★ The radio channel characteristics which may be common across different antenna ports include {Doppler Shift; Doppler Spread; Average Delay; Delay Spread; Spatial Receiver Parameters}. These are known as 'large scale' radio channel characteristics. In contrast, antenna ports are always assumed to have different 'small scale' radio channel characteristics, i.e. different fast fading

★ The term 'Spatial Receiver Parameters' refers to properties associated with the downlink received signal Angle of Arrival (AoA) at the UE, e.g. dominant AoA and average AoA

★ 3GPP introduced the concept of QCL to help the UE with its channel estimation, frequency offset estimation and synchronisation procedures. For example, if two antenna ports are categorised as being QCL in terms of Delay Spread then the UE can determine the delay spread for one antenna port and then apply the result to both antenna ports. This avoids the UE having to determine the delay spread separately for each antenna port

★ QCL antenna ports may be geographically separated. For example, the physical antenna elements may belong to different Transmit / Receive Points (TRP). This could be the case when using Co-ordinated MultiPoint (CoMP) Transmission

★ 3GPP has specified four types of QCL to indicate which large scale channel characteristics are common across the set of QCL antenna ports. These four types of QCL are labelled A, B, C and D:

- QCL Type A: {Doppler Shift; Doppler Spread; Average Delay, Delay Spread}
- QCL Type B: {Doppler Shift; Doppler Spread}
- QCL Type C: {Doppler Shift; Average Delay}
- QCL Type D: {Spatial Receiver Parameters}

★ QCL can be used to support the reception of both the PDSCH and the PDCCH. In both cases, the Base Station can indicate that the antenna port used by a specific Synchronisation Signal / Physical Broadcast Channel (SS/PBCH) Block is QCL with the antenna port used by the PDSCH or the PDCCH. Alternatively, the Base Station can indicate that the antenna port used by a specific Channel State Information (CSI) Reference Signal is QCL with the antenna port used by the PDSCH or the PDCCH

★ The Base Station uses a combination of RRC signalling, MAC Control Element signalling and PDCCH Downlink Control Information to inform the UE of which SS/PBCH Block or CSI Reference Signal can be assumed to be QCL with the PDSCH and PDCCH. This hierarchy of signalling is illustrated in Figure 122

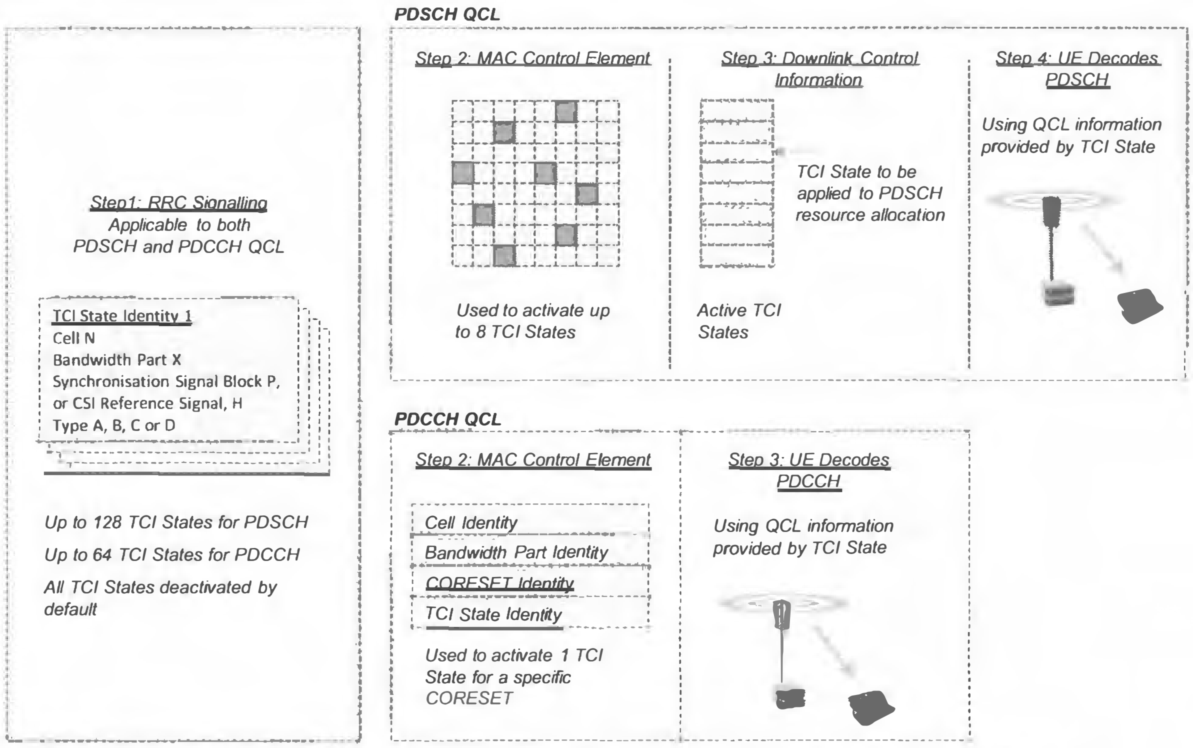


Figure 122 – Transmission Configuration Indicator (TCI) States used to specify antenna port QCL for PDSCH

★ RRC signalling is used to configure up to 128 Transmission Configuration Indicator (TCI) States for the PDSCH and up to 64 TCI States for the PDCCH. All TCI States are deactivated by default after configuration and after a handover. Each TCI State includes the identity of the relevant cell and Bandwidth Part. The TCI State also specifies the relevant SS/PBCH Block or CSI Reference Signal, and the relevant QCL Type

★ In the case of the PDSCH, MAC Control Elements are used to activate up to 8 of the configured TCI States. This is done by transmitting a bitmap, where a '1' indicates that the TCI State should be activated and a '0' indicates that the TCI state should be deactivated. A specific TCI State can then be dynamically selected and signalled using PDCCH Downlink Control Information (DCI) to indicate which of the active TCI States is applicable to a specific PDSCH resource allocation. This is done using DCI Format 1_1, i.e. the DCI which provides the resource allocation also indicates which TCI State to apply. The UE can then use the QCL information from the relevant TCI State to help decode the PDSCH

★ In the case of the PDCCH, a MAC Control Element is used to activate a single TCI State for a specific Control Resource Set (CORESET). The CORESET defines the set of Resource Blocks associated with a PDCCH Search Space. The UE can then use the QCL information from the relevant TCI State to help decode the PDCCH

★ Table 50 presents the set of 5G antenna ports standardised by 3GPP

Downlink Transmission	Antenna Ports
Synchronisation Signals	4000
PBCH	
Demodulation Reference Signal for PBCH	
PDCCH	2000
Demodulation Reference Signal for PDCCH	
PDSCH	1000 to 1011
Demodulation Reference Signal for PDSCH	
Phase Tracking Reference Signal for PDSCH	1000 to 1005
Channel State Information Reference Signal	3000 to 3031

Uplink Transmission	Antenna Ports
PUSCH	0 to 11
Demodulation Reference Signal for PUSCH	
Phase Tracking Reference Signal for PUSCH	0 to 5
PUCCH	2000
Demodulation Reference Signal for PUCCH	
Sounding Reference Signal	1000 to 1003
PRACH	4000

Table 50 – Antenna Ports standardised for New Radio (NR)

★ 3GPP References: TS 38.211, TS 38.212, TS 38.214, TS 38.331, TS 38.321

2.7 MODULATION

★ Modulation symbols are mapped onto Resource Elements before generating the waveform for transmission across the air-interface. The modulation scheme determines the capacity of each Resource Element. For example, a Resource Element which accommodates a QPSK modulation symbol transfers 2 bits of information, whereas a Resource Element which accommodates a 256QAM modulation symbol transfers 8 bits of information

★ Different modulation schemes can be applied to adjacent Resource Elements, e.g. a PDSCH Resource Element allocated to UE 1 can use QPSK, while an adjacent PDSCH Resource Element allocated to UE 2 can use 64QAM

★ Table 51 presents the modulation schemes used by each physical channel. The 'Bits per Symbol' column quantifies the capacity of a single modulation symbol. This is also known as the modulation order

Modulation Scheme	Bits per Symbol (Modulation Order)	PUSCH	PUCCH Format 1	PUCCH Format 2	PUCCH Formats 3 & 4	PDSCH	PBCH	PDCCH
π/2 BPSK	1	✓ (Note 1)	-	-	✓	-	-	-
BPSK	1	-	✓	-	-	-	-	-
QPSK	2	✓	✓	✓	✓	✓	✓	✓
16QAM	4	✓	-	-	-	✓	-	-
64QAM	6	✓	-	-	-	✓	-	-
256QAM	8	✓	-	-	-	✓	-	-

Note 1: only permitted when the DFT-S-OFDM waveform is selected for the PUSCH, i.e. Transform Precoding is applied

Table 51 – Modulation Schemes used by each Physical Channel

★ The Physical Uplink Shared Channel (PUSCH) and Physical Downlink Shared Channel (PDSCH) are the physical channels which are responsible to transferring application data. These channels require the greatest range of modulation schemes. High modulation orders are required to transfer high throughputs in good coverage, while low modulation orders are required to maximise coverage. Link Adaptation is responsible for selecting the appropriate modulation scheme at any point in time. In general, Link Adaptation bases its decisions upon coverage conditions, the quantity of data to be transferred and the quantity of Resource Elements allocated

★ Both the PDSCH and PUSCH support QPSK, 16QAM, 64QAM and 256QAM. In addition, the PUSCH supports π/2 BPSK. This additional modulation scheme is used to help boost uplink coverage performance. π/2 BPSK is only permitted when the PUSCH is using the DFT-S-OFDM waveform. This waveform is also designed to boost uplink coverage

★ π/2 BPSK has been adopted rather than BPSK because it offers a lower Peak to Average Power Ratio (PAPR). BPSK suffers from 'zero crossings' every time the bit stream changes from '0' to '1' or from '1' to '0'. These 'zero crossings' are caused by the 180° phase change when moving from one modulation constellation point to the other. 'Zero crossings' cause the signal envelope (amplitude) to pass through zero and consequently this results in a high PAPR

★ A high PAPR means that the transmitter has to operate with a lower average operating point on the linear section of the amplifier characteristic otherwise the peaks will reach the non-linear section and experience distortion. Operating at a lower average operating point is less efficient for the amplifier and also reduces the average output power, i.e. there are impacts upon both the UE battery life and the link budget

★ The modulation constellations for BPSK and π/2 BPSK are compared in Figure 123. BPSK uses a static pair of constellation points. π/2 BPSK uses a constellation which rotates by 90° between consecutive modulation symbols. This rotation reduces the maximum phase change from 180° to 90° and avoids the 'zero crossings'. This means that π/2 BPSK has a lower PAPR which allows the amplifier to use a higher average operating point without experiencing distortion. Smaller phase changes between symbols also has the benefit of reducing the magnitude of the side lobes in the frequency domain

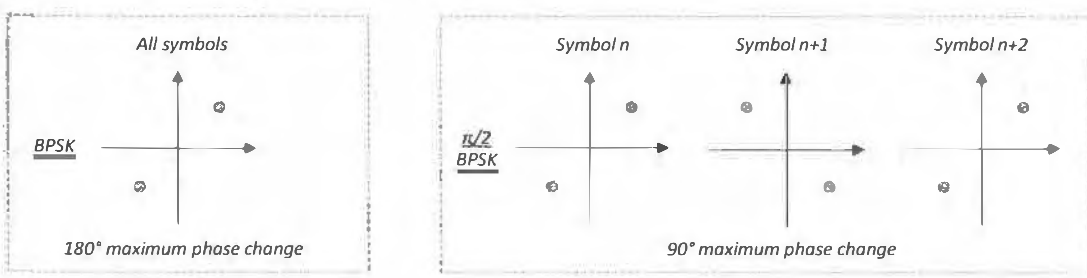


Figure 123 – Comparison of Modulation Constellations for BPSK and π/2 BPSK

★ The modulation scheme used by the Physical Uplink Control Channel (PUCCH) depends upon the PUCCH format. In general, lower order modulation schemes are used by the PUCCH to help ensure reliable reception across the whole coverage area

- o PUCCH format 0 is not shown in Table 51 because it does not use a modulation scheme. Information is transferred by the UE selecting and transmitting a specific sequence from a set of allocated sequences. For example, selecting 1 sequence from a set of 4 sequences can be used to transfer 2 bits of information because each sequence can be associated with a unique combination of 2 bits

- o PUCCH format 1 can use either BPSK or QPSK depending upon the quantity of information to be transferred. BPSK is used when PUCCH format 1 transfers a single bit of information, whereas QPSK is used when PUCCH format 1 transfers two bits of information

- o PUCCH format 2 always uses QPSK. In this case, the quantity of information being transferred is larger so modulation results in a series of modulation symbols

- o PUCCH formats 3 and 4 can use either $\pi/2$ BPSK or QPSK depending upon the configuration. The Base Station can configure the UE to use $\pi/2$ BPSK if there is a requirement to maximise coverage performance

★ The Physical Random Access Channel (PRACH) is not shown in Table 51 because it does not use a modulation scheme. Instead, the PRACH is a specific sequence of complex numbers. The PRACH corresponds to Message 1 (MSG1) of the Random Access procedure, i.e. the Random Access preamble.. The primary purpose of the PRACH is to initiate the Random Access procedure and to initialise uplink Timing Advance (the Base Station provides the UE with a Timing Advance command within MSG2 based upon the timing of MSG1). There are 64 sequences associated with each Random Access occasion. These sequences can be divided into groups such that sequence selection provides some additional information to the Base Station, e.g. if the UE selects a sequence from Group B then it indicates that the UE has a relatively large data volume to transfer and that the path loss between the UE and the Base Station is relatively small

★ The Physical Broadcast Channel (PBCH) and Physical Downlink Control Channel (PDCCH) both use QPSK. Similar to the PUCCH, a lower order modulation scheme is used to help ensure reliable reception across the whole coverage area. The PBCH also uses a low coding rate so transmissions include a large quantity of redundancy to further help reliable reception. Link Adaptation can be used to manage the number of Resource Elements allocated to the PDCCH. UE which are in good coverage can be allocated a smaller number of Resource Elements leading to a higher coding rate (less redundancy) but a smaller resource consumption. UE which are in poor coverage can be allocated an increased number of Resource Elements leading to a lower coding rate (more redundancy) but a higher resource consumption

★ Bits are mapped onto modulation symbols using Gray coding. This approach helps to minimise bit errors by mapping the bits such that neighbouring modulation symbols differ by only a single bit. If the receiver misinterprets a modulation symbol for its neighbour then only a single bit error is introduced. The concept of Gray coding for 16QAM is illustrated in Figure 124. The first two bits identify the quadrant while the second two bits identify the location within the quadrant

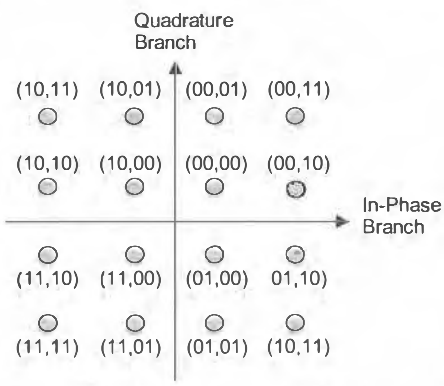


Figure 124 – Modulation constellation for 16QAM

★ Physical signals do not use modulation schemes. Physical signals are sequences of complex numbers and those sequences are mapped directly onto their allocated Resource Elements before generating the waveform for transmission across the air-interface

★ 3GPP References: TS 38.211

2.8 CYCLIC PREFIX

★ The cyclic prefix provides protection against both Inter Symbol Interference (ISI) and Inter Carrier Interference (ICI), i.e. interference between subcarriers. It is transmitted at the start of every symbol and is generated by copying the end of the payload belonging to that symbol. Figure 125 illustrates the general concept

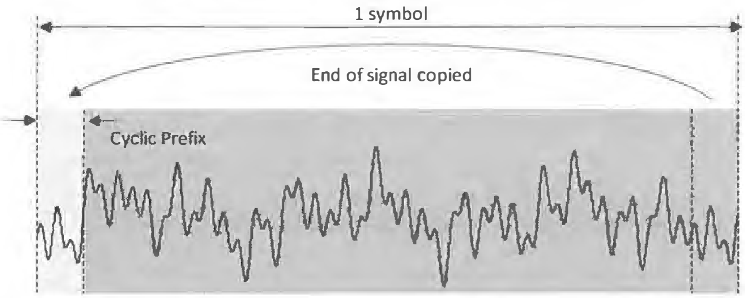


Figure 125 – General concept of the Cyclic Prefix

★ The radio propagation channel between the base station and the UE introduces delay spread in the time domain. Delay spread is generated by the transmitted signal reaching the receiver via multiple paths which have different distances and thus different delays

★ The delay spread associated with the propagation channel can be quantified from its impulse response. The impulse response represents the received signal when the transmitter sends a single impulse of power. The impulse response for a typical delay spread channel is shown in Figure 126. In general, delay spread components with increasing delay have lower average power because they have longer propagation paths. Delay spread components fade up-and-down independently so their instantaneous powers vary over time

Figure 126 – Delay Spread visible from Impulse Response of Propagation Channel

★ If the cyclic prefix was not present then delay spread would cause ISI because the delay spread components from one symbol would be received during the reception of the subsequent symbol. The cyclic prefix helps to avoid ISI by providing a guard period between symbols. This guard period provides a time window for the delay spread components belonging to the previous symbol to arrive before the start of the next symbol's payload

★ From the perspective of avoiding ISI, the guard period could be a period of discontinuous transmission, or could be a transmission of anything else. However, from the perspective of avoiding ICI, it is necessary for the guard period to include a copy of the end of the symbol payload, i.e. the cyclic prefix.

★ Understanding how the cyclic prefix helps to avoid ICI requires some mathematical background regarding the properties of convolution in the time domain and multiplication in the frequency domain.

- o when a time domain signal is transmitted across the air-interface then the received signal is given by the convolution of the transmitted signal and the channel impulse response (convolution refers to the summation of multiple versions of the transmitted signal, where each version has a different delay and power profile)
- o receivers which operate in the time domain have to identify, synchronise and combine each delay spread component. These operations require significant processing power. Any delay spread components which are not synchronised and combined generate interference. A significant benefit of OFDM is that the receiver can avoid these complex time domain operations by processing the received signal in the frequency domain
- o for a 'time continuous' signal, convolution in the time domain is equivalent to multiplication in the frequency domain. This mathematical property means that the receiver can remove the impact of the propagation channel and capture the energy from all delay spread components by a simple multiplication in the frequency domain
- o however, digital receivers do not operate on 'time continuous' signals so the convolution / multiplication property does not apply. Instead, for a 'discrete time' (sampled) signal, 'circular' convolution in the time domain is equivalent to multiplication in the frequency domain
- o copying the end of the payload and transmitting as the cyclic prefix ensures that there is a 'circular' convolution between the transmitted signal and the propagation channel impulse response. This allows the receiver to apply a simple multiplication to capture the energy from all delay spread components. If a 'circular' convolution was not completed then the receiver would experience ICI when completing the frequency domain multiplication

★ Avoiding both ISI and ICI requires that the duration of the cyclic prefix should be greater than the delay spread associated with the propagation channel. However, the cyclic prefix represents an overhead which reduces spectrum efficiency. Thus, the duration of the cyclic prefix should not be longer than necessary. If the delay spread exceeds the duration of the cyclic prefix then both ISI and ICI will be generated

★ 3GPP has specified two categories of cyclic prefix – Normal Cyclic Prefix (NCP) and Extended Cyclic Prefix (ECP). The NCP is specified for all subcarrier spacings whereas the ECP is currently only specified for the 60 kHz subcarrier spacing. Table 52 presents the duration of the cyclic prefix for each numerology when using the NCP

Subcarrier Spacing	Long Symbols (Note 1)				Remaining Symbols			
	CP Duration	Equivalent Distance	Payload Duration	Overhead	CP Duration	Equivalent Distance	Payload Duration	Overhead
15 kHz	5.21 μs	1563 m	66.67 μs	7.8 %	4.69 μs	1406 m	66.67 μs	7.0 %
30 kHz	2.86 μs	859 m	33.33 μs	8.6 %	2.34 μs	703 m	33.33 μs	
60 kHz	1.69 μs	508 m	16.67 μs	10.2 %	1.17 μs	352 m	16.67 μs	
120 kHz	1.11 μs	332 m	8.33 μs	13.3 %	0.59 μs	176 m	8.33 μs	
240 kHz	0.81 μs	244 m	4.17 μs	19.5 %	0.29 μs	88 m	4.17 μs	

Note 1: each numerology has 2 long symbols per 1 ms subframe. These long symbols are illustrated in Figure 98 (section 2.2)

Table 52 – Normal Cyclic Prefix Durations

★ As indicated by Table 52, each numerology has 2 longer symbols within each 1 ms subframe. These longer symbols are generated by increasing the duration of the normal cyclic prefix. They ensure that each numerology has an integer number of symbols within each 0.5 ms time window, while also ensuring that as many symbol boundaries as possible coincide, e.g. every symbol boundary belonging to the 15 kHz subcarrier spacing coincides with every second symbol boundary belonging to the 30 kHz subcarrier spacing

★ Cyclic prefix durations decrease as the subcarrier spacing increases. This means that smaller subcarrier spacings can tolerate larger propagation channel delay spreads. This trend is aligned with the allocation of the higher subcarrier spacings to the higher operating bands. Higher operating bands have higher propagation losses, smaller cell ranges and smaller delay spreads

★ Macrocells within urban environments typically have delay spreads in the order of 1 or 2 μs. Both microcells and indoor solutions typically have delay spreads in the order of 10 to 100 ns. Rural areas have a low delay spread when the environment is open and there is line-of-sight propagation. However, the delay spread can also become high as a result of the larger cell range and any potential distant reflectors

★ Table 53 presents the duration of the Extended Cyclic Prefix (ECP). As previously stated, 3GPP has currently specified only the 60 kHz subcarrier spacing for the ECP. The ECP increases the duration of each symbol because the duration of the cyclic prefix increases while duration of the payload remains constant. The ECP for the 60 kHz subcarrier spacing decreases the number of symbols within each 250 μs time window from 14 symbols to 12 symbols, i.e. physical layer air-interface capacity is reduced

Subcarrier Spacing	All symbols			
	CP Duration	Equivalent Distance	Payload Duration	Overhead
60 kHz	4.17 μs	1250 m	16.67 μs	25 %

Table 53 – Extended Cyclic Prefix Duration

★ 3GPP has not specified the ECP for all subcarrier spacings because the benefit is unclear and it may lead to reduced performance. Simulations illustrate that the increased overhead generated by the ECP can lead to reduced performance over a wide range of Signal to Interference plus Nosie Ratios (SINR). The benefit of the ECP is only visible at high SINR, i.e. the impact of ISI and ICI originating from delay spread is negligible compared to other sources of interference when the SINR is low. The impact of ISI and ICI originating from delay spread becomes more significant at high SINR when other sources of interference are much lower. This means that the ECP can increase the upper bound of spectrum efficiency but may reduce average performance

★ 3GPP has targeted the 60 kHz subcarrier spacing for the ECP to help provide a solution for Ultra Reliable Low Latency Communication (URLLC) within the lower operating bands. The 60 kHz subcarrier spacing is the highest subcarrier spacing supported within Frequency Range 1 (450 MHz to 6 GHz) so provides the shortest symbols and the lowest latency. Normally, the 60 kHz subcarrier spacing has increased vulnerability to delay spread due to the shorter symbols and short cyclic prefix. This tends to make transmissions less reliable. However, the ECP increases the duration of the cyclic prefix to 4.17 μs which is comparable to the 15 kHz normal cyclic prefix duration of 4.69 μs. This tends to improve the reliability of transmissions

★ The remainder of this section describes some general CP-OFDM receiver principles within the context of the cyclic prefix and delay spread. Figure 127 illustrates an example of 2 delay spread components. The second delay spread component is received later than the first delay spread component. A Fast Fourier Transform (FFT) processing window is defined at the receiver:

- o the processing window captures the main body of the CP-OFDM symbol belonging to the first delay spread component. The cyclic prefix belonging to the first delay spread component is discarded

- o the processing window captures part of the cyclic prefix and the majority of the main body of the CP-OFDM symbol belonging to the second delay spread component. Sections which fall outside the processing window are discarded

★ In the extreme case, where the delay spread is equal to the duration of the cyclic prefix then the FFT processing window fully captures the cyclic prefix belonging to the delay spread component

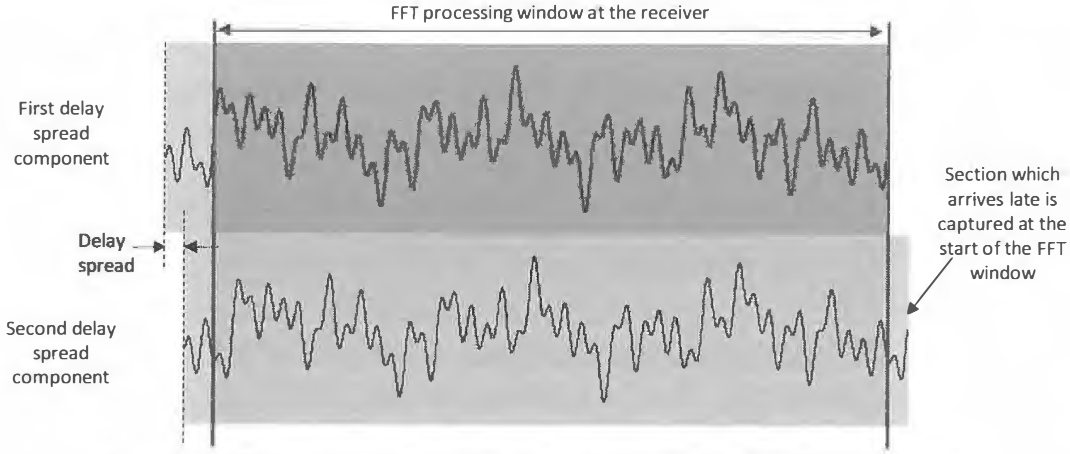


Figure 127 – Delay spread components captured by the FFT processing window at the receiver

★ The time domain representation of each delay spread component within the processing window is different (as shown in Figure 127). However, the frequency domain representation of each delay spread component within the processing window is identical. Moving a section of the time domain signal from the end, and adding it to the start does not change the frequency content of the signal, i.e. the signal includes the same set of frequency domain components and an FFT (which quantifies the set of frequency domain components included within the time domain signal) generates the same result

★ As long as the delay spread is less than the duration of the cyclic prefix, each delay spread component provides a complete representation of the signal within the FFT processing window, i.e. the same set of frequency components are generated by the FFT. This avoids the requirement to time synchronise with individual delay spread components prior to decoding

★ Figure 128 illustrates the aggregate signal captured by the receiver. The aggregate signal is the sum of all the delay spread components (only 2 are shown for simplicity). The receiver can operate directly on the aggregate signal without having to extract individual delay spread components because the frequency content of the sum of delay spread components, is the same as the frequency content of each individual delay spread component. The aggregate signal captures the energy from all delay spread components so generates a higher quality result from the FFT

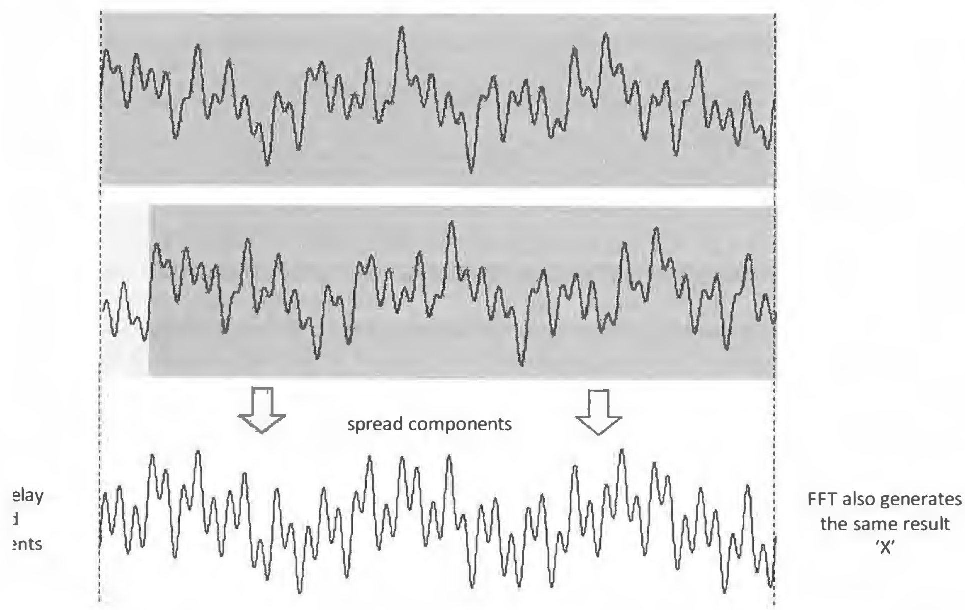


Figure 128 – Sum of delay spread components captured by FFT processing window at the receiver

★ 3GPP References: TS 38.211

2.9 WAVEFORM

★ The waveform is the baseband signal which is mixed to RF before being radiated across the air-interface. 3GPP has specified two waveforms for New Radio (NR) based upon Orthogonal Frequency Division Multiplexing (OFDM):

  - Cyclic Prefix OFDM (CP-OFDM), applicable to both the uplink and downlink
  - Discrete Fourier Transform Spread OFDM (DFT-S-OFDM), applicable to the uplink only

★ It is mandatory for UE to support both waveforms in the uplink direction. The Base Station selects the waveform to be used for the PUSCH and provides instructions to the UE. In the case of MSG3 belonging to the random access procedure, instructions are provided within SIB1 or alternatively can be provided using dedicated signalling. Dedicated signalling is used to provide instructions for subsequent PUSCH transmissions

★ DFT-S-OFDM has a lower Peak-to-Average Power Ratio (PAPR) than CP-OFDM. This allows the UE to transmit with a higher average power and so improves the uplink coverage performance. 3GPP has specified that DFT-S-OFDM only supports single stream transmission, i.e. MIMO is not supported. This means that CP-OFDM offers improved throughputs and capacity, while DFT-S-OFDM offers improved coverage. In the case of MSG3, DFT-S-OFDM may be selected to cater for all coverage conditions across the cell. In the case of subsequent PUSCH transmissions, the Base Station may dynamically reconfigure the UE according to coverage conditions

★ OFDM can transfer large numbers of modulation symbols simultaneously by multiplexing large numbers of subcarriers. These subcarriers are tightly packed to achieve high spectrum efficiency. In addition, they are carefully positioned in the frequency domain to ensure that they are orthogonal to one another, i.e. they do not generate interference towards each other. Figure 129 illustrates a set of orthogonal subcarriers. Each subcarrier appears as a sinc function in the frequency domain, which corresponds to a rectangular pulse in the time domain. The subcarriers are arranged to ensure that the peak of one sinc function coincides with zero crossings of all other subcarriers. If the subcarrier is sampled at its peak in the frequency domain then there will be no interference from the other subcarriers

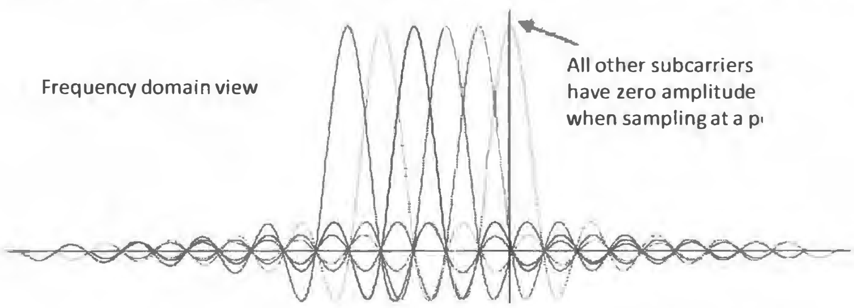


Figure 129 – Orthogonal subcarriers for OFDM

★ Each subcarrier accommodates 1 modulation symbol within the duration of 1 time domain OFDM symbol. The Inverse Fast Fourier Transform (IFFT) is used to generate the time domain OFDM symbol from a combination of the modulated subcarriers

★ OFDM is tolerant to delay spread because its time domain symbols have relatively long durations (depending upon the numerology). This is possible because data is transferred in parallel (across subcarriers) rather than in serial

  - a typical OFDM symbol for NR has a duration of 71.35 μs (defined as 1 / subcarrier spacing of 15 kHz + an overhead for the Cyclic Prefix). A 50 MHz OFDM channel could have 3240 subcarriers spaced at 15 kHz generating a modulation symbol rate of 3240 / 71.35 μs = 45.4 Msps. If transmitting data in serial, 45.4 Msps would require a symbol period of $1 / 45.4 \times 10^6 = 0.02$ μs

★ The reduced impact of delay spread means that fading is flat in the frequency domain and receiver equalization becomes simpler. A drawback of OFDM is its relatively high Peak to Average Power Ratio (PAPR) generated by summing large numbers of subcarriers. High PAPR means that power amplifiers have to operate with increased back-off which leads to reduced efficiency. Reduced power efficiency has an impact upon battery powered handheld devices. This has resulted in an optional different multiple access scheme being selected for the uplink. A second drawback of OFDM is its sensitivity to frequency offsets which could be introduced by Doppler, or by frequency inaccuracies within local oscillators at the transmitter and receiver

★ The term OFDM can be extended to Orthogonal Frequency Division Multiple Access (OFDMA). Multiple access techniques allow resources to be shared between a group of users. In the case of OFDMA, the set of subcarriers is shared between users, e.g. subcarriers 1 to 36 are allocated to user 1, while subcarriers 37 to 96 are allocated to user 2. A Resource Block accommodates 12 subcarriers so the previous example would be equivalent to allocating 3 Resource Blocks to user 1, and 5 Resource Blocks to user 2. Common multiple access techniques are presented in Table 54

	FDMA	TDMA	CDMA	OFDMA
Resource Allocation	RF Carriers	Time Slots	Codes	Subcarriers
Example System	AMPS	GSM	UMTS	LTE / New Radio

Table 54 – Multiple access techniques

2.9.1 CP-OFDM

★ 3GPP TS 38.211 specifies two equations for generating the CP-OFDM waveform. The first is applicable to all physical channels and signals except the PRACH, whereas the second is applicable to the PRACH. The first equation is shown below. This equation represents an Inverse Fast Fourier Transform (IFFT), i.e. the equation generates a time domain signal from a frequency domain signal by summing a set of modulated subcarriers

Time domain result for symbol l, antenna port p and numerology μ

Summation across all subcarriers

Content of Resource Element (subcarrier k, symbol l)

Subcarrier Index

Subcarrier Spacing

Time Index

$$s_l^{(p,\mu)}(t) = \sum_{k=0}^{12\times N_{grid}^{size,\mu}-1} a_{k,l}^{(p,\mu)} \times e^{j2\pi\left(k+k_0^\mu-6\times N_{grid}^{size,\mu}\right)\times\Delta f\times\left(t-N_{CP,l}^{\mu}\times T_c-t_{start,l}^{\mu}\right)}$$

$$t_{start,l}^{\mu} \le t < t_{start,l}^{\mu} + \left(N_u^\mu + N_{CP,l}^{\mu}\right)\times T_c$$

Time window associated with symbol l and numerology μ

$$l \in \left\{0, 1, \ldots, N_{slot}^{subframe,\mu} \times N_{symb}^{slot} - 1\right\}$$

Set of symbols belonging to a slot for numerology μ

p is the antenna port

μ is the subcarrier spacing index

$a_{k,l}^{(p,\mu)}$ is the content of Resource Element (subcarrier k and symbol l)

Subcarrier offset used to ensure that the first subcarrier of Common Resource Block is aligned with other numerologies

$$k_0^\mu = 12 \times \left(N_{grid,x}^{start,\mu} + N_{grid,x}^{size,\mu}/2\right) - 12 \times \left(N_{grid,x}^{start,\mu_0} + N_{grid,x}^{size,\mu_0}/2\right) \times 2^{\mu_0-\mu}$$

Δf is the subcarrier spacing

$N_{grid}^{size,\mu}$ is the number of Resource Blocks

Time unit (based upon subcarrier spacing of 480 kHz and FFT size of 4096)

$$T_c = 1/\left(\Delta f_{ref} \times N_f\right) = 1/(480\,000 \times 4096) = 0.5086\ ns$$

Cyclic Prefix duration

$$N_{CP,l}^{\mu} = \begin{cases} 512 \times 64 \times 2^{-\mu} & extended\ cyclic\ prefix \\ 144 \times 64 \times 2^{-\mu} + 1024 & normal\ cyclic\ prefix, l = 0\ or\ l = 7 \times 2^{\mu} \\ 144 \times 64 \times 2^{-\mu} & normal\ cyclic\ prefix,\ l \neq 0\ or\ l \neq 7 \times 2^{\mu} \end{cases}$$

$$t_{start,l}^{\mu} = \begin{cases} 0 & l = 0 \\ t_{start,l-1}^{\mu} + \left(N_u^\mu + N_{CP,l-1}^{\mu}\right)\times T_c & otherwise \end{cases}$$

Start of time window associated with symbol l and numerology μ

★ The summation uses the variable 'k' which ranges from 0 to the total number of subcarriers. The baseband signal is centered around 0 Hz so half of the total number of subcarriers is subtracted from the value of 'k' when generating the 'Subcarrier Index'. This leads to the subcarrier index being negative for the first half of the range of 'k', and either 0 or positive for the second half of the range of 'k'

★ This indicates that the 'Subcarrier Index' can have a value of 0 which corresponds to the DC subcarrier, i.e. the subcarrier with a frequency of 0 Hz. The DC subcarrier is typically excluded (LTE does not use the DC subcarrier) because it can suffer interference from local oscillator leakage. This issue is illustrated in Figure 130. The local oscillator signal at the receiver 'leaks' backwards through the filter and low noise amplifier before following the wanted signal forwards through the amplifier and filter. The amplified 'leaked' signal is then mixed with the local oscillator signal itself to generate interference at 0 Hz, i.e. mixing two signals with equal frequencies generates a signal at 0 Hz. This unwanted signal at 0 Hz interferes with any wanted signal at 0 Hz, i.e. the DC subcarrier

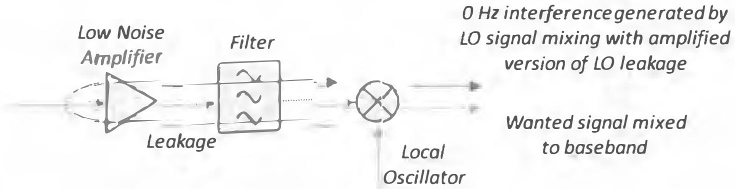


Figure 130 – DC Interference generated by Local Oscillator Leakage

★ New Radio (NR) allows the DC subcarrier to be used based upon the assumption that modern transceivers are able to manage the impact of local oscillator leakage. Nevertheless, the DC subcarrier may be at a disadvantage relative to other subcarriers

★ The subcarrier index also includes a k_0^μ variable which is used to ensure that Common Resource Blocks belonging to different numerologies are aligned at 'Point A' as illustrated in Figure 108 (section 2.3.1)

★ The $a_{k,l}^{(p,\mu)}$ variable represents the content of the Resource Element associated with subcarrier 'k' and symbol 'l'. For example, this could be a modulation symbol belonging to the PDSCH or PUSCH, or it could be an entry from a sequence belonging to a Synchronisation Signal or Demodulation Reference Signal

★ The $a_{k,l}^{(p,\mu)}$ variable is multiplied by a complex phasor of the form $e^{j\omega t}$, where $\omega = 2\pi f$. This complex phasor represents the subcarrier which is modulated by the content of the Resource Element. The frequency 'f' is generated from the Subcarrier Index multiplied by the subcarrier spacing. The time 't' is generated from the Time Index

★ The Time Index would normally be expected to have the format $(t - N_{CP,l}^\mu \times T_c)$. This leads to a negative Time Index until $t = N_{CP,l}^\mu \times T_c$. This initial period with a negative Time Index generates the cyclic prefix. However, the Time Index shown above has the format $(t - N_{CP,l}^\mu \times T_c - t_{start,l}^\mu)$. The additional $t_{start,l}^\mu$ variable is required to compensate for phase offsets generated by the UE and Base Station assuming different center frequencies, e.g. when the active Bandwidth Part is not centered across the channel bandwidth

★ Figure 131 provides a graphical representation of generating the CP-OFDM waveform. The Resource Element grid is populated by the set of Physical Channels and Physical Signals. Each column of the Resource Element grid is used to generate a CP-OFDM symbol. The summation of results generated by multiplying the column of Resource Elements with the appropriate set of complex phasors corresponds to the Inverse Fast Fourier Transform (IFFT)

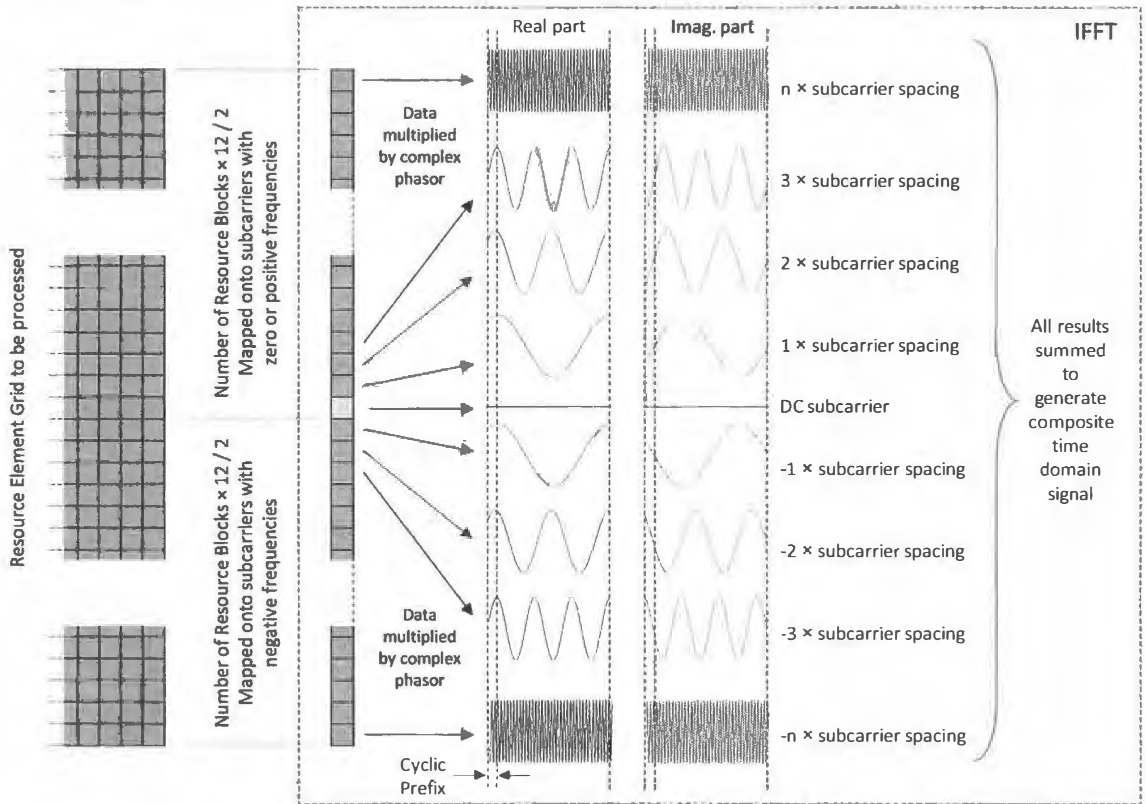


Figure 131 – Generation of CP-OFDM waveform

★ The content of each Resource Element is multiplied by a complex phasor with the appropriate subcarrier frequency

- o the lower half set of Resource Elements are multiplied by complex phasors with negative frequencies (complex phasors rotating in a clockwise direction). If the subcarrier spacing is 15 kHz, then the highest Resource Element will be multiplied by a complex phasor rotating at a frequency of -15 kHz, while the second highest Resource Element will be multiplied by a complex phasor rotating at a frequency of -30 kHz, and so on
- o the lowest Resource Element belonging to the upper half of Resource Elements is multiplied by a complex phasor with zero frequency (DC subcarrier)
- o the remaining Resource Elements belonging to the upper half of Resource Elements are multiplied by complex phasors with a positive frequency (complex phasors rotating in an anti-clockwise direction). If the subcarrier spacing is 15 kHz, then the second lowest Resource Element will be multiplied by a complex phasor rotating at a frequency of +15 kHz, while the third lowest Resource Element will be multiplied by a complex phasor rotating at a frequency of +30 kHz, and so on

★ The duration of the multiplication corresponds to the duration of a CP-OFDM symbol, and can be divided into 2 parts:

- o a relatively short first part which corresponds to the cyclic prefix:
- o a longer second part which corresponds to the main body of the CP-OFDM symbol

★ The results from each complex phasor multiplication are summed to generate the time domain digital baseband signal. The spectrum of the baseband signal is centered around 0 Hz. The digital baseband signal is subsequently converted to an analogue baseband signal before being mixed to the appropriate RF carrier frequency. These steps are illustrated in Figure 132

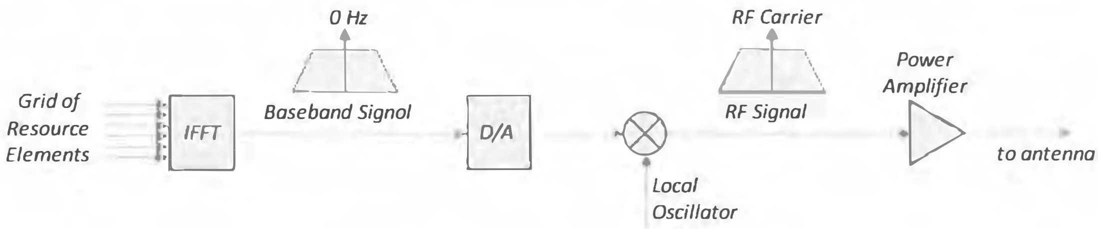


Figure 132 – Baseband Signal mixed to RF Signal

★ The equation used to generate the CP-OFDM waveform for the PRACH is shown below. Similar to the first equation, this equation represents an Inverse Fast Fourier Transform (IFFT). The general format of the two equations is the same, i.e. a summation of complex phasors (subcarriers) that have been modulated by a set of Resource Elements

Time domain result for symbol l, antenna port p and numerology μ

Summation across all subcarriers

Content of Resource Element (subcarrier k, symbol l)

Subcarrier Index

Subcarrier Spacing

Time Index

$$s_l^{(p,\mu)}(t) = \sum_{k=0}^{L_{RA}-1} a_k^{(p,RA)} \times e^{j2\pi\left(k+k_1\times\frac{\Delta f}{\Delta f_{RA}}+\bar{k}\right)\times\Delta f_{RA}\times\left(t-N_{CP,l}^{RA}\times T_c-t_{start}^{RA}\right)}$$

$$k_1 = k_0^\mu + 12\times\left(N_{BWP,i}^{start} - N_{grid}^{start,\mu}\right) + 12\times n_{RA}^{start} + 12\times n_{RA}\times N_{RB}^{RA} - N_{grid}^{size,\mu}\times 6$$

$$k_0^\mu = 12\times\left(N_{grid}^{start,\mu} + N_{grid}^{size,\mu}\,/\,2\right) - 12\times\left(N_{grid}^{start,\mu_0} + N_{grid}^{size,\mu_0}\,/\,2\right)\times 2^{\mu_0-\mu}$$

$$t_{start}^{RA} \le t < t_{start}^{RA} + \left(N_u + N_{CP,l}^{RA}\right)\times T_c$$

$$t_{start}^{RA} = t_{start,l}^{\mu} = \begin{cases} 0 & l=0 \\ t_{start,l-1}^{\mu} + \left(N_u^\mu + N_{CP,l-1}^{\mu}\right)\times T_c & otherwise \end{cases}$$

★ In this case, the summation is applied across L_{RA} subcarriers, where L_{RA} is equal to the length of the PRACH sequence (139 for a short PRACH or 839 for a long PRACH). Each Resource Element within the summation corresponds to an entry from the PRACH sequence

★ The Subcarrier Index includes a factor to account for the difference between the PRACH subcarrier spacing (Δf_{RA}) and the subcarrier spacing of the relevant uplink Bandwidth Part (Δf). The PRACH subcarrier spacing can be 1.25, 5, 15, 30, 60 or 120 kHz, i.e. a larger range of values relative to those used by the PUSCH

★ The Subcarrier Index includes a factor k_1 which accounts for the frequency domain position of the PRACH within the Bandwidth Part, i.e. n_{RA}^{start} identifies the first Resource Block allocated to the PRACH (defined by the *msg1-FrequencyStart* information element within SIB1, or dedicated RRC signalling). If multiple PRACH are stacked in the frequency domain then n_{RA} provides the offset to the appropriate instance of the PRACH. N_{RB}^{RA} defines the number of Resource Blocks occupied by each PRACH instance

★ The Subcarrier Index also includes a factor $\bar{k}$ which is always set equal to 2 when using a short PRACH, but has a value which depends upon the combination of PRACH and PUSCH subcarrier spacings when using a long PRACH. This variable is used to provide the appropriate subcarrier alignment between the PRACH and the main Resource Block grid

★ The subcarrier index μ is set equal to 0 for subcarrier spacings of 1.25 and 5 kHz. It adopts the usual values of 0, 1, 2 and 3 for subcarrier spacings of 15, 30, 60 and 120 kHz respectively

★ 3GPP References: TS 38.211

2.9.2 DFT-S-OFDM

★ Discrete Fourier Transform Spread Orthogonal Frequency Division Multiplexing (DFT-S-OFDM) is generated using a combination of 'Transform Precoding' and CP-OFDM. This concept is illustrated in Figure 133. DFT-S-OFDM is only applicable to the uplink and is intended for coverage limited scenarios. 3GPP specifies that it can only be used when a single transmission layer is allocated to the UE

★ The 'Transform Precoding' operation requires additional computational complexity but decreases the relatively high Peak to Average Power (PAPR) associated with CP-OFDM

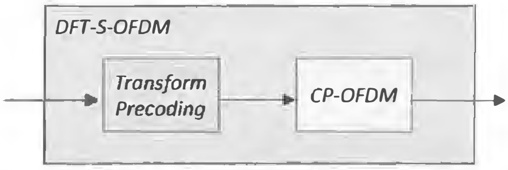


Figure 133 – DFT-S-OFDM generated as a combination of Transform Precoding and CP-OFDMA

★ 3GPP TS 38.211 specifies 'Transform Precoding' using the equation shown below. This equation represents a Fast Fourier Transform (FFT), i.e. the equation translates a time domain signal into a frequency domain signal

$$y^{(0)}(l \times M_{sc}^{PUSCH} + k) = \frac{1}{\sqrt{M_{sc}^{PUSCH}}} \sum_{i=0}^{M_{sc}^{PUSCH}-1} x^{(0)}(l \times M_{sc}^{PUSCH} + i) \times e^{-j\frac{2\pi ik}{M_{sc}^{PUSCH}}}$$

$$k = 0 \text{ to } M_{sc}^{PUSCH} - 1 \qquad l = 0 \text{ to } M_{symb}^{layer} / M_{sc}^{PUSCH} - 1$$

★ Figure 134 provides a graphical representation of 'Transform Precoding'. The modulation symbols to be transmitted by the UE are divided into sets. The number of modulation symbols belonging to each set is equal to the number of PUSCH subcarriers allocated to the UE (M_{SC}^{PUSCH}). This means the number of sets is given by $M_{symb}^{layer}/M_{SC}^{PUSCH}$ where M_{symb}^{layer} is equal to the total number of modulation symbols to be processed

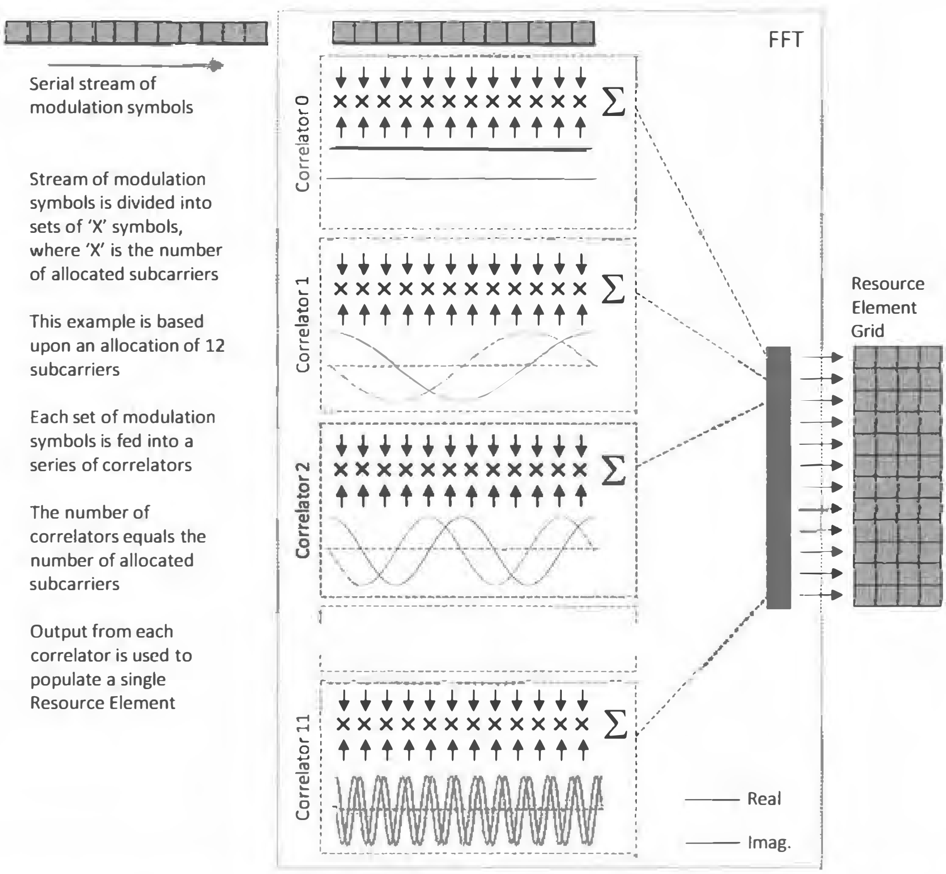


Figure 134 – Transform Precoding using a set of Correlators to generate the frequency domain signal

- ★ Each set of modulation symbols is processed by an FFT function which generates a frequency domain representation of the symbols. The FFT function is a block of correlators which extracts a set of frequency components from the set of modulation symbols
- ★ The first correlator (shown at the top of Figure 134) extracts the DC component by taking an average of the modulation symbols. The second correlator extracts the frequency component defined by a single cycle of a sine/cosine. The final correlator extracts the frequency component defined by 'X-1' cycles of a sine/cosine. The number of correlators is equal to the number of allocated subcarriers so there is a single correlator result for each subcarrier
- ★ The output from each correlator is used to populate a single Resource Element. The resulting modulation symbol rate is the same as if the modulation symbols were mapped directly onto the set of Resource Elements
- ★ 3GPP References: TS 38.211

2.10 TRANSMITTER AND RECEIVER CHAIN

- ★ A general transmitter and receiver chain is illustrated in Figure 135. This is a high level representation but the main functions are shown. In this example, the transmitter does not include an FFT stage for Transform Precoding so the figure is applicable to CP-OFDM rather than DFT-S-OFDM. The figure can be applied to both the uplink and downlink transmission directions
- ★ The functions provided by the receiver are the inverse of those provided by the transmitter. The receiver will also include additional functions to help support the demodulation process. For example, there will be a channel estimation function which tracks and helps to compensate for the impact of the radio propagation channel

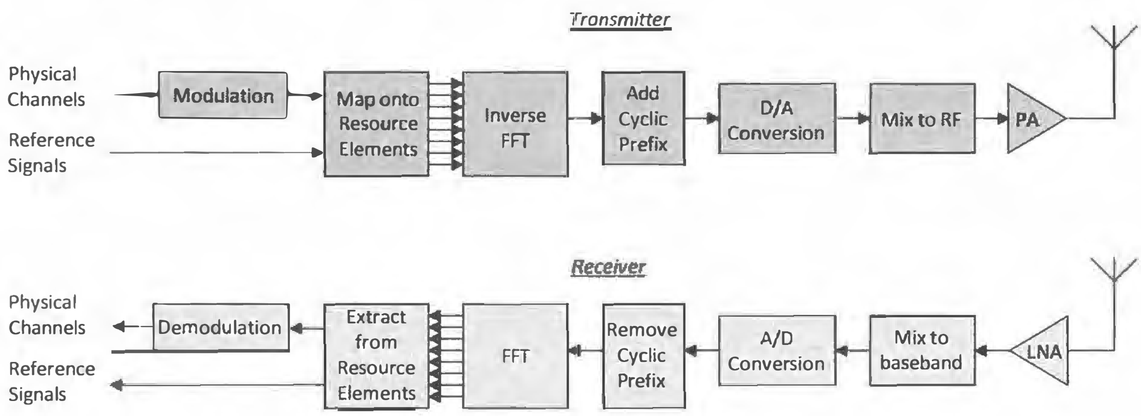


Figure 135 – Transmitter and receiver chain for OFDMA

- ★ The transmitter includes an Inverse Fast Fourier Transform (IFFT) to translate each column of modulated Resource Elements into an OFDM symbol. In contrast, the receiver includes a Fast Fourier Transform (FFT) to translate each OFDM symbol back into a column of Resource Elements. The set of modulation symbols can then be extracted from the column of Resource Elements
- ★ A cyclic prefix is added at the transmitter and removed at the receiver. The cyclic prefix provides a guard period to help prevent Inter-Symbol Interference (ISI) caused by the propagation channel delay spread. Generating the cyclic prefix by copying the end of the symbol means that the received signal is a circular convolution between the transmitted symbol and the propagation channel impulse response. This characteristic allows the impact of the propagation channel to be removed at the receiver using a simple multiplication without generating Inter Carrier Interference (ICI)
- ★ The transmitter includes a Power Amplifier (PA) to increase the signal strength to a level which can be transmitted across the air-interface. The receiver includes a Low Noise Amplifier (LNA) to boost the wanted signal strength before it is degraded by the noise figures of the remaining RF components within the receive path. In the uplink direction, a conventional Base Station architecture can use a Mast Head Amplifier (MHA) / Tower Mounter Amplifier (TMA) to provide the LNA. A Base Station architecture using an active antenna includes the LNA within the active antenna itself

3 DOWNLINK SIGNALS AND CHANNELS

3.1 DOWNLINK CHANNEL MAPPINGS

- ★ Logical channels transfer data (RLC PDU) between the RLC and MAC layers. Transport channels transfer data (MAC PDU) between the MAC and Physical layers. MAC PDU are also known as Transport Blocks. Physical channels transfer data across the air-interface
- ★ Physical signals are used by the Physical layer for synchronisation, channel quality measurements and channel estimation
- ★ The mappings between the various channel types are illustrated in Figure 136. This figure also illustrates the set of downlink signals

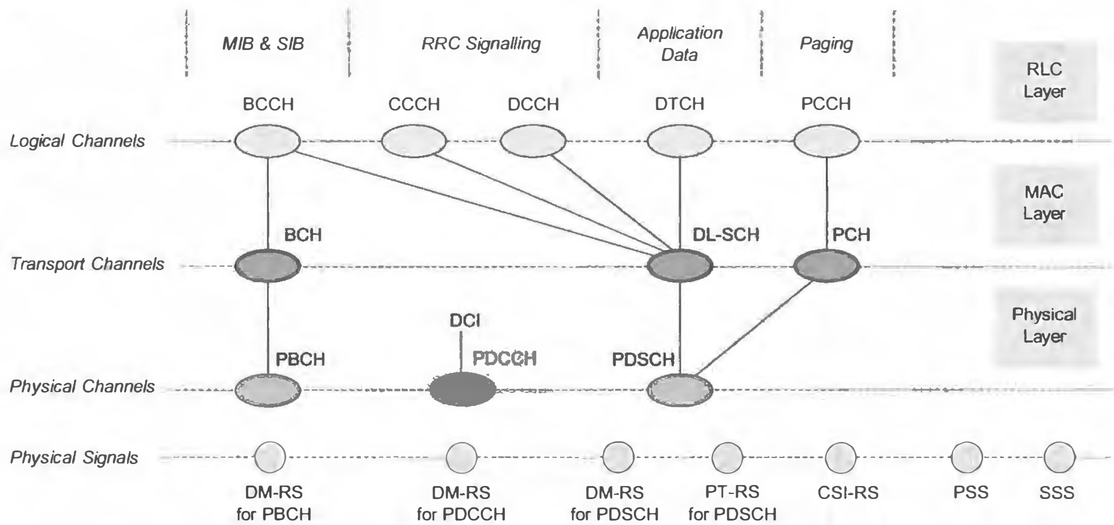


Figure 136 – Mapping of downlink logical channels onto transport channels and physical channels

- ★ The Broadcast Control Channel (BCCH) is used to transfer both the Master Information Block (MIB) and System Information Blocks (SIB). The MIB is mapped onto the BCH and PBCH, whereas the SIB are mapped onto the DL-SCH and PDSCH
- ★ The Common Control Channel (CCCH) and Dedicated Control Channel (DCCH) are used to transfer RRC signalling messages, i.e. data belonging to the set of Signalling Radio Bearers (SRB). All SRB data is mapped onto the DL-SCH and PDSCH
- ★ The Dedicated Traffic Channel (DTCH) is used to transfer application data. All application data is mapped onto the DL-SCH and PDSCH
- ★ The Paging Control Channel (PCCH) is used to transfer paging messages. All paging messages are mapped onto the PCH and PDSCH
- ★ The PDCCH physical channel is not used to transfer higher layer information, so does not have associated logical nor transport channels. The PDCCH transfers Downlink Control Information (DCI). Downlink Control Information is used by the Base Station packet scheduler to allocate both uplink and downlink resources (PUSCH and PDSCH resources respectively). DCI can also be used to provide uplink power control commands, configure the slot format and indicate that pre-emption has occurred
- ★ There are Demodulation Reference Signals (DMRS) for the PBCH, PDCCH and PDSCH. These Reference Signals are sequences which are known to the UE. The UE compares the received version of the sequence with the known reference to estimate the impact of the propagation channel. The UE can then apply an inverse of the propagation channel during the demodulation process
- ★ The Phase Tracking Reference Signal (PTRS) is used to compensate for phase noise generated by the local oscillators at both the transmitter and receiver. Phase noise is not a significant issue for the lower operating bands but becomes more significant for the higher operating bands. The PTRS can also be used to compliment the Demodulation Reference Signal (DMRS) for the PDSCH. It is applicable to both the lower and higher operating bands when complimenting the DMRS
- ★ The Channel State Information Reference Signal (CSI RS) is used by the UE to measure and report channel quality, e.g. Channel Quality Indicator (CQI) reports. This information can be used by the link adaptation algorithm within the Base Station to help schedule appropriate throughputs. It can also be used for Beam Management and Connected Mode mobility procedures
- ★ The Primary Synchronisation Signal (PSS) and Secondary Synchronisation Signal (SSS) are used during the cell search procedure and also during Beam Management procedures. The SSS is used for Reference Signal Received Power (RSRP) and Reference Signal Received Quality (RSRQ) measurements. RSRP measurements can be used for open loop power control calculations, while both RSRP and RSRQ can be used to trigger mobility procedures
- ★ 3GPP References: TS 38.211, TS 38.212, TS 38.321, TS 38.322

3.2 SYNCHRONISATION SIGNALS

★ New Radio (NR) supports both Primary and Secondary Synchronisation Signals (PSS and SSS). A UE uses the Synchronisation Signals for:

  - initial time and frequency synchronisation when first accessing a cell
  - identifying the Physical layer Cell Identity (PCI) belonging to a cell
    - NR supports 1008 PCI which are organised into 336 groups of 3
  - completing RSRP, RSRQ and SINR measurements from the Secondary Synchronisation Signal (SSS)
  - the SSS can also be used as an additional Demodulation Reference Signal (DMRS) for the PBCH

★ Both the PSS and SSS are sequences of 127 BPSK symbols which are mapped onto 127 Resource Elements

★ The PSS is generated by applying 1 of 3 cyclic shifts to a sequence of 127 BPSK symbols (cyclic shifts of 0, 43 and 86). These cyclic shifts lead to 3 versions of the PSS which are re-used across the entire network. The cyclic shift acts as a pointer to 1 of 3 PCI within a PCI group

★ The SSS is generated as a product of 2 sequences which depend upon both the pointer towards the PCI group (1 out of 336) and the pointer towards the PCI within the group (1 out of 3), i.e. there are 1008 SSS sequences. The UE has to identify 1 out of 336 SSS sequences after the PSS cyclic shift has been identified

★ The sequences used for the PSS and SSS have been selected to have:

  - good auto-correlation properties, i.e. each sequence generates a high result when correlated with a synchronised version of itself, and generates a low result when correlated with an unsynchronised version of itself
  - good cross correlation properties, i.e. the sequence generates a low result when correlated with other sequences

★ These properties help to improve detection in poor signal to noise ratio conditions

★ A set of 4 subcarrier spacings have been specified for the Synchronisation Signals (15, 30, 120 and 240 kHz)

  - the 15 and 30 kHz subcarrier spacings are applicable to Frequency Range 1 (450 MHz to 6 GHz)
  - the 120 and 240 kHz subcarrier spacings are applicable to Frequency Range 2 (24.25 GHz to 52.6 GHz)

★ 3GPP has specified 'default' subcarrier spacings for each operating band. Specifying a single default subcarrier spacing for a specific operating band helps the UE to complete the cell search procedure with less delay and less power consumption. The default subcarrier spacings specified for each operating band are presented in Table 55

Subcarrier Spacing for Synchronisation Signals	Synchronisation Signal Length	Bandwidth Occupied by SS/PBCH Block (20 Resource Blocks)	Operating Bands with Subcarrier Spacing as Default
15 kHz	127	3.6 MHz	n1, n2, n3, n5, n7, n8, n12, n20, n25, n28, n34, n38, n39, n40, n41, n50, n51, n65, n66, n70, n71, n74, n75, n76
30 kHz		7.2 MHz	n5, n41, n66, n77, n78, n79
120 kHz		28.8 MHz	n257, n258, n260, n261
240 kHz		57.6 MHz	n257, n258, n260, n261

Table 55 – Mapping between Subcarrier Spacing and Operating Bands for the Synchronisation Signals

★ The Synchronisation Signals are transmitted as part of the SS/PBCH Block (section 3.4) which occupies 20 Resource Blocks. This means that the 15 kHz subcarrier spacing generates an SS/PBCH Block which occupies 15 × 20 × 12 = 3.6 MHz, while the 30 kHz subcarrier spacing generates an SS/PBCH Block which occupies 30 × 20 × 12 = 7.2 MHz. This leads to the conclusion that any Frequency Range 1 operating band which supports the 5 MHz channel bandwidth should use the 15 kHz subcarrier spacing as a default (because 20 Resource Blocks cannot be accommodated within 5 MHz when using the 30 kHz subcarrier spacing)

★ Some operating bands have been specified with multiple default subcarrier spacings, e.g. operating band n5 has default subcarrier spacings of both 15 and 30 kHz. This increases the processing required during the cell search procedure but provides operators with increased flexibility, i.e. operators deploying a 5 MHz channel can use the 15 kHz subcarrier spacing, while operators deploying larger channel bandwidths can use the 30 kHz subcarrier spacing

★ Non-default subcarrier spacings can be used for cells which the UE is not expected to discover autonomously. For example, a UE connected to an E-UTRAN – New Radio Dual Connectivity (EN-DC) Base Station will access the E-UTRAN (4G) cell and use that cell as the primary serving cell. The E-UTRAN Base Station can then provide the UE with information regarding the subcarrier spacing used by the Synchronisation Signals of the New Radio cell. This subcarrier spacing may be a non-default value. Figure 137 illustrates the use of default and non-default subcarrier spacings for the Synchronisation Signals

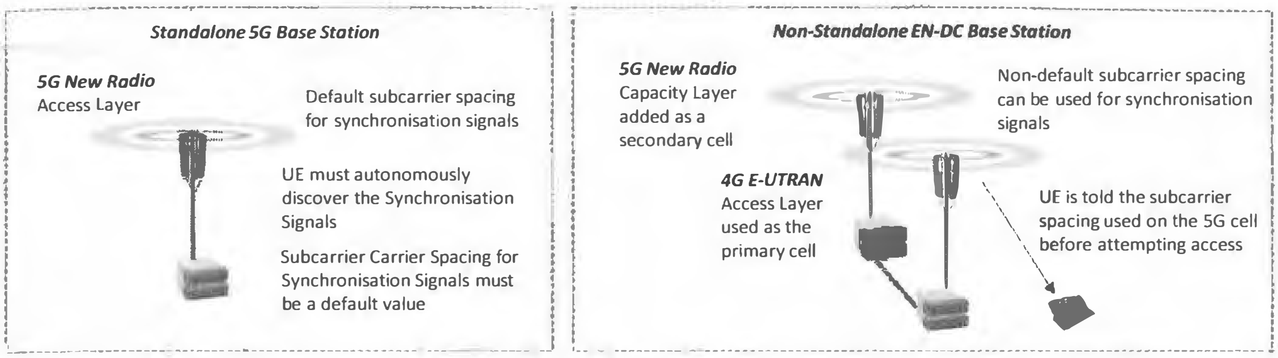


Figure 137 – Example use of default and non-default subcarrier spacings for the Synchronisation Signals

- A benefit of using the 30 kHz subcarrier spacing is the ability to share spectrum with 4G (Dynamic Spectrum Sharing is described in section 17). An SS-PBCH Block occupies 4 symbols in the time domain. When using the 30 kHz subcarrier spacing, these 4 symbols can be accommodated within 2 symbols belonging to the 4G system (which uses a 15 kHz subcarrier spacing). This provides the potential to transmit a 5G SS/PBCH Block within a 4G channel bandwidth without coinciding with the 4G Cell Specific Reference Signal. This deployment scenario is illustrated in Figure 138.

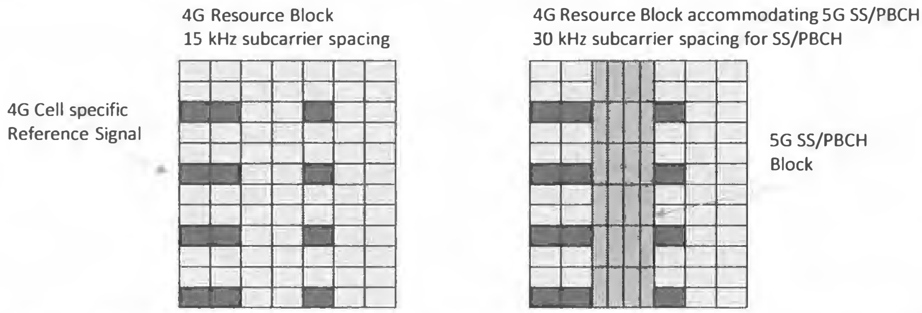


Figure 138 – 4G Resource Block accommodating a 5G SS/PBCH Block when using the 30 kHz subcarrier spacing

- A drawback of using the 30 kHz subcarrier spacing is the reduced cyclic prefix duration which leads to increased vulnerability to propagation channel delay spread
- The subcarrier spacing used for the Synchronisation Signals does not have to equal the subcarrier spacing used for the transfer of application data on the PDSCH
- Section 2.5.2 describes the frequency raster used by the Synchronisation Signals. This frequency raster defines the set of frequencies that UE search when completing initial cell access. Synchronisation Signals can also be transmitted away from the standardised frequency raster but these instances are not used for the initial cell search procedure. They may be used for RSRP measurements after a UE has accessed a cell
- Section 3.4 describes the time and frequency domain resource allocations for the Synchronisation Signals
- 3GPP References: TS 38.211, TS 38.104

3.3 PHYSICAL BROADCAST CHANNEL

★ The Physical Broadcast Channel (PBCH) is used to broadcast the Master Information Block (MIB) using the BCH transport channel and BCCH logical channel. A UE decodes the PBCH immediately after detecting the Synchronisation Signals. The MIB provides key information required to access the cell

★ The Base Station transmits the PBCH with the Primary and Secondary Synchronisation Signals within an SS/PBCH Block (section 3.4)

★ The MAC layer provides the Physical layer with a BCH transport block. This transport block is the MIB which has a size of 24 bits. The MIB includes timing information in terms of the 6 Most Significant Bits (MSB) of the System Frame Number (SFN). The 4 Least Significant Bits (LSB) are not included within the MIB. This means that the content of the MIB changes every 160 ms because the SFN increments every 10 ms

★ The Physical layer of the Base Station attaches additional information to the MIB before it is processed for transmission across the air-interface. This additional information includes the 4 LSB of the SFN. Adding these bits at the Physical layer reduces the rate at which the RRC layer has to update the MIB. In the case of Frequency Range 1 (450 MHz to 6 GHz) the Physical layer also includes information regarding the subcarrier offset between the SS/PBCH Block and the main Resource Block grid. The complete content of the MIB and the additional information attached by the Physical layer is presented in section 6.1

★ Figure 139 illustrates the Physical layer attaching an additional 8 bits of information to the MIB before the subsequent processing

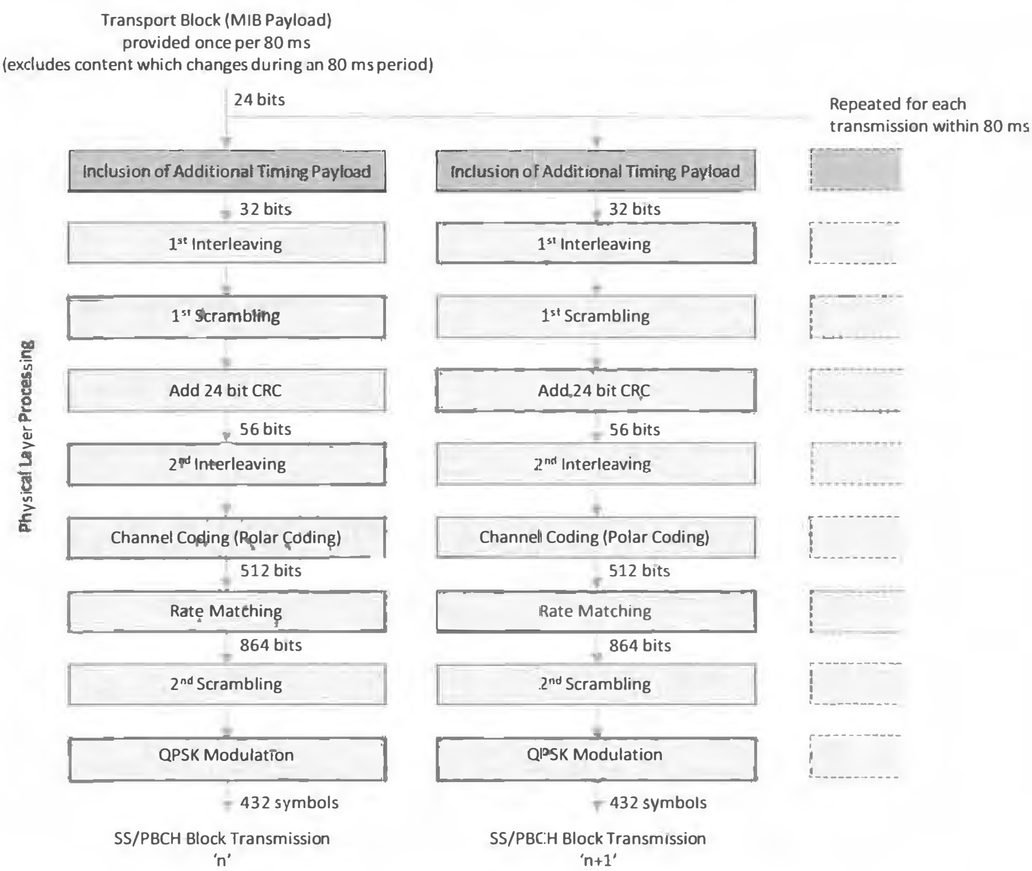


Figure 139 – Physical layer processing for the PBCH

★ Once the 8 bits of additional information have been added to the transport block, a first stage of interleaving is applied. Interleaving simply changes the order of the bits within the packet. This is done using a fixed re-ordering pattern which remains constant for all PBCH transmissions. Interleaving is used to control the order of the bits being fed into the channel coding block. Polar coding provides a non-uniform reliability for the set of input bits. Interleaving is used to control which bits are transferred with the highest reliability and which bits are transferred with a lower reliability. In this case, the timing information bits (10 bits for the SFN; 1 bit for the Half Frame Index; 3 bits for the SS/PBCH Block Index) are mapped into the positions with the lowest reliability. This strategy has been adopted based upon the assumption that many networks will be time synchronised so when the PBCH is being read as part of a mobility procedure then the timing information will already be known and so it is more important to prioritise the remainder of the payload. This argument also applies to UE which are re-reading the PBCH from the current serving cell, i.e. the synchronisation information is already known and it is more important to prioritise the remainder of the payload

- It should be noted that there is a second interleaving stage just prior to channel coding. It is the combination of these two interleaving stages which moves the timing information bits into the least reliable positions
- A first stage of scrambling is applied after the first stage of interleaving. The following timing information bits are excluded from the scrambling procedure:
  - 2nd and 3rd Least Significant Bits (LSB) of the System Frame Number (SFN)
  - 1 bit Half Frame Index
  - 1st, 2nd, 3rd Least Significant Bits (LSB) of the SS/PBCH Block Index

  Scrambling uses a pseudo random sequence to 'randomly' change some bits from '1' to '0' and other bits from '0' to '1'. The order of the bits is not changed. The scrambling sequence is initialised using the Physical layer Cell Identity (PCI) so neighbouring cells will use different scrambling sequences. The objective of the scrambling is to randomise the bit stream and thus randomise the intercell interference experienced by neighbouring cells. The impact of intercell interference is reduced if the interference appears random (similar to thermal noise)
- Randomisation of the bit stream is further improved by giving the scrambling sequence a time dependency. The 2nd and 3rd LSB of the SFN are used to determine which part of the scrambling sequence is used for each PBCH transmission. The 2nd and 3rd LSB are used rather than the 1st and 2nd LSB because the default PBCH transmission period is 20 ms. The 1st LSB of the SFN toggles between '0' and '1' every 10 ms and so does not change when sampled every 20 ms. The 2nd and 3rd LSB of the SFN are excluded from the scrambling process to allow the UE receiver to de-scramble the payload without any blind detection attempts. The UE will already know the PCI from the Synchronisation Signals and will be able to read the 2nd and 3rd LSB of the SFN directly from the PBCH payload. This allows the UE to identify the scrambling sequence used at the transmitter and thus complete the de-scrambling
- 24 Cyclic Redundancy Check (CRC) bits are calculated from the set of 32 bits and are subsequently concatenated to generate a resultant packet size of 56 bits. These CRC bits are used at the UE receiver to detect whether or not there are any bit errors within the decoded packet
- The 2nd stage of interleaving is applied prior to channel coding. Similar to the 1st stage of interleaving, the bit positions are changed to determine which parts of the payload are transmitted with the highest reliability and which parts of the payload are transmitted with a lower reliability. The 2nd stage of interleaving moves the CRC bits into the positions with the highest reliability, i.e. the CRC bits are treated as the most important bits
- In principle it would be possible to combine the two interleaving stages into a single stage of interleaving. They have been specified separately because the 2nd stage of interleaving and the channel coding has been re-used from the PDCCH. Thus, these processes are common with the processing of the PDCCH payload, whereas the 1st stage of interleaving is specific to the PBCH
- Polar Coding is used for the PBCH channel coding. This is in contrast to 4G which uses convolutional coding for the PBCH. The Polar Coding increases the number of bits from 56 to 512, i.e. a coding rate of 56 / 512 = 0.11
- Rate Matching is applied to ensure that the number of bits corresponds to the capacity of the Physical Channel. Each transmission of the PBCH is allocated 432 Resource Elements. The PBCH is always transmitted using QPSK modulation so the 432 Resource Elements are able to accommodate 432 QPSK symbols which transfer 864 bits of information. The Rate Matching procedure applies repetition to generate 864 bits from the set of 512 Polar coded bits
- A second phase of scrambling is applied before modulation. The scrambling sequence is initialised using the Physical layer Cell Identity (PCI). The section of the scrambling sequence which is used for scrambling is dependent upon:
  - 2 least significant bits of the SS/PBCH Block Index, for operating bands below 3 GHz
  - 3 least significant bits of the SS/PBCH Block Index, for operating bands above 3 GHz

  The UE will be able to de-scramble the received data without any blind decoding attempts because the PCI will already be known from the Synchronisation Signals and the SS/PBCH Block Index bits will already be known from the PBCH Demodulation Reference Signal
- UE receiving the PBCH in good coverage conditions can receive and decode the payload using a single instance of the PBCH. UE in weaker coverage conditions may need to receive multiple instances of the PBCH prior to successful decoding. UE can use soft combining to improve the signal to noise ratio when receiving multiple instances of the PBCH. The drawback of soft combining is increased delay caused by the UE having to wait for multiple PBCH transmissions
- 3GPP References: TS 38.211, TS 38.212

3.4 SS/PBCH BLOCKS AND BURSTS

★ Synchronisation Signal / Physical Broadcast Channel (SS/PBCH) Blocks are used during the cell search procedure, i.e. UE search for Synchronisation Signals when scanning for a cell to camp on. UE then decode the PBCH before proceeding to decode other system information which is transmitted on the PDSCH. SS/PBCH Blocks are also used for RSRP, RSRQ and SINR measurements

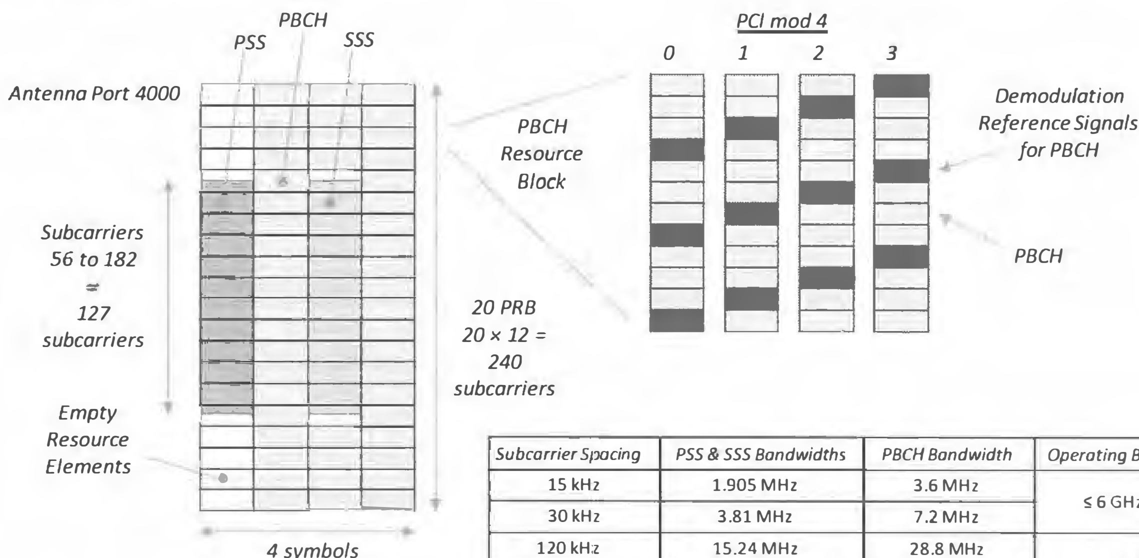
★ An SS/PBCH Block is a downlink transmission occupying 20 Resource Blocks in the frequency domain and 4 symbols in the time domain. It includes the Primary Synchronisation Signal (PSS), the Secondary Synchronisation Signal (SSS) and the PBCH. 3GPP has specified the bandwidth of the SS/PBCH Block to ensure that it does not exceed the minimum UE bandwidth capability requirement for a specific operating band, i.e. all UE must be capable of receiving an SS/PBCH Block

★ The structure of an SS/PBCH Block is illustrated in Figure 140. The PSS occupies 127 subcarriers within the first symbol, whereas the SSS occupies 127 subcarriers within the third symbol. The PBCH occupies 20 Resource Blocks within the second and forth symbols. It also occupies 8 Resource Blocks within the third symbol. The whole SS/PBCH Block is transmitted using antenna port 4000

★ The Resource Blocks allocated to the PBCH accommodate both the PBCH payload and the PBCH Demodulation Reference Signal (DMRS). The DMRS occupies 25% of the Resource Elements allocated to the PBCH so the PBCH payload has $48 \times 12 \times 0.75 = 432$ Resource Elements. The PBCH uses QPSK modulation so this equates to 864 bits

★ The Resource Elements occupied by the PBCH DMRS are dependent upon the Physical layer Cell Identity (PCI). The DMRS occupies 1 in 4 Resource Elements so a 'PCI mod 4' rule has been specified to determine its location. The UE is able to deduce the PCI from the Primary and Secondary Synchronisation Signals so the UE knows where to expect the DMRS when decoding the PBCH payload

★ The UE can use the SSS as an additional Demodulation Reference Signal due to its location within the PBCH, i.e. the propagation channel experienced by the SSS will be similar to the propagation channel experienced by the PBCH so the UE can use both the SSS and the PBCH DMRS to determine the impact of the propagation channel and then apply the inverse to the PBCH payload before attempting to decode



Subcarrier Spacing	PSS & SSS Bandwidths	PBCH Bandwidth	Operating Bands
15 kHz	1.905 MHz	3.6 MHz	≤ 6 GHz
30 kHz	3.81 MHz	7.2 MHz	
120 kHz	15.24 MHz	28.8 MHz	> 6 GHz
240 kHz	30.48 MHz	57.6 MHz	

Figure 140 – Structure of an SS/PBCH Block

★ 3GPP has specified 4 subcarrier spacings for the SS/PBCH Block. Subcarrier spacings of 15 kHz and 30 kHz are applicable to operating bands below 6 GHz. Subcarrier spacings of 120 kHz and 240 kHz are applicable to operating bands above 6 GHz. 3GPP TS 38.104 specifies default SS/PBCH Block subcarrier spacings for each operating band (Table 52 and Table 53 in section 2.5.2). This helps to simplify the cell search procedure and reduce the delay associated with camping on a cell

★ The subcarrier spacing used for the SS/PBCH Block does not need to match the subcarrier spacing used for the remaining physical channels and signals. For example, the SS/PBCH Block could use a subcarrier spacing of 15 kHz while the PDSCH uses a subcarrier spacing of 30 kHz

★ The SSS, PBCH and DMRS for PBCH are transmitted with equal Energy per Resource Element (EPRE). This means that each Resource Element is transmitted with equal power. 3GPP specifies that the PSS can be transmitted with the same EPRE as the SSS/PBCH/DMRS, or it can be transmitted with 3 dB more EPRE. There is scope to increase the transmit power of the PSS because there are unused Resource Elements both above and below the PSS. Increasing the EPRE by 3 dB means that the total power within each symbol of the SS/PBCH Block remains approximately constant

★ The network vendor selects the PSS EPRE relative to the SSS/PBCH/DMRS EPRE. The UE is not provided with information regarding the selection between 0 dB and 3 dB so the UE is required to deduce the offset. Having knowledge of the offset is useful for UE which are capable of Interference Cancellation (IC). Knowledge of the offset simplifies the generation of the signal to be subtracted from the wanted signal. In addition, having knowledge of the offset is useful for the UE receiver Automatic Gain Control (AGC) which can be tuned according to the power of each symbol belonging to the SS/PBCH Block

★ The frequency domain position of an SS/PBCH Block within the channel bandwidth can be specified using a Resource Block offset and a subcarrier offset:

- o N_{CRB}^{SSB} defines a Resource Block offset between Common Resource Block 0 and the Common Resource Block which overlaps with the start of the SS/PBCH. The numerology used for the Common Resource Block numbering is set equal to the value of *subCarrierSpacingCommon* provided by the MIB. The value of N_{CRB}^{SSB} is broadcast within SIB1 using the *offsetToPointA* information element

- o k_{SSB} defines a subcarrier offset from subcarrier 0 of the Common Resource Block identified by *offsetToPointA* to subcarrier 0 of the SS/PBCH. In the case of Frequency Range 1, k_{SSB} is based upon a 15 kHz subcarrier spacing while the SS/PBCH can use subcarrier spacings of 15 or 30 kHz, and *subCarrierSpacingCommon* can be set to either 15 or 30 kHz. The MIB provides *ssb-SubcarrierOffset* which defines the 4 Least Significant Bits of the subcarrier offset (k_{SSB}). In the case of Frequency Range 2 (24.25 GHz to 52.60 GHz), the Subcarrier Offset requires a range from 0 to 11 and these 4 bits are sufficient. In the case of Frequency Range 1 (450 MHz to 6 GHz), the Subcarrier Offset requires a range from 0 to 23 so a 5th bit is required. This 5th bit (the Most Significant Bit) is included within the Physical layer payload of the PBCH and is transmitted in combination with the MIB

★ Figure 109 within section 2.3.1 illustrates two examples of the Resource Block and subcarrier offsets for Frequency Range 1. Figure 110 illustrates two examples of the Resource Block and subcarrier offsets for Frequency Range 2. Figure 141 is a simplified diagram to illustrate the general concept

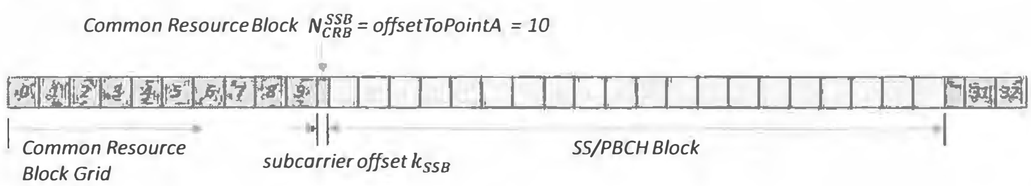


Figure 141 – Frequency domain position of an SS/PBCH Block

★ Alternatively, the frequency domain position of an SS/PBCH Block within the channel bandwidth can be specified using a pair of absolute frequencies. Dedicated signalling can be used to provide both absolute frequencies within the *FrequencyInfoDL* parameter structure. The *absoluteFrequencyPointA* information element specifies the position of the channel bandwidth using a New Radio ARFCN (NR-ARFCN) value. Similarly, the *absoluteFrequencySSB* information element specifies the position of the SS/PBCH Block using an NR-ARFCN value

★ An 'SS/PBCH Burst':

- o includes one or more SS/PBCH Blocks
- o the maximum number of SS/PBCH Blocks within a burst depends upon the operating band
- o is contained within a 5 ms time window, i.e. half a radio frame

★ SS/PBCH Bursts are used to address the requirements of beamforming and beam sweeping. Each SS/PBCH Block belonging to an SS/PBCH Burst is allocated to a beam. This general concept is illustrated in Figure 142

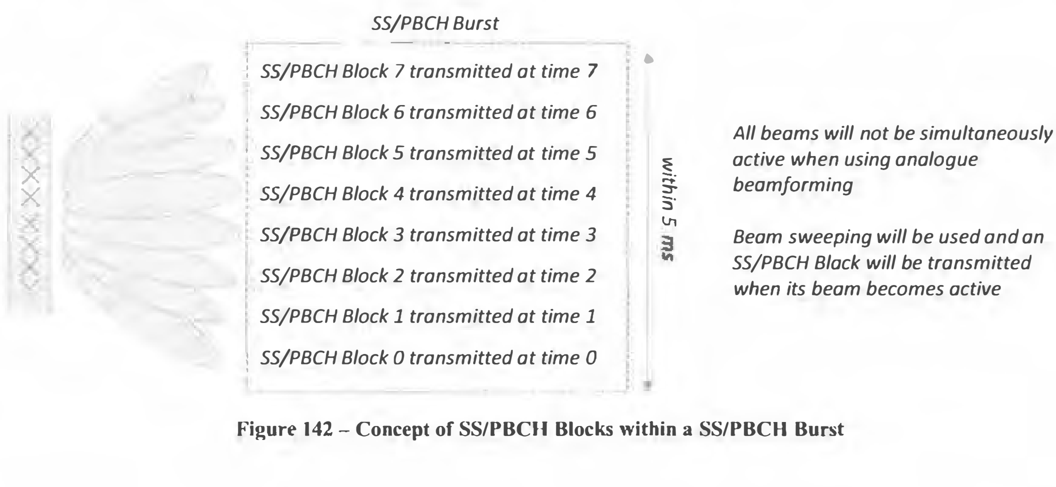


Figure 142 – Concept of SS/PBCH Blocks within a SS/PBCH Burst

★ In the case of digital beamforming, all beams are simultaneously active but each beam is allocated a separate SS/PBCH Block within the SS/PBCH Burst so each beam transmits its SS/PBCH Block with different timing. This allows the UE to clearly separate the transmissions from each beam and beam indices can be identified based upon the timing of the SS/PBCH Block

★ In the case of analogue beamforming, beams are not all simultaneously active and beam sweeping is used. Similar to digital beamforming, each beam is allocated a separate SS/PBCH Block within the SS/PBCH Burst so each beam transmits its SS/PBCH Block with different timing, i.e. when the beam becomes active. Beam sweeping is applied throughout the duration of each SS/PBCH Burst but the Packet Scheduler is free to select the active beam(s) during the time between SS/PBCH Bursts, e.g. if all of the traffic is in a single direction then the Packet Scheduler may activate only a single beam between SS/PBCH beam sweeps

★ Table 56 presents the set of symbols which have been specified as candidates for the start of an SS/PBCH transmission. There can be a maximum of 4 SS/PBCH Blocks within a Burst Set when using an operating band below 3 GHz. This increases to 8 when using an operating band between 3 and 6 GHz. The maximum increases to 64 when using operating bands above 6 GHz. This trend reflects the maximum number of beams which are expected for the various operating bands, i.e. higher operating bands with smaller wavelengths and smaller antenna elements can benefit from an increased number of beams

Subcarrier Spacing	Slots per 5 ms Half Frame	Symbols per Half Frame (5 subframes)	Symbols which are candidates for starting SS/PBCH Block transmissions		
			≤ 3 GHz 4 Candidates	> 3 GHz, ≤ 6 GHz 8 Candidates	> 6 GHz 64 Candidates
15 kHz	5	70	2, 8, 16, 22 (2 subframes)	2, 8, 16, 22, 30, 36, 44, 50 (4 subframes)	-
30 kHz	10	140	4, 8, 16, 20 (1 subframe)	4, 8, 16, 20, 32, 36, 44, 48 (2 subframes)	-
			2, 8, 16, 22 (1 subframe) *See Note 1*	2, 8, 16, 22, 30, 36, 44, 50 (2 subframes) *See Note 1*	-
120 kHz	40	560	-	-	{4, 8, 16, 20} + 28 × n where n = 0, 1, 2, 3, 5, 6, 7, 8, 10, 11, 12, 13, 15, 16, 17, 18 {4, 8, 16, 20, 32, 36, 44, 48, 60, 64, 72, 76, 88, 92, 100, 104, 144, 148, 156, 160, 172, 176, 184, 188, 200, 204, 212, 216, 228, 232, 240, 244, 284, 288, 296, 300, 312, 316, 324, 328, 340, 344, 352, 356, 368, 372, 380, 384, 424, 428, 436, 440, 452, 456, 464, 468, 480, 484, 492, 496, 508, 512, 520, 524} (5 subframes)
240 kHz	80	1120	-	-	{8, 12, 16, 20, 32, 36, 40, 44} + 56 × n where n = 0, 1, 2, 3, 5, 6, 7, 8 {8, 12, 16, 20, 32, 36, 40, 44, 64, 68, 72, 76, 88, 92, 96, 100, 120, 124, 128, 132, 144, 148, 152, 156, 176, 180, 184, 188, 200, 204, 208, 212, 288, 292, 296, 300, 312, 316, 320, 324, 344, 348, 352, 356, 368, 372, 376, 380, 400, 404, 408, 412, 424, 428, 432, 436, 456, 460, 464, 468, 480, 484, 488, 492} (3 subframes)

Note 1: in this specific case, the 3 GHz threshold is applicable to FDD operating bands. The threshold is reduced to 2.4 GHz for TDD operating bands. This increases the number of TDD operating bands which can use 8 SS/PBCH Blocks

Table 56 – Candidates for the starting symbol of SS/PBCH Blocks

★ A single slot can accommodate up to 2 SS/PBCH Blocks so the number of slots required to transmit a specific number of SS/PBCH Blocks is given by ROUNDUP(Number of SS/PBCH Blocks / 2)

★ It is not mandatory to use all of the candidate starting positions. For example, a cell operating below 3 GHz may not use beamforming and may use only a single SS/PBCH starting position, i.e. there is a single SS/PBCH Block within the SS/PBCH Burst

★ SIB1 can broadcast the information elements shown within Table 57. When using an operating band below 3 GHz, the 4 leftmost bits of *inOneGroup* are used to indicate which SS/PBCH Blocks are active. When using an operating band between 3 and 6 GHz, all 8 bits of *inOneGroup* are used to indicate which SS/PBCH Blocks are active. When using an operating band above 6 GHz, the 64 SS/PBCH Blocks are divided into 8 groups. The *inOneGroup* bit string indicates which SS/PBCH Blocks within a group are active, while the *groupPresence* bit string indicates which groups are active. The parameter structure also specifies the periodicity of the SS/PBCH Burst and the downlink transmit power of a single Resource Element used by the SSS/PBCH/DMRS

ServingCellConfigCommonSIB		
ssb-PositionsInBurst	inOneGroup	BIT STRING {8 bits}
	groupPresence	BIT STRING {8 bits}
ssb-PeriodicityServingCell	5, 10, 20, 40, 80, 160 ms	
ss-PBCH-BlockPower	-60 to 50 dBm	

Table 57 – Extract from ServingCellConfigCommonSIB broadcast by SIB1

★ Alternatively, dedicated signalling can be used to provide the information elements shown within Table 58. In this case, each frequency range has its own bit string to explicitly indicate which SS/PBCH Blocks are active. The bit string for operating bands above 6 GHz has a length of 64 bits, in contrast to the 16 bits which can be included within SIB1. The bit string of 64 bits provides increased flexibility when using dedicated signalling, while the set of 16 bits within SIB1 helps to restrict the message size

ServingCellConfigCommon		
ssb-PositionsInBurst	CHOICE	
	shortBitmap	BIT STRING {4 bits}
	mediumBitmap	BIT STRING {8 bits}
	longBitmap	BIT STRING {64 bits}
ssb-PeriodicityServingCell	5, 10, 20, 40, 80, 160 ms	
ss-PBCH-BlockPower	-60 to 50 dBm	

Table 58 – Extract from ServingCellConfigCommon provided using dedicated signalling

★ The SS/PBCH Block starting symbols have been selected to avoid symbols which may be allocated to the uplink and downlink control channels, i.e. the downlink control channels may be allocated symbols at the start of a slot, while the uplink control channels may be allocated symbols at the end of a slot. Figure 143 illustrates the timing of the SS/PBCH Blocks when using the 15 kHz and 30 kHz subcarrier spacings. Note that only 2 of the 4 SS/PBCH Blocks are shown for the 15 kHz subcarrier spacing

- o the 15 kHz option and the first 30 kHz option have similar time domain patterns. Both allow 2 downlink control channel symbols at the start of the slot when the PDCCH uses a 15 kHz subcarrier spacing, or 3 downlink control channel symbols when the PDCCH uses a 30 kHz subcarrier spacing. They can also accommodate uplink control channels in the same way. If the PUCCH is using a 15 kHz subcarrier spacing then symbol 6 from the 15 kHz option or symbols 12 and 13 from the first 30 kHz option can be used to accommodate timing advance and transceiver switching, while symbol 7 from the 15 kHz option or symbols 14 and 15 from the first 30 kHz option can be used to accommodate the PUCCH
- o the second 30 kHz option has been specified to help support Ultra Reliable Low Latency Communications (URLLC). This case allows more frequent switching between uplink and downlink, i.e. less delay between transferring data and receiving the acknowledgement. Downlink control and data can be transferred during symbols 0 and 1, while symbol 6 can be used to accommodate timing advance and transceiver switching, while symbol 7 can be used to transfer the uplink acknowledgement

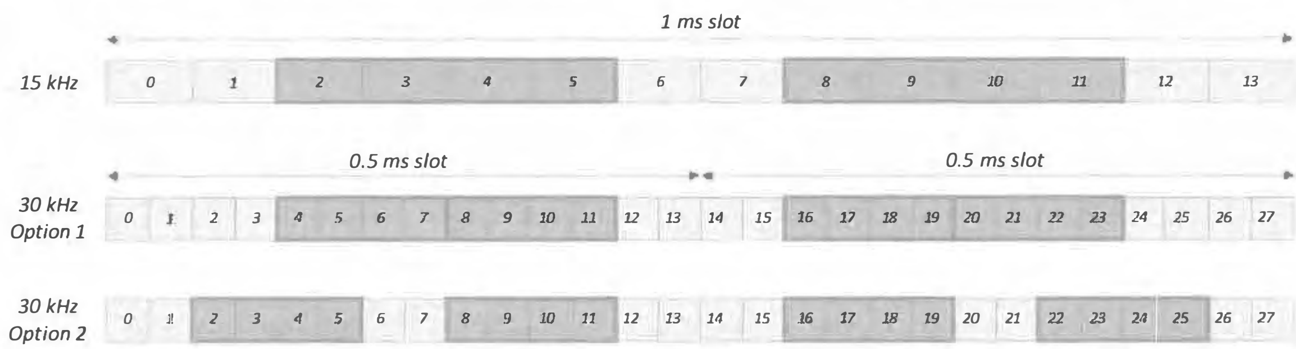


Figure 143 – Timing of SS/PBCH Blocks for 15 kHz and 30 kHz subcarrier spacing

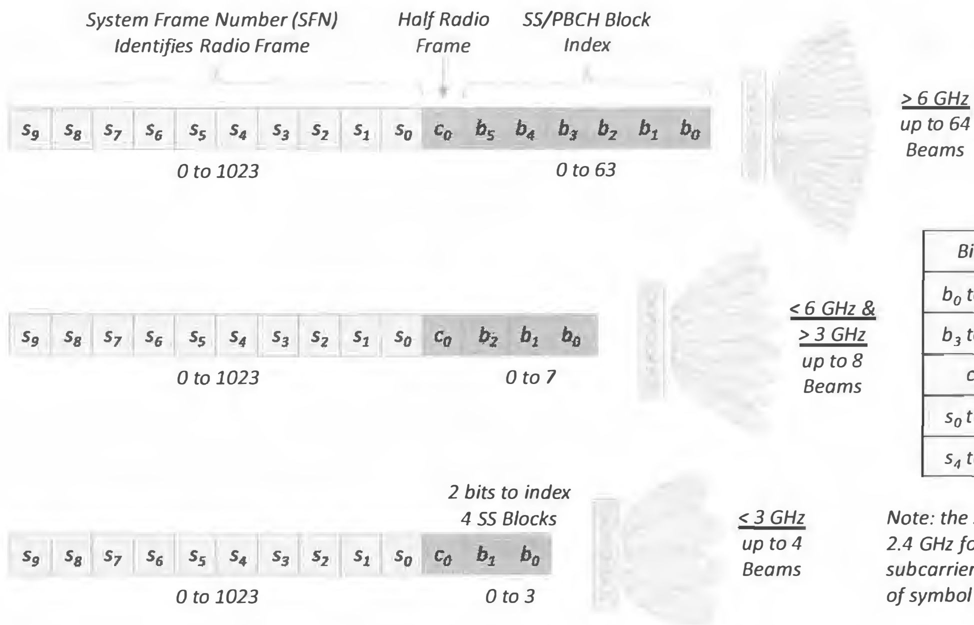
★ When a UE first acquires an SS/PBCH Block, the UE does not immediately know which SS/PBCH Block within the burst has been received. For example, if the Base Station is operating above 6 GHz and is transmitting 64 SS/PBCH Blocks within each burst then the UE does not immediately know which of the 64 SS/PBCH Blocks has been received

★ An SS/PBCH Block can be identified using a combination of the System Frame Number (SFN), the Half Radio Frame, and the SS/PBCH Block Index. The combination of this information uniquely identifies the SS/PBCH Block within a 10.24 second time window. Figure 144 illustrates this timing information for each frequency range. The UE can achieve radio frame, slot and symbol synchronisation once this information has been acquired

★ The 6 Most Significant Bits (MSB) of the SFN are extracted from the content of the Master Information Block (MIB). The 4 Least Significant Bits (LSB) of the SFN are extracted from the Physical layer payload of the PBCH, i.e. they are transmitted in combination with the MIB on the PBCH

★ The Half Radio Frame flag is extracted from the Physical layer payload of the PBCH. In the case of operating bands below 3 GHz, the Half Radio Frame flag can also be deduced from the PBCH DMRS scrambling sequence

★ In the case of operating bands above 3 GHz, the 3 LSB of the SS/PBCH Block Index are deduced from the PBCH DMRS scrambling sequence. Operating bands below 3 GHz only require 2 bits so the third bit is used to indicate the Half Radio Frame flag. Operating bands above 6 GHz require 6 bits for the SS/PBCH Block Index. The additional 3 bits are extracted from the Physical layer payload of the PBCH



Bits	Signalled Using
b_0 to b_2	PBCH DMRS
b_3 to b_5	PBCH Payload
c_0	PBCH Payload
s_0 to s_3	PBCH Payload
s_4 to s_9	MIB Content

Note: the 3 GHz threshold is changed to 2.4 GHz for TDD when using the 30 kHz subcarrier spacing with the second set of symbol timings (Table 53)

Figure 144 – Timing information used to index each SS/PBCH Block transmission

★ A UE can be requested to report the SS/PBCH Block index when providing measurement results. This allows the Base Station to identify the beam from which the measurements were recorded. The relevant section from an RRC: *Measurement Report* message is shown in Table 59

MeasResultNR			
ResultsPerSSB-IndexList	SEQUENCE {1 to 64 instances}		
	ssb-Index	0 to 63	
	ssb-Results	rsrp	0 to 127
		rsrq	0 to 127
		sinr	0 to 127

Table 59 – Extract from *MeasResultNR* applicable to measurement reporting for specific SS/PBCH Blocks

★ Inclusion of the SS/PBCH Block Index within an RRC: *Measurement Report* increases the complexity of the measurement reporting process. If the UE is only required to report the measurements themselves then the UE only needs to detect and measure the Secondary Synchronisation Signal (SSS). If the UE is required to report both the measurements and the SS/PBCH Block Index then the UE also has to detect and decode the PBCH. The SS/PBCH Block Index may not be required for some measurements, e.g. neighbour cell measurements, so the measurement process can be simplified by allowing the UE to report only the measurements themselves

★ 3GPP References: TS 38.211, TS 38.212, TS 38.213

3.5 PHYSICAL DOWNLINK CONTROL CHANNEL

★ The Physical Downlink Control Channel (PDCCH) is used to transfer Downlink Control Information (DCI). This corresponds to Physical layer signalling from layer 1, in contrast to RRC signalling from layer 3 or the use of MAC Control Elements from layer 2. 3GPP has specified a set of DCI Formats to accommodate a range of PDCCH payloads:

- o DCI Format 0_0 'fallback' DCI format for uplink resource allocations on the PUSCH
- o DCI Format 0_1 'standard' DCI format for uplink resource allocations on the PUSCH
- o DCI Format 1_0 'fallback' DCI format for downlink resource allocations on the PDSCH
- o DCI Format 1_1 'standard' DCI format for downlink resource allocations on the PDSCH
- o DCI Format 2_0 provision of Slot Format Indicators (SFI)
- o DCI Format 2_1 provision of Pre-emption Indications
- o DCI Format 2_2 provision of closed loop power control commands applicable to the PUCCH and PUSCH
- o DCI Format 2_3 provision of closed loop power control commands applicable to the SRS

The content of each DCI Format is described in sections 3.5.4 to 3.5.11

★ DCI Formats 2_0, 2_1, 2_2 and 2_3 are used to provide 'UE Group Common Signalling'. These DCI Formats are designed to address a group of UE and can accommodate payloads for each UE within the group. The payload belonging to a specific UE has a specific position within the DCI so each UE is able to extract its own information while ignoring the information intended for other UE

★ Figure 145 illustrates the general mapping of DCI onto the PDCCH physical channel. The PDCCH occupies a specific number of Resource Elements according to its aggregation level. An aggregation level is quantified in terms of the number of Control Channel Elements (CCE) that it occupies. 1 CCE is equivalent to 6 Resource Element Groups (REG) which is also equivalent to 72 Resource Elements. The link adaption algorithm within the Base Station assigns a specific aggregation level according to the size of the DCI payload and the UE coverage conditions. Small payloads can be accommodated using lower aggregation levels. UE which experience poor coverage are normally allocated higher aggregation levels to allow increased channel coding gain, i.e. higher quantities of redundancy

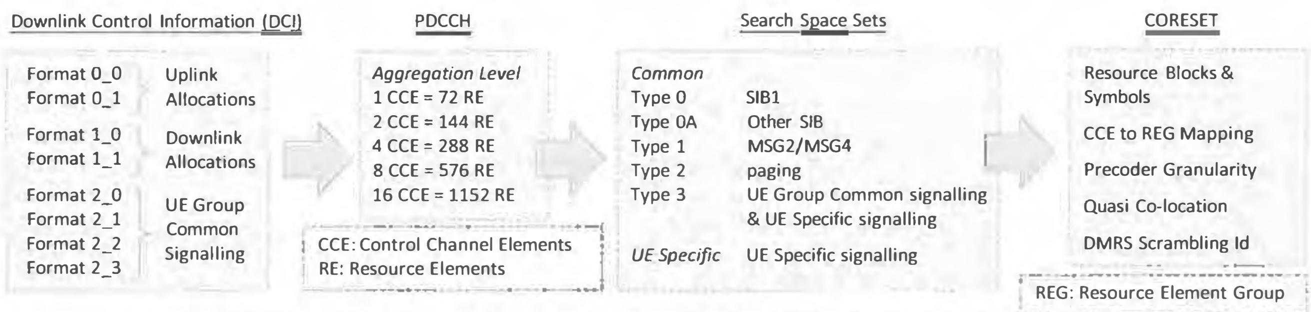


Figure 145 – Mapping of DCI Formats onto the PDCCH, Search Space Sets and Control Resource Sets

★ The PDCCH is mapped onto a specific Search Space Set according to the content of the DCI. For example, if the DCI is being used to provide a resource allocation for MSG2 during the random access procedure, then the PDCCH is mapped onto a Type 1 Common Search Space Set. Alternatively, if the DCI is being used to provide a resource allocation for the transfer of application data then the PDCCH can be mapped onto the UE Specific Search Space Set. Each Search Space Set has got a specific periodicity. This periodicity impacts latency because it determines the average waiting time for a resource allocation opportunity

★ Each Search Space Set is mapped onto a specific Control Resource Set (CORESET). The CORESET defines the set of Resource Blocks and the number of symbols available to the Search Space Set. Various other physical layer characteristics are also defined by the CORESET. These are described in the next section

★ A UE is required to deduce which DCI Format is being received at any point in time. This can be achieved using a combination of the following:

- o PDCCH Search Space Set
- o type of RNTI used to scramble the CRC bits which are attached to the DCI payload
- o size of DCI payload
- o information within the DCI payload

★ For example, if a UE is scanning a Type 2 Common Search Space Set then it knows that it should be checking for DCI Format 1_0 because DCI Format 1_0 is used to provide resource allocations for paging messages. Alternatively, if a UE is scanning a UE Specific Search Space Set then it knows that it should be checking for DCI Formats 0_0, 0_1, 1_0 and 1_1

★ Table 60 presents the set of Radio Network Temporary Identifiers (RNTI) specified by 3GPP. These RNTI are used to scramble the CRC bits which are attached to the DCI payload during Physical layer processing. This is used as a way to address either an individual UE, a group of UE or all UE. The Base Station allocates a unique C-RNTI to each UE within a cell when the UE establishes an RRC connection (either from RRC Idle mode or an incoming handover). If a UE receives a DCI Format 0_1 (for example) and obtains a successful CRC result after de-scrambling the CRC bits using its C-RNTI then the UE knows that the resource allocation is being sent to that UE rather than another UE. The Base Station can allocate a single INT-RNTI to a group of UE. All UE within that group will obtain a successful CRC result after de-scrambling the CRC bits attached to a DCI Format 2_1 payload. 3GPP has specified single fixed values for the SI-RNTI and P-RNTI. These fixed values are applicable to all UE

RNTI	DCI Format	Application	Value
SI-RNTI	1_0	PDSCH resources for System Information	FFFF
P-RNTI	1_0	PDSCH resources for Paging messages	FFFE
RA-RNTI	1_0	PDSCH resources for Random Access Response (RAR)	
TC-RNTI	0_0, 1_0	PUSCH resources for MSG3 re-transmissions, PDSCH resources for MSG4	
C-RNTI	0_0, 0_1, 1_0, 1_1	PUSCH and PDSCH resources for application data and control plane signalling	
MCS-C-RNTI	0_0, 0_1, 1_0, 1_1	Dynamic selection of low Spectral Efficiency MCS Table for PDSCH and PUSCH	
CS-RNTI	0_0, 0_1, 1_0, 1_1	Configured Grant Scheduling for PUSCH, Semi-Persistent Scheduling for PDSCH	
TPC-PUSCH-RNTI	2_2	Closed loop uplink power control commands for the PUSCH	0001 - FFEF
TPC-PUCCH-RNTI	2_2	Closed loop uplink power control commands for the PUCCH	
TPC-SRS-RNTI	2_3	Closed loop uplink power control commands for the SRS	
INT-RNTI	2_1	Interruption signalled using Pre-emption Indications	
SFI-RNTI	2_0	Dynamic changes to the slot format signalled using Slot Format Indicators (SFI)	
SP-CSI-RNTI	0_1	Trigger to activate/deactivate Semi-Persistent CSI reporting from the UE	

Table 60 – Types of Radio Network Temporary Identifiers (RNTI)

★ The size of the DCI payload can also be used to identify a specific DCI Format. The UE calculates the size of some DCI Formats based upon its configuration. For example, the UE can calculate the size of DCI Formats 0_0, 0_1, 1_0 and 1_1. DCI Formats 0_0 and 1_0 can have equal size, i.e. the pair of 'Fallback' DCI Formats. In some cases, the Base Station explicitly signals the size of a particular DCI Format, e.g. the UE is explicitly told the size of DCI Formats 2_0 and 2_1

★ Specifying multiple DCI Formats with an equal size payload reduces the number of blind decoding attempts required by the UE. For example, if DCI Format 'A' has a payload size of 30 bits and DCI Format 'B' has a payload size of 40 bits. Initially, the UE does not know which DCI Format is being received. The UE has to attempt decoding a payload size of 30 bits before checking the CRC bits to determine whether or not decoding was successful. If unsuccessful, the UE has to attempt decoding a payload size of 40 bits before checking the CRC bits. If both DCI Formats have an equal payload size, the UE only has to attempt decoding once. If the CRC bits indicate that decoding is successful then the UE has to rely upon information within the payload to differentiate between Formats 'A' and 'B', e.g. a single bit of information could be used as a flag to indicate which DCI Format is being received

★ DCI Formats 0_0 and 1_0 include a 1 bit flag to differentiate them, i.e. the flag is set to '0' to indicate an uplink resource allocation and is set to '1' to indicate a downlink resource allocation. Similarly, DCI Formats 0_1 and 1_1 also include a 1 bit uplink/downlink resource allocation flag

★ Figure 146 illustrates the Physical layer processing applied to the DCI Format payload before mapping onto the PDCCH.

★ Cyclic Redundancy Check (CRC) bits are added to allow error detection at the UE. The PDCCH does not have any mechanism which allows the UE to directly indicate successful/unsuccessful reception. Instead, the Base Station has to rely upon indirect mechanisms, e.g. if the Base Station uses the PDCCH to allocate uplink resources on the PUSCH but the Base Station does not receive a PUSCH transmission then it can deduce that the UE failed to receive the PDCCH. A set of 24 CRC bits are calculated from the PDCCH payload. These CRC bits are scrambled using the relevant RNTI. Scrambling changes some bits from '1' to '0' and other bits from '0' to '1'. The order of the bits is not changed.

★ Channel coding is applied after the CRC bits have been added. Polar coding is used as a channel coding solution for the PDCCH. The coding rate depends upon the aggregation level allocated to the PDCCH, i.e. the number of Control Channel Elements (CCE). Table 61 presents the set of aggregation levels specified by 3GPP. The number of Resource Elements shown in this table is required to accommodate both the PDCCH and the PDCCH Demodulation Reference Signal (DMRS), i.e. not all Resource Elements are available to transfer the payload

★ UE in weak coverage are likely to be allocated a higher aggregation level. This increases the number of Resource Elements which are available to transfer the PDCCH payload and allows the use of a lower coding rate (higher redundancy). UE in good coverage are likely to be allocated a lower aggregation level. This decreases the number of Resource Elements which are available to transfer the PDCCH payload and leads to a higher coding rate (lower redundancy). CCE and Resource Element Groups (REG) are described in section 3.5.1

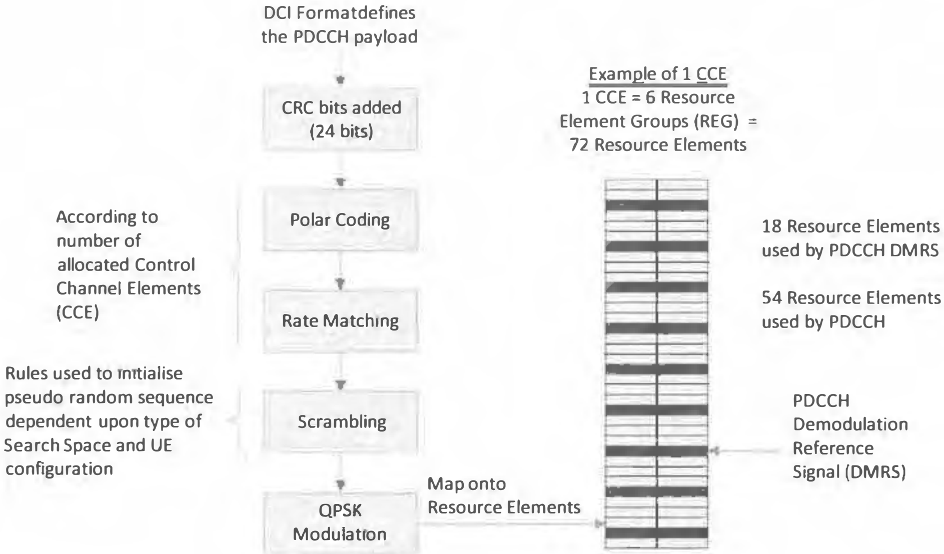


Figure 146 – Physical layer processing for the PDCCH

Aggregation Level	CCE	Resource Element Groups (REG)	Resource Elements
1	1	6	72
2	2	12	144
4	4	24	288
8	8	48	576
16	16	96	1152

Table 61 – PDCCH Aggregation Levels

★ Rate Matching is applied after channel coding to ensure that the number of bits matches the capacity of the Resource Elements available to the PDCCH after accounting for the Demodulation Reference Signal (DMRS). A single CCE can accommodate 108 bits after accounting for the DMRS. Rate Matching also includes an interleaving operation to change the order of the transmitted bits

★ The resultant bits are scrambled using a pseudo random sequence. Initialisation of the pseudo random sequence depends upon the type of Search Space and whether or not the UE has been configured with a *pdcch-DMRS-ScramblingID*. If a Common Search Space is used then the pseudo random sequence is always initialised using the PCI which has been allocated to the cell. If a UE Specific Search Space is used and the UE has been configured with a *pdcch-DMRS-ScramblingID* then the pseudo random sequence is initialised using a combination of the C-RNTI and the *pdcch-DMRS-ScramblingID*. If a UE Specific Search Space is used but the UE has not been configured with a *pdcch-DMRS-ScramblingID* then the pseudo random sequence is initialised using the PCI which has been allocated to the cell

★ QPSK modulation is applied to generate the set of modulation symbols which are mapped onto the allocated Resource Elements. There are 54 Resource Elements available per CCE after accounting for the DMRS

★ The PDCCH and DMRS are transmitted using a single antenna port, i.e. antenna port 2000. Beamforming can be applied to improve downlink coverage. If using a Common Search Space to allocate resources for a paging message or the broadcast of system information then it will be necessary to repeat the PDCCH transmission using multiple beams to ensure that the PDCCH is transmitted across the whole cell. In other cases, the PDCCH can be transmitted using a single beam, e.g. when using a UE Specific Search Space

★ The PDCCH can be transmitted with or without transmit diversity. 3GPP has not specified the precoding for PDCCH transmit diversity but network vendors can implement solutions which are transparent to the UE. The same precoding is applied to both the PDCCH and the DMRS so the UE can use the DMRS to estimate the composite propagation channel (including precoding). The Base Station may apply the same precoding to all Resource Blocks used by the PDCCH, or may apply different precoding to different Resource Blocks. At least some information regarding the precoder granularity in the frequency domain can be provided as part of the Control Resource Set (CORESET) configuration (*precoderGranularity* information element within Table 62, section 3.5.1).

★ 3GPP References: TS 38.211, TS 38.212, TS 38.213, TS 38.321

3.5.1 CONTROL RESOURCE SET (CORESET)

★ The Base Station transmits the PDCCH using Resource Elements which belong to a Control Resource Set (CORESET). A maximum of 3 CORESETs can be configured for an active downlink Bandwidth Part belonging to a specific serving cell. Table 62 presents the parameter structure used to configure a CORESET

★ The *controlResourceSetId* identifies the CORESET within a specific serving cell. It has a range from 0 to 11 which can be used across all Bandwidth Parts belonging to a specific serving cell. Identity 0 is used for the CORESET configured by the *controlResourceSetZero* information element within the Master Information Block (MIB) and within the *ServingCellConfigCommon* parameter structure

★ The Resource Blocks allocated to the CORESET are specified using the *frequencyDomainResources* information element. This information element provides a string of 45 bits where each bit corresponds to a set of 6 contiguous Resource Blocks within the downlink Bandwidth Part, i.e. the bit string caters for a maximum of 6 × 45 = 270 Resource Blocks. A set of 6 contiguous Resource Blocks is included within the CORESET if the corresponding bit within the bit string is set to '1'

★ The number of symbols allocated to the CORESET is specified using the *duration* information element. A CORESET can be configured with a duration of 1, 2 or 3 symbols. The duration is fixed once it has been configured, i.e. it is semi-static. This is in contrast to 4G which allows the number of symbols allocated to the PDCCH to dynamically change over time as the cell load increases and decreases. In the case of 4G, the PCFICH physical channel is used to signal the number of symbols allocated to the PDCCH at any point in time. NR does not have a PCFICH physical channel. This approach helps to simplify the decoding process because the UE does not need to decode the PCFICH before decoding the PDCCH

★ The CORESET duration of 3 symbols is only permitted if the *dmrs-typeA-Position* information element has been set to 3 (rather than 2). The value of 3 corresponds to the 4th symbol which means that the CORESET can occupy the first 3 symbols without coinciding with the DMRS used by the PDSCH. Note that the CORESET configuration does not specify the actual symbols occupied by the CORESET, i.e. the configuration does not specify a starting symbol. The precise timing of the CORESET is defined within the Search Space Set configuration. This allows multiple Search Space Sets to re-use the same CORESET but with different timings

ControlResourceSet			
controlResourceSetId	0 to 11		
frequencyDomainResources	BIT STRING (45 bits)		
duration	1 to 3		
cce-REG-MappingType	CHOICE		
	interleaved		nonInterleaved
	reg-BundleSize	2, 3, 6	-
	interleaverSize	2, 3, 6	
	shiftIndex	0 to 274	
precoderGranularity	sameAsREG-bundle, allContiguousRBs		
tci-StatesPDCCH-ToAddList	SEQUENCE { TCI-StateId }		
tci-StatesPDCCH-ToReleaseList	SEQUENCE { TCI-StateId }		
tci-PresentInDCI	enabled		
pdcch-DMRS-ScramblingID	0 to 65535		

Table 62 – Parameter structure used to configure a Control Resource Set (CORESET)

★ The Resource Elements belonging to a CORESET are organised into Resource Element Groups (REG). A single REG is 1 Resource Block in the frequency domain and 1 symbol in the time domain, i.e. 12 Resource Elements

★ Multiple REG are used to generate Control Channel Elements (CCE). A single CCE is generated using 6 REG, i.e. 72 Resource Elements. 3GPP has specified both non-interleaved and interleaved mappings between REG and CCE. The *cce-REG-MappingType* information element within Table 62 is used to select between the non-interleaved and interleaved options

★ Examples of the non-interleaved mapping are illustrated in Figure 147. The CCE are generated from bundles of 6 consecutively numbered REG. REG numbering increases with time before increasing with frequency. The non-interleaved solution can be used for interference co-ordination with neighbouring cells because the downlink power is restricted to a smaller section of the Bandwidth Part, i.e. one cell uses one section of the Bandwidth Part while a neighbouring cell uses a different section of the Bandwidth Part

★ The interleaved solution can provide frequency diversity because the allocated REG can be distributed across the Bandwidth Part. When using the interleaved solution, REG Bundles are generated from 2, 3 or 6 REG (as specified by *reg-BundleSize*). REG Bundle sizes of 2 and 6 are permitted when either 1 or 2 symbols are allocated to the CORESET. REG Bundle sizes of 3 and 6 are permitted when 3 symbols are allocated to the CORESET. CCE are generated by grouping the REG Bundles. For example, 2 REG Bundles are grouped to generate a CCE when the REG Bundle size is 3 REG. An interleaver depth (as specified by *interleaverSize*) is configured to determine the number of sections that the CORESET bandwidth is divided into when applying the interleaving

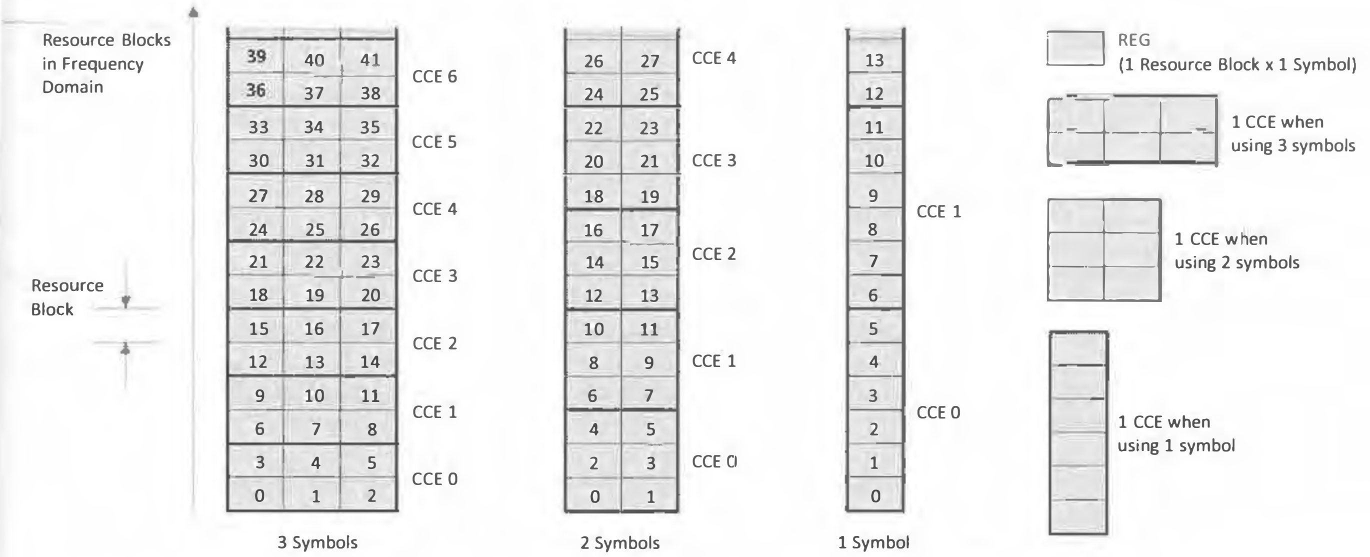


Figure 147 – Non-interleaved mapping of CCE onto REG

★ Some examples of interleaved REG to CCE mappings are illustrated in Figure 148. All examples assume that 3 symbols have been allocated to the CORESET. The first two examples assume a REG Bundle size of 6 REG. This leads to 1 REG Bundle per CCE (similar to the non-interleaved mapping). The first example is based upon an interleaver depth of 3 so the CORESET bandwidth is divided into 3 sections and CCE numbering rotates around those sections (only part of the CORESET bandwidth is shown in Figure 148). The second example is based upon an interleaver depth of 6 so the CORESET bandwidth is divided into 6 sections and CCE numbering rotates around those sections. The third example assumes a REG Bundle size of 3 REG. This leads to 2 REG Bundles per CCE. An interleaver depth of 6 is applied so the CORESET bandwidth is divided into 6 sections and CCE numbering rotates around those sections. However, in this case the CCE numbering increments across every second section because each CCE requires 2 REG Bundles

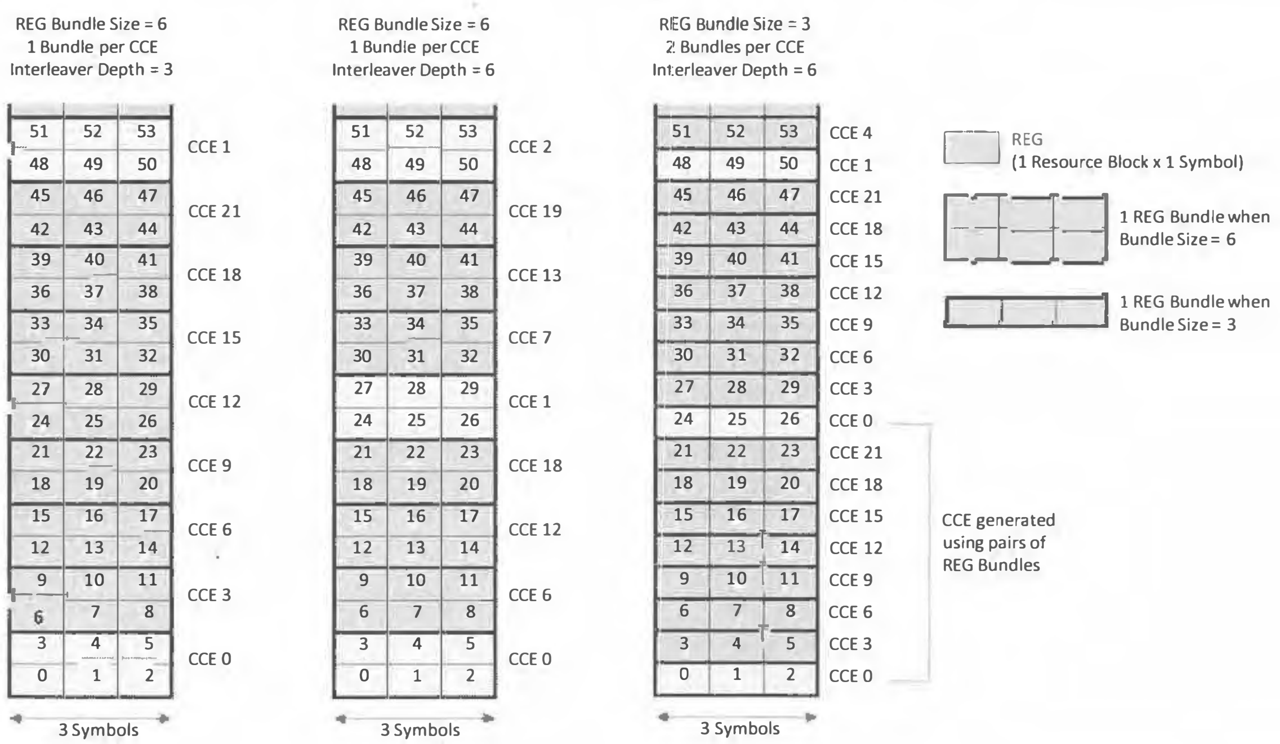


Figure 148 – Interleaved mapping of CCE from REG

★ The *shiftIndex* information element can be used to apply a cyclic shift to the interleaving pattern. If the CORESET is configured by the Master Information Block (MIB) or by SIB 1, the cyclic shift is defined by the PCI rather than by the *shiftIndex* information element. The cyclic shift moves the CCE pattern upwards, with wraparound from the top to the bottom

★ The PDCCH and its Demodulation Reference Signal (DMRS) are transmitted using a single antenna port (antenna port 2000). The Base Station can apply precoding to this antenna port to generate a beam in the direction of the UE. This precoding is transparent to the UE but downlink performance can be improved if the UE has at least some knowledge of the precoding. The *precoderGranularity* information element provides the UE with information regarding the frequency selectivity of the precoding applied by the Base Station. If *precoderGranularity* is set to '*sameAsREG-bundle*' then the UE assumes that the Base Station applies the same precoding weights to all Resource Blocks within a REG Bundle. Otherwise, if *precoderGranularity* is set to '*allContiguousRBs*' then the UE assumes that the Base Station applies the same precoding weights to all Resource Blocks belonging to contiguous REG Bundles

★ The UE can also be provided with Quasi Co-Location (QCL) information to support successful reception of the PDCCH. QCL means that transmissions from different antenna ports share some common characteristics. For example, they may experience the same Doppler shift, Doppler spread, average delay and delay spread. The CORESET can be Quasi Co-Located with a Synchronisation Signal Block (SSB), or with a CSI Reference Signal. Providing the UE with knowledge of this Quasi Co-Location can help the UE to complete channel estimation, frequency offset estimation and synchronisation (QCL is introduced in section 2.6)

★ Quasi Co-Location is configured within the *ControlResourceSet* parameter structure by listing the identity of one or more Transmission Configuration Indicator (TCI) States. Each identity points towards a *TCI-State* parameter structure, as shown in Table 63. This parameter structure specifies either 1 or 2 instances of Quasi Co-Location (*qcl-Type2* is optional). In each case, either an SSB or a CSI Reference Signal is linked to a specific *qcl-Type*. 3GPP has specified 4 types of QCL to indicate which large scale channel characteristics are common between the PDCCH and the SSB/CSI Reference Signal. These 4 types of QCL are labelled A, B, C and D:

- o QCL Type A: {Doppler Shift; Doppler Spread; Average Delay, Delay Spread}
- o QCL Type B: {Doppler Shift; Doppler Spread}
- o QCL Type C: {Doppler Shift; Average Delay}
- o QCL Type D: {Spatial Receiver Parameters}

TCI-State					
tci-StateId	0 to 11				
qcl-Type1	ServCellIndex	0 to 31			
	bwp-Id	0 to 4			
	referenceSignal	CHOICE			
		csi-rs		ssb	
		NZP-CSI-RS-ResourceId	0 to 191	SSB-Index	0 to 63
	qcl-Type	typeA, typeB, typeC, typeD			
qcl-Type2	ServCellIndex	0 to 31			
	bwp-Id				
	referenceSignal	CHOICE			
		csi-rs		ssb	
		NZP-CSI-RS-ResourceId	0 to 191	SSB-Index	0 to 63
	qcl-Type	typeA, typeB, typeC, typeD			

Table 63 – Transmission Configuration Indicator (TCI) State parameter structure

★ If only a single TCI State is listed within the *ControlResourceSet* parameter structure then the UE assumes Quasi Co-Location between the PDCCH and the SSB/CSI Reference Signal specified by that TCI State. If multiple TCI States are listed within the *ControlResourceSet* parameter structure then the UE requires an activation command to identify which TCI State to apply. The 'TCI State Indication for UE-specific PDCCH' MAC Control Element is used to provide the activation command. This MAC Control Element is illustrated in Figure 149. If multiple TCI States are listed within the *ControlResourceSet* parameter structure but the UE has not received an activation command then the UE can assume Quasi Co-Location between the PDCCH and the SSB selected during the initial access procedure

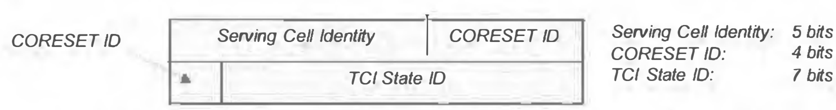


Figure 149 – TCI State Indication for UE-specific PDCCH MAC Control Element

★ The *tci-PresentInDCI* information element specifies whether or not DCI Format 1_1 includes the 'Transmission Configuration Indication' field. This field is applicable to the reception of the PDSCH, i.e. it can be used to activate TCI States for the PDSCH

★ The *pdcch-DMRS-ScramblingID* information element can be used to initialise the pseudo random sequence which populates the DMRS Resource Elements. If this information element is not provided, the Physical layer Cell Identity (PCI) is used instead. This information element can also be used in combination with the C-RNTI to initialise the scrambling sequence for the PDCCH payload when using a UE Specific Search Space (see section 3.5)

3.5.2 SEARCH SPACE SETS

★ A Search Space uses a Control Resource Set (CORESET) to define the specific Resource Blocks and symbols where the UE attempts to decode the PDCCH. A UE attempts 'blind' decoding within the Search Space because the UE does not know the aggregation level being used, nor does it know the position of the PDCCH amongst the set of CCE. In addition, the UE may not know the DCI Format being transmitted which means the UE does not know the size of the payload

★ Blind decoding generates a significant processing load at the UE so 3GPP has specified a set of restrictions to help limit the processing requirement. The first restriction (presented in Table 64) is the maximum number of PDCCH candidates per slot and per serving cell. This restriction is a function of the subcarrier spacing because high subcarrier spacings allow less time for a UE to complete its search, i.e. the slots are shorter. A UE is expected to be capable of completing 44 blind decoding attempts when the subcarrier spacing is 15 kHz. The Base Station can configure the UE to distribute these 44 attempts across a range of aggregation levels. The requirement decreases to 20 blind decoding attempts when the subcarrier spacing is 120 kHz

★ The second restriction (also presented in Table 64) is the maximum number of CCE which require channel estimation per slot and per serving cell. In the case of 4G, the PDCCH does not have a Demodulation Reference Signal (DMRS) and the Cell specific Reference Signal is used for channel estimation. In the case of 5G, the PDCCH has a DMRS for channel estimation. Channel estimation requires baseband processing so there is a limit to the number of channel estimates which can be generated per slot. This restriction also depends upon the subcarrier spacing because high subcarrier spacings allow less time for a UE to complete the channel estimates

	Subcarrier Spacing			
	15 kHz	30 kHz	60 kHz	120 kHz
Maximum PDCCH candidates per slot and per serving cell	44	36	22	20
Maximum CCE requiring channel estimation per slot and per serving cell	56	56	48	32

Table 64 – Restrictions per subcarrier spacing to limit the UE processing requirement for blind decoding of the PDCCH

★ In addition to the restrictions presented in Table 64, 3GPP has specified that a UE needs to be capable of monitoring up to 3 DCI Format sizes per serving cell for DCI Formats which use the C-RNTI to scramble the CRC bits. The UE also needs to be capable of monitoring a fourth DCI Format size per serving cell for DCI Formats which do not use the C-RNTI to scramble the CRC bits

★ Table 65 presents the categories of Search Space Sets which have been standardised by 3GPP. There are 'Common' and 'UE Specific' Search Space Sets. Common Search Space Sets are further categorised as Type 0, 0A, 1, 2 and 3

Type		RNTI	DCI Format	Application
Common	Type 0	SI-RNTI	1_0	SIB1
	Type 0A	SI-RNTI	1_0	SIB2, SIB3, SIB4, etc
	Type 1	RA-RNTI, TC-RNTI	0_0, 1_0	MSG2 / MSG3 / MSG4
	Type 2	P-RNTI	1_0	Paging
	Type 3	INT-RNTI, SFI-RNTI, TPC-PUSCH-RNTI, TPC-PUCCH-RNTI, TPC-SRS-RNTI, C-RNTI, MCS-C-RNTI, CS-RNTI	0_0, 1_0, 2_0, 2_1, 2_2, 2_3	UE Group Common signalling & UE data transfer using Fallback DCI Formats
UE Specific		C-RNTI, MCS-C-RNTI, CS-RNTI	0_0, 0_1, 1_0, 1_1	UE data transfer

Table 65 – Categories of Search Space Sets

★ A Type 0 Common Search Space Set is used for PDCCH transmissions which provide resource allocations for System Information Block 1 (SIB1). This Search Space Set is configured within the Master Information Block (MIB) on the PBCH. It can also be configured using the *searchSpaceSIB1* and *searchSpaceZero* information elements within the *PDCCH-ConfigCommon* parameter structure shown in Table 66. The *PDCCH-ConfigCommon* parameter structure includes both *searchSpaceZero* and *controlResourceSetZero* information elements. These are the same information elements as those used by the MIB. Their use is described in greater detail in Section 3.5.3. The Search Space set configured by the *searchSpaceSIB1* information element is mapped onto the Control Resource Set (CORESET) with identity 0

★ A Type 0A Common Search Space Set is used for PDCCH transmissions which provide resource allocations for Other System Information (OSI), i.e. SIB2, SIB3, SIB4, etc. This Search Space Set can be configured within SIB1 using the *searchSpaceOtherSystemInformation* information element which belongs to the *PDCCH-ConfigCommon* parameter structure shown in Table 66. The *searchSpaceOtherSystemInformation* information element configures the identity of the Search Space Set which is to be used as the Type 0A Common Search Space Set. The Search Space Set itself is configured using the *SearchSpace* parameter structure presented later in this section. The *PDCCH-ConfigCommon* parameter structure can also be provided to the UE using dedicated signalling (in addition to being broadcast within SIB1)

★ A Type 1 Common Search Space Set is used for PDCCH transmissions which provide resource allocations for uplink and downlink messages associated with the random access procedure, i.e. MSG2, MSG3 and MSG4. DCI Format 1_0 is used in combination with an RA-RNTI to allocate resources for MSG2 (Random Access Response). The uplink resource allocation for the first transmission of

MSG3 is included within the Random Access Response so PDCCH reception is not necessary. However, MSG3 re-transmissions are scheduled using DCI Format 0_1 in combination with a TC-RNTI. DCI Format 1_0 is used in combination with a TC-RNTI to allocate resources for MSG4

★ A Type 1 Common Search Space Set can be configured within SIB1 or by using dedicated signalling. The *ra-SearchSpace* information element shown in Table 66 configures the identity of the Search Space Set which is to be used as the Type 1 Common Search Space Set. The Search Space Set itself is configured using the *SearchSpace* parameter structure presented later in this section

★ A Type 2 Common Search Space Set is used for PDCCH transmissions which provide resource allocations for paging messages. This Search Space Set can be configured within SIB1 or by using dedicated signalling. The *pagingSearchSpace* information element shown in Table 66 configures the identity of the Search Space Set which is to be used as the Type 2 Common Search Space Set. The Search Space Set itself is configured using the SearchSpace parameter structure presented later in this section

PDCCH-ConfigCommon	
controlResourceSetZero	0 to 15
commonControlResourceSet	*ControlResourceSet* (Table 62)
searchSpaceZero	0 to 15
commonSearchSpaceList	1 to 4 instances of *SearchSpace* (Table 68)
searchSpaceSIB1	0 to 39
searchSpaceOtherSystemInformation	0 to 39
pagingSearchSpace	0 to 39
ra-SearchSpace	0 to 39

Table 66 – *PDCCH-ConfigCommon* parameter structure

★ A Type 3 Common Search Space Set is used for PDCCH transmissions which provide resource allocations for UE Group Common signalling, i.e. based upon DCI Format 2_0 with an SFI-RNTI; DCI Format 2_1 with an INT-RNTI; DCI Format 2_2 with a TPC-PUSCH-RNTI or TPC-PUCCH-RNTI; DCI Format 2_3 with a TPC-SRS-RNTI. A Type 3 Common Search Space Set can also be used for PDCCH transmissions which provide resource allocations for the 'fallback' DCI Formats 0_0 and 1_0 in combination with a C-RNTI, MCS-C-RNTI or CS-RNTI

★ In contrast to the other Common Search Space Sets, a Type 3 Common Search Space Set cannot be configured using the MIB nor SIB. A Type 3 Common Search Space Set is configured using the *PDCCH-Config* parameter structure within dedicated signalling. This parameter structure is presented in Table 67. A Type 3 Common Search Space Set is configured by adding an instance of the *SearchSpace* parameter structure with the *searchSpaceType* set to 'common'. The *SearchSpace* parameter structure is presented in Table 68

PDCCH-Config	
controlResourceSetToAddModList	1 to 3 instances of *ControlResourceSet* (Table 62)
controlResourceSetToReleaseList	1 to 3 instances of *ControlResourceSetId*
searchSpacesToAddModList	1 to 10 instances of *SearchSpace* (Table 68)
searchSpacesToReleaseList	1 to 10 instances of *SearchSpaceId*
downlinkPreemption	SetupRelease { *DownlinkPreemption* }
tpc-PUSCH	SetupRelease { *PUSCH-TPC-CommandConfig* }
tpc-PUCCH	SetupRelease { *PUCCH-TPC-CommandConfig* }
tpc-SRS	SetupRelease { *SRS-TPC-CommandConfig* }

Table 67 – *PDCCH-Config* parameter structure

★ A UE Specific Search Space Set is used for PDCCH transmissions which provide resource allocations for uplink and downlink data transfer. DCI Formats 0_0 and 0_1 provide uplink resource allocations, while DCI Formats 1_0 and 1_1 provide downlink resource allocations. Both the C-RNTI and MCS-C-RNTI can be used for the allocation of dynamic grants. This pair of RNTI allows rapid switching between the standard MCS table and the low spectral efficiency MCS table, i.e. the C-RNTI indicates that the UE should use the standard MCS table, while the MCS-C-RNTI indicates that the UE should use the low spectral efficiency MCS table. The CS-RNTI can be used to activate and deactivate Scheduled Grant transmissions in the uplink and Semi-Persistent Scheduling (SPS) in the downlink

★ Similar to a Type 3 Common Search Space Set, UE Specific Search Space Sets are configured using the *PDCCH-Config* parameter structure (Table 67) within dedicated signalling. A UE Specific Search Space Set is configured by adding an instance of the *SearchSpace* parameter structure (Table 68) with the *searchSpaceType* set to 'ue-Specific'

SearchSpace						
searchSpaceId	0 to 39					
controlResourceSetId	0 to 11					
monitoringSlotPeriodicityAndOffset	CHOICE					
	1 slot	-	10 slots	0 to 9	160	0 to 159
	2 slots	0 to 1	16 slots	0 to 15	320	0 to 319
	4 slots	0 to 3	20 slots	0 to 19	640	0 to 639
	5 slots	0 to 4	40 slots	0 to 39	1280	0 to 1279
	8 slots	0 to 7	80 slots	0 to 79	2560 slots	0 to 2559
duration	2 to 2559					
monitoringSymbolsWithinSlot	BIT STRING (14 bits)					
nrofCandidates	aggregationLevel1	0, 1, 2, 3, 4, 5, 6, 8				
	aggregationLevel2	0, 1, 2, 3, 4, 5, 6, 8				
	aggregationLevel4	0, 1, 2, 3, 4, 5, 6, 8				
	aggregationLevel8	0, 1, 2, 3, 4, 5, 6, 8				
	aggregationLevel16	0, 1, 2, 3, 4, 5, 6, 8				
searchSpaceType	CHOICE					
	common				ue-Specific	
	dci-Format0-0-AndFormat1-0				dci-Formats	formats0-0-And-1-0, formats0-1-And-1-1
	dci-Format2-0	nrofCandidates-SFI	aggregationLevel1	1, 2		
			aggregationLevel2	1, 2		
			aggregationLevel4	1, 2		
			aggregationLevel8	1, 2		
			aggregationLevel16	1, 2		
	dci-Format2-1					
	dci-Format2-2					
	dci-Format2-3					

Table 68 – Parameter structure used to configure a Search Space Set

★ The *searchSpaceId* serves as an identity for the Search Space Set being configured. The *controlResourceSetId* identifies the Control Resource Set (COREST) that the Search Space Set is mapped onto. The CORESET determines the specific Resource Blocks available to the Search Space Set and also the number of symbols

★ The *monitoringSlotPeriodicityAndOffset* configures the timing of the Search Space Set. A Search Space Set occurs during $slot^{\mu}_{s,f}$ within $Frame_f$ when the following equality is true:

$$\left(Frame_f \times N^{frame,\mu}_{slot} + slot^{\mu}_{s,f} - Offset_{p,s}\right) mod\ Periodicity_{p,s} = 0$$

For example, if the periodicity is set to 10 slots and the offset is set to 5 slots while the numerology determines that there are 20 slots per frame (30 kHz subcarrier spacing) then the Search Space Set occurs during slots 5 and 15 of every frame

★ The *duration* information element is optional and should not be confused with the *duration* information element belonging to the CORESET (Table 62). The Search Space Set *duration* specifies that the Search Space Set extends across multiple consecutive slots. For example, if the *duration* was set to 3 for the previous example then the Search Space Set would include slots 5, 6, 7, 15, 16 and 17 of every radio frame

★ The *monitoringSymbolsWithinSlot* information element specifies the starting symbol(s) for the Search Space Set within the slot. This information element is a bit string where each bit corresponds to a symbol within the slot. A single bit will be set to '1' if there is a single instance of the Search Space Set within the slot. Figure 150 illustrates examples for a mobile broadband device and a low latency device. The mobile broadband device is configured to monitor the PDCCH at the start of every slot. This is analogous to 4G which allows PDCCH transmission during the first symbols belonging to each subframe. In this example, the CORESET *duration* is assumed to be 2 symbols for the mobile broadband device. The low latency device is configured to monitor the PDCCH during every second symbol. This helps to minimise delay when allocating resources to the low latency device. In this example, the CORESET *duration* is assumed to be 1 symbol

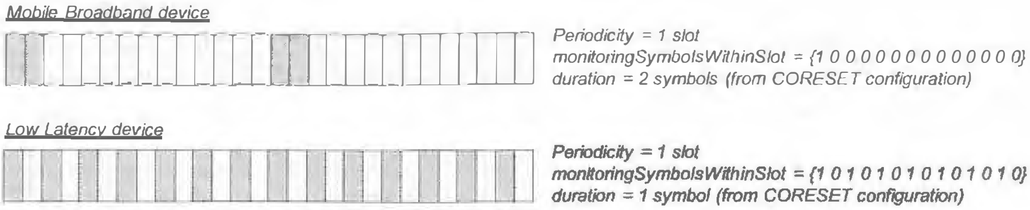


Figure 150 – Example Search Space Set timing for mobile broadband and low latency devices

- The *nrofCandidates* information element specifies the number of candidate PDCCH transmissions for each aggregation level. This provides the Base Station with the flexibility to focus the UE blind decoding attempts upon the most appropriate aggregation levels. For example, normal coverage scenarios may not use aggregation level 16 which was introduced for extreme coverage conditions (aggregation level 16 was not specified for 4G). In this case, the number of aggregation level 16 candidates could be set to 0 to avoid the UE attempting unnecessary blind decoding. Small cell scenarios are more likely to use the lower aggregation levels so the number of candidates for these aggregation levels could be set higher

- The *searchSpaceType* can be set to either 'Common' or 'UE Specific' according to the category of Search Space Set being configured:

  - in the case of a Common Search Space Set, inclusion of the *dci-Format0-0-AndFormat1-0* information element indicates that the UE should monitor for the 'fallback' DCI formats 0_0 and 1_0 within the Common Search Space Set. The DCI formats can address the UE using a C-RNTI, CS-RNTI, SP-CS-RNTI, RA-RNTI, TC-RNTI, P-RNTI or SI-RNTI

  - inclusion of the *dci-Format2-0 – nrofCandidates-SFI* information element indicates that the UE should monitor for DCI Format 2-0 using its SFI-RNTI. The information element specifies the aggregation level to be used for DCI Format 2-0 (only a single aggregation level from the set of 5 aggregation levels is included within the parameter structure sent to the UE). The number of candidates for this aggregation level is specified as either 1 or 2. This approach reduces the number of blind decoding attempts, i.e. the UE has to search for only a single aggregation level with only 1 or 2 candidates

  - similarly, inclusion of the *dci-Format2-1*, *dci-Format2-2* and *dci-Format2-3* information elements indicates that the UE should monitor the Search Space Set for the relevant DCI Format

  - in the case of a UE Specific Search Space Set, the *dci-Formats* information element indicates whether the UE should monitor for the 'fallback' DCI Formats 0_0 and 1_0, or the 'standard' DCI Formats 0_1 and 1_1

- 3GPP References: TS 38.213, TS 38.331

3.5.3 SEARCH SPACE SET (SIB1)

★ During initial network access, a UE completes a band scan for the Synchronisation Signals and subsequently decodes the PBCH. The PBCH provides sufficient information to allow the UE to proceed to decode System Information Block 1 (SIB1). SIB1 is broadcast on the PDSCH using a resource allocation provided by the PDCCH. The PDCCH transmits DCI Format 1_0 within Common Search Space Type 0. The Control Resource Set (CORESET) and Common Search Space Type 0 configurations required by the UE to receive the relevant PDCCH are provided by the PBCH information elements:

- o *subCarrierSpacingCommon* scs15or60, scs30or120kHz
- o *PDCCH-ConfigSIB1 - controlResourceSetZero* 0 to 15 (4 bits)
- o *PDCCH-ConfigSIB1 - searchSpaceZero* 0 to 15 (4 bits)

★ If the UE detects an SS/PBCH Block within Frequency Range 1 (450 MHz to 6 GHz), the *subCarrierSpacingCommon* information element specifies that the PDCCH subcarrier spacing is either 15 or 30 kHz. Alternatively, if the UE detects an SS/PBCH Block within Frequency Range 2 (24.25 GHz to 52.6 GHz), the *subCarrierSpacingCommon* information element specifies that the PDCCH subcarrier spacing is either 60 or 120 kHz

★ The *controlResourceSetZero* information element is used as a pointer to a row within a CORESET configuration table. 3GPP has specified multiple tables for this purpose. Each table is applicable to a specific combination of SS/PBCH subcarrier spacing and PDCCH subcarrier spacing. Table 69 presents an example for the {15 kHz, 15 kHz} combination

<table>
<tr><th>Index</th><th>Multiplexing Pattern</th><th>Number of Resource Blocks</th><th>Number of Symbols</th><th>Resource Block Offset</th></tr>
<tr><td>0</td><td rowspan="15">1</td><td rowspan="6">24
(4.32 MHz)</td><td rowspan="3">2</td><td>0</td></tr>
<tr><td>1</td><td>2</td></tr>
<tr><td>2</td><td>4</td></tr>
<tr><td>3</td><td rowspan="3">3</td><td>0</td></tr>
<tr><td>4</td><td>2</td></tr>
<tr><td>5</td><td>4</td></tr>
<tr><td>6</td><td rowspan="6">48
(8.64 MHz)</td><td rowspan="2">1</td><td>12</td></tr>
<tr><td>7</td><td>16</td></tr>
<tr><td>8</td><td rowspan="2">2</td><td>12</td></tr>
<tr><td>9</td><td>16</td></tr>
<tr><td>10</td><td rowspan="2">3</td><td>12</td></tr>
<tr><td>11</td><td>16</td></tr>
<tr><td>12</td><td rowspan="3">96
(17.28 MHz)</td><td>1</td><td rowspan="3">38</td></tr>
<tr><td>13</td><td>2</td></tr>
<tr><td>14</td><td>3</td></tr>
<tr><td>15</td><td colspan="4">Reserved</td></tr>
</table>

Table 69 – CORESET Configuration Table for SS/PBCH subcarrier spacing of 15 kHz and PDCCH subcarrier spacing of 15 kHz

★ This example specifies CORESET bandwidths of 24, 48 and 96 Resource Blocks, and CORESET durations of 1, 2 and 3 symbols. The bandwidth of 24 Resource Blocks is only permitted when using either 2 or 3 symbols. This ensures that there is always at least 48 Resource Element Groups (REG) within the CORESET, i.e. at least 8 CCE. Maximising the number of CCE allows the use of higher aggregation levels for the PDCCH which helps to improve coverage

★ The number of Resource Blocks allocated to the CORESET can be configured according to the channel bandwidth, e.g. 24 Resource Blocks can be configured for the 5 MHz channel bandwidth, 48 Resource Blocks can be configured for the 10 MHz and 15 MHz channel bandwidths and 96 Resource Blocks can be configured for larger channel bandwidths

★ Table 69 also specifies a Resource Block Offset between the SS/PBCH Block and the CORESET, i.e. it defines the frequency domain position of the CORESET relative to the frequency domain position of the SS/PBCH Block. Figure 151 illustrates the set of allowed offsets for the CORESET size of 24 Resource Blocks. This figure shows that the CORESET extends a maximum of 4 Resource Blocks beyond the bandwidth of the SS/PBCH, i.e. the total bandwidth never exceeds 24 Resource Blocks

★ These frequency offsets are required because the SS/PBCH may not be positioned at the center of the channel bandwidth. If the SS/PBCH is positioned at the bottom of a 5 MHz channel bandwidth then the 0 Resource Block Offset would be necessary. Likewise, if the SS/PBCH is positioned at the top of a 5 MHz channel bandwidth then the 4 Resource Block Offset would be necessary

★ As illustrated by Figure 151, the SS/PBCH and CORESET are Time Division Multiplexed (TDM). This corresponds to 'Multiplexing Pattern 1', as specified in Table 69. 'Multiplexing Pattern 1' is always used for operating bands within Frequency Range 1. Operating bands within Frequency Range 1 can use SS/PBCH subcarrier spacings of 15 kHz or 30 kHz. 3GPP has specified tables similar to Table 69, for SS/PBCH subcarrier spacing and PDCCH subcarrier spacing combinations of {15, 30}, {30, 15} and {30, 30} kHz

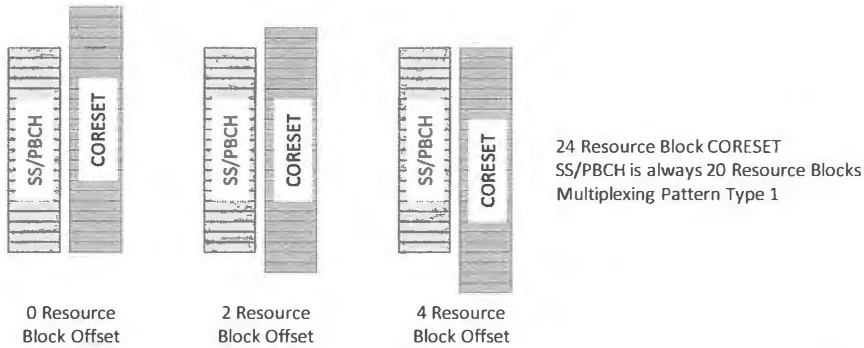


Figure 151 – Resource Block Offsets for CORESET size of 24 Resource Blocks (Multiplexing Pattern 1)

★ Returning to the information provided by the PBCH, the *searchSpaceZero* information element is used as a pointer to a row within a Search Space Set configuration table. 3GPP has specified multiple tables for this purpose. Each table is applicable to a specific Multiplexing Pattern and Frequency Range. Table 70 presents an example for Multiplexing Pattern 1 in Frequency Range 1. All of the information within this table is related to the timing of the Search Space Set

★ The 'O' variable specifies a slot offset relative to the start of the frame. 3GPP has specified that each SS/PBCH Block has its own Type 0 Common Search Space Set. Thus, there is a sequence of Type 0 Common Search Space Sets for a burst of SS/PBCH Blocks. The slot offset defines the starting slot for that sequence of Search Space Sets

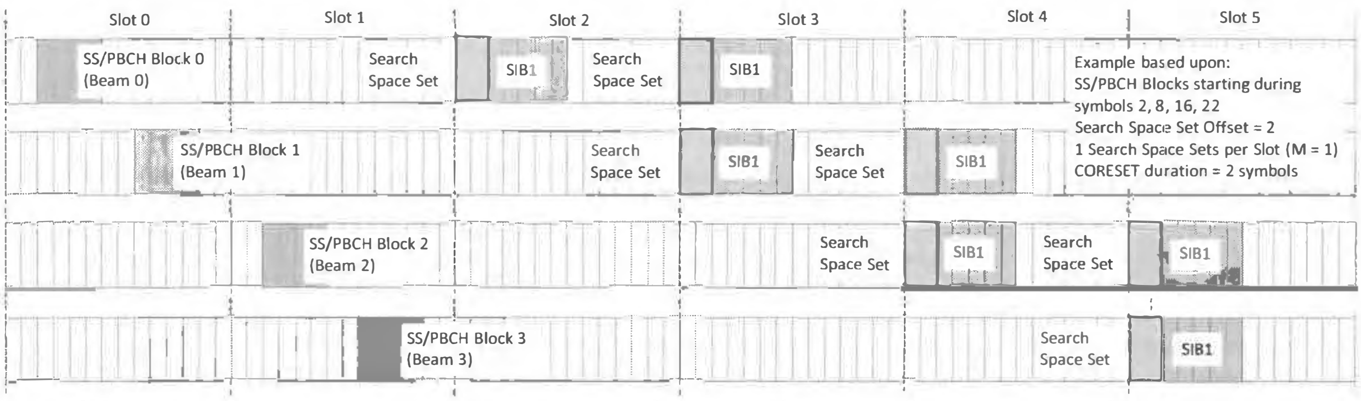
★ The 'M' variable is related to the Number of Search Space Sets per Slot. When there are 2 Search Space Sets per Slot then 'M' always equals 1/2. The value of 'M' is used in an equation to calculate the slot number for a specific SS/PBCH Block. The value of 1/2 means that 2 consecutive SS/PBCH Blocks have their Search Space Sets within the same slot. A value of 1 means that consecutive SS/PBCH Blocks have their Search Space Sets within consecutive slots, while a value of 2 means that consecutive SS/PBCH Blocks have their Search Space Sets separated by 2 slots

★ The 'First Symbol Index' specifies the starting symbol for the Search Space Set within the slot. In general, the Search Space Sets are located towards the start of the slot, i.e. many of the rows within Table 70 have a First Symbol Index of 0. When there are 2 Search Space Sets within the same slot, the Search Space Sets occupy a contiguous block of symbols at the start of the slot. The first Search Space Set starts at symbol 0, while the second Search Space Set starts at a symbol index which is defined by the duration of the CORESET (the CORESET duration determines the number of symbols occupied by each Search Space Set)

Index	O	Number of Search Space Sets per Slot	M	First Symbol Index
0	0	1	1	0
1		2	1/2	{0 if 'i' is even} {$N_{symb}^{CORESET}$ if 'i' is odd}
2	2	1	1	0
3		2	1/2	{0 if 'i' is even} {$N_{symb}^{CORESET}$ if 'i' is odd}
4	5	1	1	0
5		2	1/2	{0 if 'i' is even} {$N_{symb}^{CORESET}$ if 'i' is odd}
6	7	1	1	0
7		2	1/2	{0 if 'i' is even} {$N_{symb}^{CORESET}$ if 'i' is odd}
8	0	1	2	0
9	5			0
10	0		1	1
11				2
12	2			1
13				2
14	5			1
15				2

Table 70 – Search Space Set configuration table for Multiplexing Pattern 1 and Frequency Range 1

★ Figure 152 illustrates an example of the timing for Type 0 Common Search Space Sets for Frequency Range 1 using Multiplexing Pattern 1. This example assumes 4 SS/PBCH Blocks which start during symbols 2, 8, 16 and 22 (as presented in section 3.4). 3GPP specifies that there are 2 Search Space Sets in consecutive slots with a period of 20 ms when using Multiplexing Pattern 1. The offset value within Table 70 defines the slot for the first of these 2 Search Space Sets. The example in Figure 152 assumes an offset of 2 slots which means that the first Search Space Set is located within slot 2. The example also assumes 1 Search Space Set per slot (M = 1) and a first symbol index of 0. Note that the specification of 1 Search Space Set per slot refers to the first Search Space Set belonging to each SS/PBCH Block. Figure 152 illustrates that the second Search Space Set belonging to SS/PBCH 0 overlaps with the first Search Space Set belonging to SS/PBCH 1. Thus, there is only 1 'first' Search Space Set per slot but there are up to 2 Search Space Sets per slot when considering both the first and second Search Space Sets. This example is based upon Frequency Range 1 and it is assumed that digital beamforming is used to provide spatial separation between each SS/PBCH transmission. This means that all beams can be transmitted simultaneously and that transmissions can overlap in the time and frequency domains because they are isolated in the spatial domain



Note: this figure illustrates 2 'candidate' SIB1 transmissions for each SS/PBCH Block. In practice, only 1 of the 2 candidates is expected to be used, i.e. the Base Station scheduler can select between the 2 candidates. The UE will check both Search Space Sets for SIB1 PDSCH resource allocations

Figure 152 – Example Type 0 Common Search Space Sets for SS/PBCH Blocks 0, 1, 2 and 3 (1 Search Space Set per Slot, Multiplexing Pattern 1)

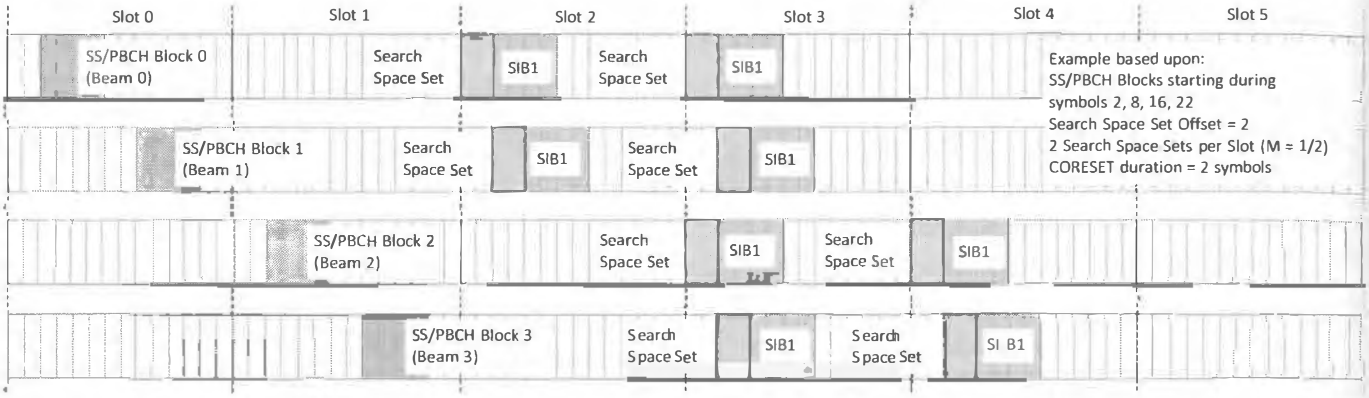
★ When receiving SIB1, a UE relies upon a 3GPP standardised look-up table for interpretation of the time domain resource allocation within DCI Format 1_0 (in contrast to using a Base Station configured look-up table). A subset of the 3GPP standardised look-up table for Multiplexing Pattern 1 is presented in Table 71. The appropriate row from within this table is selected using a combination of the *Time Domain Resource Assignment* within DCI Format 1_0 (which corresponds to the 'Index') and the *dmrs-TypeA-Position* information element from within the MIB. The UE is then able to deduce the PDSCH Mapping Type, the Slot Offset, the Starting Symbol and the Length of the resource allocation

★ The example illustrated in Figure 152 assumes a Starting Symbol of 2 and a Length of 5. Figure 152 does not explicitly indicate whether PDSCH Mapping Type A or B is used although it can be deduced from Table 71 that Mapping Type A is applicable. The values within Table 71 have been specified to ensure that the PDSCH used to transfer SIB1 has a 'front loaded' Demodulation Reference Signal (DMRS), i.e. the DMRS occupies the first symbol belonging to the PDSCH resource allocation. This allows the UE to generate a channel estimate with minimal delay. PDSCH Mapping Type B always has a 'front loaded' DMRS whenever it is used. In general, Mapping Type A does not always have a 'front loaded' DMRS but the Starting Symbols specified in Table 71 have been set equal to the *dmrs-TypeA-Position* so in this case the resource allocation starts with a DMRS transmission

Index	dmrs-TypeA-Position	PDSCH Mapping Type	Slot Offset (K_0)	Starting Symbol (S)	Length (L)
1	2	Type A	0	2	12
	3			3	11
2	2			2	10
	3			3	9
3	2			2	9
	3			3	8
4	2			2	7
	3			3	6
5	2			2	5
	3			3	4
6	2	Type B		9	4
	3			10	4
7	2			4	4
	3			6	4

Table 71 – 3GPP standardised Default PDSCH Time Domain Resource Allocation 'A' (only subset of full table is shown)

★ A second example of the timing associated with Type 0 Common Search Space Sets is illustrated in Figure 153. This example is based upon 2 Search Space Sets per Slot (M = 1/2). This means that SS/PBCH Blocks 0 and 1 have their first Search Space Sets within the same slot. Similarly, SS/PBCH Blocks 2 and 3 have their first Search Space Sets within the same slot. This example illustrates the 'First Symbol Index' rule for 2 Search Space Sets per Slot (shown in Table 70), i.e. {0 if 'i' is even} {$N_{symb}^{CORESET}$ if 'i' is odd}. SS/PBCH Blocks 0 and 2 have a first symbol index equal to 0, while SS/PBCH Blocks 1 and 3 have a first symbol index equal to 2, which results from $N_{symb}^{CORESET} = 2$



Note: this figure illustrates 2 'candidate' SIB1 transmissions for each SS/PBCH Block. In practice, only 1 of the 2 candidates is expected to be used, i.e. the Base Station scheduler can select between the 2 candidates. The UE will check both Search Space Sets for SIB1 PDSCH resource allocations

Figure 153 – Example Type 0 Common Search Space Sets for SS/PBCH Blocks 0, 1, 2 and 3 (2 Search Space Sets per Slot, Multiplexing Pattern 1)

★ Now considering the reception of SIB1 within Frequency Range 2, the *controlResourceSetZero* information element points to a row within a different set of look-up tables, i.e. those which are applicable to the SS/PBCH and PDCCH subcarrier spacings belonging to Frequency Range 2. 3GPP has specified separate look-up tables for the following combinations of SS/PBCH and PDCCH subcarrier spacings: {120, 60}, {120, 120}, {240, 60} and {240, 120} kHz. Table 72 presents the look-up table for the {120, 120} kHz combination

★ Operating bands within Frequency Range 2 have been specified to use Multiplexing Patterns 1, 2 and 3. Table 72 specifies that Multiplexing Patterns 1 and 3 are applicable to the {120, 120} kHz combination of subcarrier spacings. Figure 154 illustrates Multiplexing Pattern 3 when 24 Resource Blocks are allocated to the CORESET. The Resource Block offset of -20 positions the CORESET above the SS/PBCH Block (which has 20 Resource Blocks). The Resource Block offset of 24 positions the CORESET below the SS/PBCH. Table 72 also specifies a Resource Block offset of -21. This offset is applicable when the SS/PBCH and CORESET Resource Blocks are not aligned in the frequency domain. In this case, the offset is rounded to -21 to avoid overlap between the SS/PBCH and CORESET

★ A CORESET always has a duration of 2 symbols when using Multiplexing Pattern 3. This leads to either 48 or 96 Resource Element Groups (REG) within the CORESET, i.e. either 8 or 16 CCE

★ Figure 154 illustrates that the CORESET is time aligned with the start of the SS/PBCH Block when using Multiplexing Pattern 3. This time alignment does not originate from the information presented within Table 72. Timing information is based upon the *searchSpaceZero* information element presented at the start of this section. This information element points to a row within a Search Space Set configuration table. However, the table which is applicable to Multiplexing Pattern 3 has only a single row and that row simply specifies that the start of the Search Space Set is time aligned with the start of the associated SS/PBCH. There is a one-to-one mapping between SS/PBCH Block and Type 0 Common Search Space Set so every SS/PBCH Block has its own Search Space Set

Index	Multiplexing Pattern	Number of Resource Blocks	Number of Symbols	Resource Block Offset
0	1	24 (34.56 MHz)	2	0
1				4
2		48 (69.12 MHz)	1	14
3			2	14
4	3	24 (34.56 MHz)		-20 if $k_{SSB} = 0$ or -21 if $k_{SSB} > 0$
5				24
6		48 (69.12 MHz)		-20 if $k_{SSB} = 0$ or -21 if $k_{SSB} > 0$
7				48

Table 72 – CORESET Configuration Table for SS/PBCH subcarrier spacing of 120 kHz and PDCCH subcarrier spacing of 120 kHz

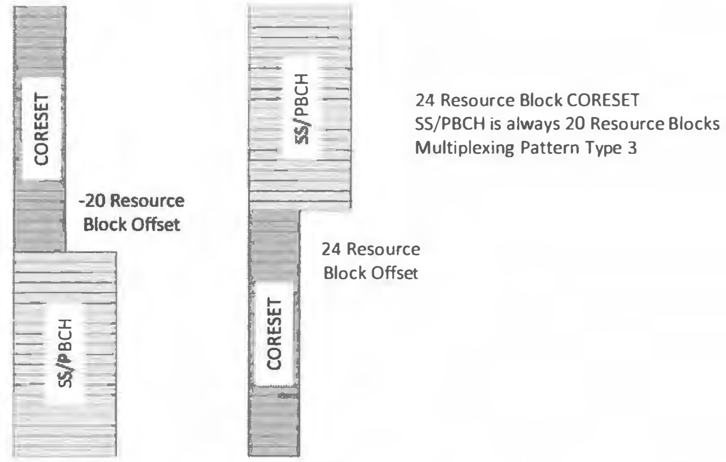


Figure 154 – Resource Block Offsets for CORESET size of 24 Resource Blocks (Multiplexing Pattern 3)

★ Figure 155 illustrates the timing for Type 0 Common Search Space Sets when using Multiplexing Pattern 3. This example is based upon 8 SS/PBCH Blocks which start during symbols 2, 8, 16, 20, 30, 36, 44 and 48 (as presented in section 3.4). In contrast to Multiplexing Pattern 1, there is only a single Search Space Set associated with each SS/PBCH Block. The SS/PBCH Block and the Search Space Set are confined to a limited number of symbols in the time domain to remain compatible with analogue beamforming. When using analogue beamforming, an individual beam is only active for a relatively short period of time and all transmissions have to be completed within that period

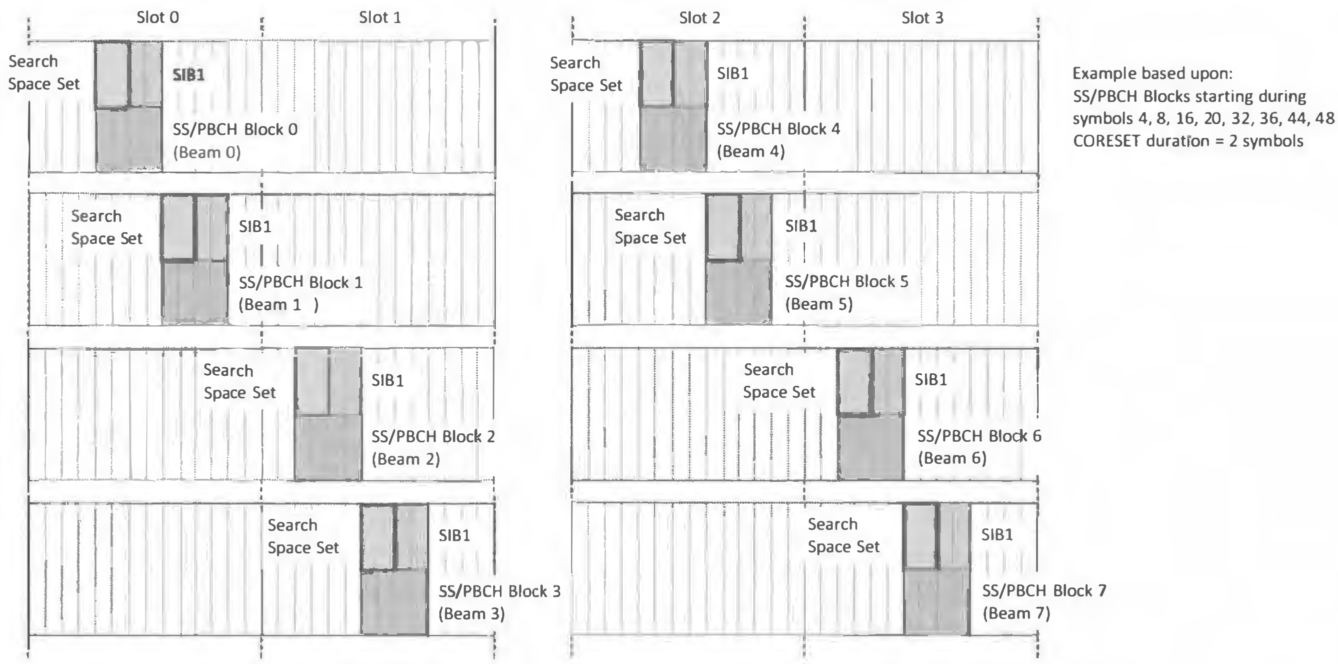


Figure 155 – Type 0 Common Search Space Sets for SS/PBCH Blocks 0 to 7 (Multiplexing Pattern 3)

★ A UE extracts the time domain resource allocation for the SIB from the PDCCH within the Type 0 Common Search Space. The time domain resource allocation defines the set of symbols used by the PDSCH, Similar to Multiplexing Pattern 1, the UE relies upon a 3GPP standardised look-up table for interpretation of the time domain resource allocation within DCI Format 1_0 (in contrast to using a Base Station configured look-up table). In the case of Multiplexing Pattern 1, the UE applies 3GPP default table 'A' presented as Table 71. In the case of Multiplexing Pattern 3, the UE applies 3GPP default table 'C'. Table 73 presents the rows from 3GPP default table 'C' which are applicable to the reception of SIB1

★ In this case, the *dmrs-TypeA-Position* information element from the MIB has no impact upon the resource allocation. All resource allocations use PDSCH Mapping Type B meaning that the first symbol of the resource allocation is always occupied by the Demodulation Reference Signal (DMRS). A range of Starting Symbols are specified to accommodate the range of SS/PBCH timings. The example shown in Figure 155 uses Starting Symbols equal to 4, 6, 8 and 10. PDSCH durations of 2 and 4 symbols can be allocated although the example illustrated in Figure 155 only uses allocations of 2 symbols

Index	dmrs-TypeA-Position	PDSCH Mapping Type	Slot Offset (K_0)	Starting Symbol (S)	Length (L)
2	2 or 3	Type B	0	4	2
3				6	
4				8	
5				10	
8				2	4
9				4	
10				6	
11				8	
12				10	

Table 73 – 3GPP standardised Default PDSCH Time Domain Resource Allocation 'C' (only rows applicable to Type 0 Common Search Space)

★ The previous examples have focused upon Multiplexing Patterns 1 and 3. 3GPP has also specified Multiplexing Pattern 2 which is applicable to Frequency Range 2 when the SS/PBCH and PDCCH subcarrier spacing combination is either {120, 60} or {240, 120} kHz. Similar to Multiplexing Patterns 1 and 3, the *controlResourceSetZero* information element is used as a pointer to a row within a CORESET configuration table. Figure 156 illustrates the position of the CORESET relative to the SS/PBCH Block when using Multiplexing Pattern 2 with a CORESET which has 24 Resource Blocks. From a frequency domain perspective, it is similar to Multiplexing Pattern 3. However, from a time domain perspective Multiplexing Pattern 2 schedules the Search Space Set associated with the CORESET in advance of the SS/PBCH Block

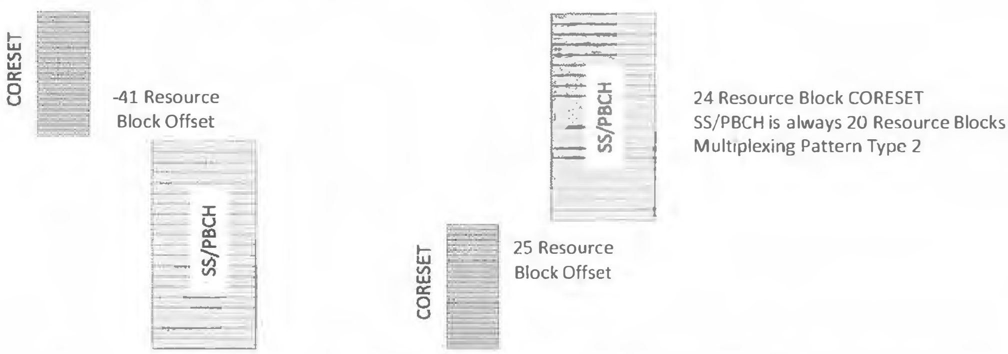


Figure 156 – Resource Block Offsets for CORESET size of 24 Resource Blocks (Multiplexing Pattern 2)

★ The reasoning for this approach originates from the ratio of the SS/PBCH and PDCCH subcarrier spacings. The SS/PBCH subcarrier spacing is double the PDCCH subcarrier spacing for both scenarios which use Multiplexing Pattern 2. This means that the PDCCH symbol duration is double the SS/PBCH symbol duration. The SS/PBCH occupies 4 symbols so the PDCCH can occupy 2 symbols within the same time domain window. In the case of Multiplexing Pattern 3, both the PDCCH and PDSCH are transmitted within the SS/PBCH time domain window. In the case of the {120, 60} and {240, 120} kHz subcarrier spacing combinations, it is more challenging to accommodate both the PDCCH and PDSCH because there are only 2 symbols available. So in this case, the PDCCH is transmitted in advance of the SS/PBCH while the PDSCH is transmitted within the time window of the SS/PBCH

★ Figure 157 illustrates an example of the timing associated with Multiplexing Pattern 2. This example illustrates SS/PBCH Blocks 0 to 7 which have starting symbols of 8, 12, 16, 20, 32, 36, 40 and 44 (as presented in section 3.4 for the 240 kHz subcarrier spacing). Similar to Multiplexing Pattern 3, there is only a single Search Space Set associated with each SS/PBCH Block. The CORESET always has a duration of 1 symbol when using Multiplexing Pattern 2

★ The timing of the Search Space Set which is mapped onto the CORESET is based upon the *searchSpaceZero* information element presented at the start of this section. This information element points to a row within a Search Space Set configuration table. 3GPP has specified 2 tables – one for the {120, 60} kHz subcarrier spacing combination and one for the {240, 120} kHz combination. Both tables have only a single row so the *searchSpaceZero* pointer is not really required. The single row specifies Starting Symbols for each instance of the Search Space Set such that they do not overlap with each other, nor do they overlap with the SS/PBCH

★ The time domain resource allocation for the PDSCH transferring the SIB is extracted from the PDCCH. Similar to Multiplexing Patterns 1 and 3, the UE relies upon a 3GPP standardised look-up table for interpretation of the time domain resource allocation within DCI Format 1_0. In the case of Multiplexing Pattern 2, the UE applies 3GPP default table 'B' presented as Table 74. All resource allocations use PDSCH Mapping Type B meaning that the first symbol of the resource allocation is always occupied by the Demodulation Reference Signal (DMRS). A range of Starting Symbols are specified to accommodate the range of SS/PBCH timings. The example shown in Figure 157 uses Starting Symbols equal to 2, 4, 6, 8 and 10. In contrast to default tables 'A' and 'C', default table B includes some entries with non-zero Slot Offset values. These are required because there are scenarios where the PDCCH is transmitted during slot 'n' while the PDSCH is transmitted during slot 'n+1'. There are 2 examples of this shown in Figure 157 (indicated using the 'Next slot' label)

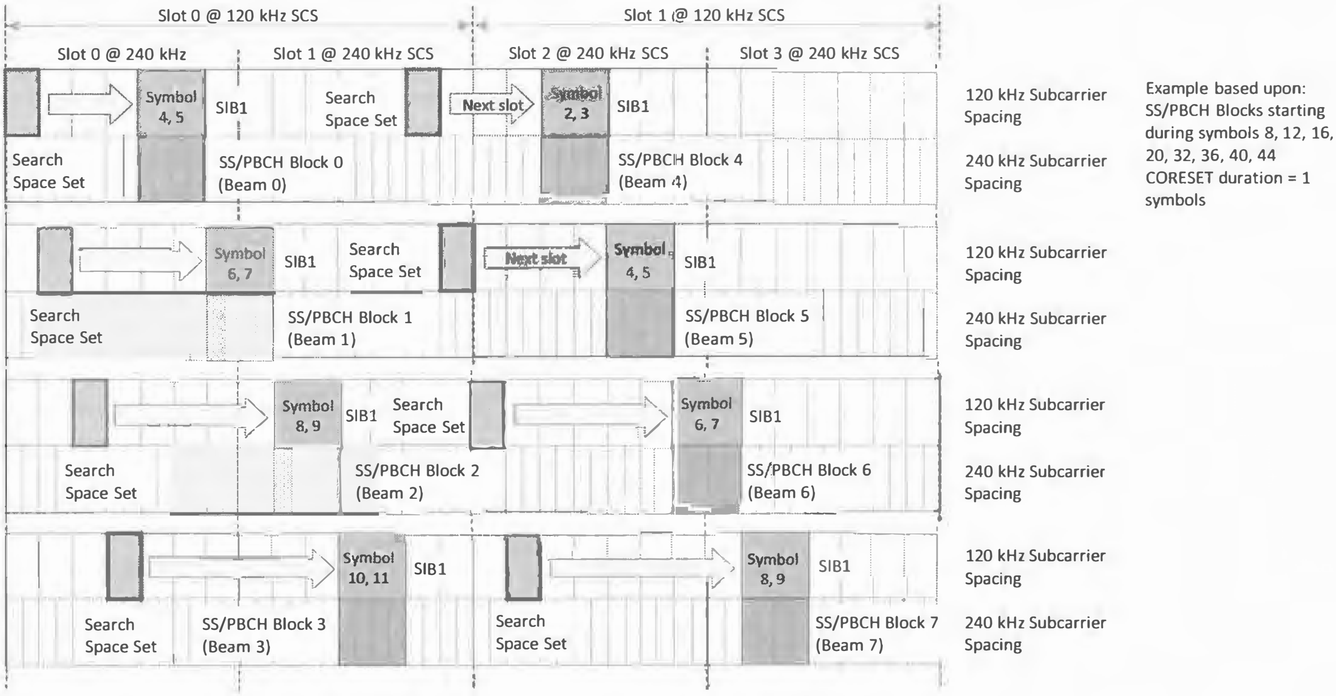


Figure 157 – Type 0 Common Search Space Sets for SS/PBCH Blocks 0 to 7
240 kHz SS/PBCH Subcarrier Spacing and 120 kHz PDCCH Subcarrier Spacing with Multiplexing Pattern 2

Index	dmrs-TypeA-Position	PDSCH Mapping Type	Slot Offset (K_0)	Starting Symbol (S)	Length (L)
1	2 or 3	Type B	0	2	2
2				4	
3				6	
4				8	
5				10	
6			1	2	
7				3	
8			0	2	4
9				4	
10				6	
11				8	
15			1	2	

Table 74 – 3GPP standardised Default PDSCH Time Domain Resource Allocation 'B' (only rows applicable to Type 0 Common Search Space)

★ Multiplexing Pattern 2 has implications upon the beam sweeping used by analogue beamforming. In the case of Multiplexing Pattern 3, the SS/PBCH, PDCCH and PDSCH for SIB1 are all transmitted using a single sweep of the beams. This is not possible when using Multiplexing Pattern 2 because transmissions belonging to each beam are interleaved in the time domain. Figure 157 illustrates that transmissions follow the sequence: Search Space Set (Beam 0), Search Space Set (Beam 1), Search Space Set (Beam 2), Search Space Set (Beam 3), SS/PBCH/PDSCH (Beam 0), SS/PBCH/PDSCH (Beam 1), SS/PBCH/PDSCH (Beam 2), SS/PBCH/PDSCH (Beam 3), etc. This pattern requires 2 beam sweeps to transmit the PDCCH, SS/PBCH and PDSCH belonging to a specific beam

★ In contrast to Multiplexing Pattern 1, which uses a period of 20 ms, Multiplexing Patterns 2 and 3 use a period which equals the period of the SS/PBCH Block transmissions

★ By default, the initial active downlink Bandwidth Part is set equal to the bandwidth and frequency domain position of the CORESET associated with the Type 0 Common Search Space Set. The Base Station can override this default configuration by signalling the *initialDownlinkBWP* parameter structure within SIB1

★ 3GPP References: TS 38.213, TS 38.331

3.5.4 DCI FORMAT 0_0

★ Downlink Control Information (DCI) Format 0_0 is used to provide resource allocations for the PUSCH. It is known as a 'Fallback' DCI Format which can be used to maintain a connection when coverage deteriorates. It has a smaller payload than DCI Format 0_1 so can benefit from increased channel coding redundancy. It may also be used to support communication during reconfigurations

★ DCI Format 0_0 supports single layer transmission on the PUSCH

★ A UE can be addressed by its C-RNTI, CS-RNTI, MCS-C-RNTI or TC-RNTI when receiving DCI Format 0_0. The UE is addressed by using the RNTI to scramble the CRC bits which are added to the DCI payload

★ The fields belonging to DCI Format 0_0 are presented in Table 75

	Number of Bits within DCI
DCI Format Identifier	1
Frequency Domain Resource Assignment	$\lceil Log_2(N_{RB}^{UL,BWP} \times (N_{RB}^{UL,BWP} + 1) / 2) \rceil$
Time Domain Resource Assignment	4
Frequency Hopping Flag	1
Modulation and Coding Scheme (MCS)	5
New Data Indicator (NDI)	1
Redundancy Version (RV)	2
HARQ Process Number	4
TPC Command for Scheduled PUSCH	2
Padding	depends upon size of DCI Format 1_0
Uplink / Supplemental Uplink Indicator	1 or 0

Table 75 – Content of DCI Format 0_0

★ DCI Format Identifier: is a flag used to differentiate between DCI Formats 0_0 and 1_0. These two DCI Formats have been specified to include an equal number of bits. This helps to simplify the UE decoding procedure by reducing the number of block sizes which the UE attempts to decode. Once the UE has obtained a positive CRC result, the DCI Format Identifier is used to determine which of the two DCI Formats has been received (a value of 0 indicates DCI Format 0_0)

★ Frequency Domain Resource Assignment: allocates a set of Resource Blocks for the PUSCH. DCI Format 0_0 always uses Resource Allocation Type 1. This means that it always allocates a set of contiguous Virtual Resource Blocks. The PUSCH uses a direct non-interleaved mapping between Virtual and Physical Resource Blocks, i.e. Virtual Resource Block 'n' is mapped onto Physical Resource Block 'n' so the allocated Physical Resource Blocks are also contiguous. The number of bits required by the Frequency Domain Resource Assignment field depends upon the number of Resource Blocks within the uplink Bandwidth Part

★ If Frequency Hopping is enabled, then 1 or 2 of the Most Significant Bits (MSB) from the Frequency Domain Resource Assignment are used to select the Frequency Hopping Offset. 1 MSB is used if the RRC layer has configured 2 frequency offsets. 2 MSB are used if the RRC layer has configured 4 frequency offsets. Using the MSB for the purposes of Frequency Hopping means that there are fewer bits available to signal the frequency domain resource assignment. This is acceptable because Frequency Hopping is applicable to smaller Resource Block allocations, i.e. the benefit of Frequency Hopping diminishes as the number of allocated Resource Blocks approaches the total number of Resource Blocks within the Bandwidth Part

★ Time Domain Resource Assignment: defines a pointer towards a row within a look-up table (either a 3GPP standardised look-up table, or an RRC configured look-up table). The look-up table defines the slot offset, the PUSCH Mapping Type, the starting symbol and the number of allocated symbols. The look-up tables have up to 16 rows so this field requires 4 bits

★ Frequency Hopping Flag: indicates whether or not Frequency Hopping is to be applied to the resource allocation

★ Modulation and Coding Scheme (MCS): defines a pointer towards a row within the relevant MCS look-up table. 3GPP has specified 5 MCS tables for the PUSCH – a 64QAM table; a 256QAM table, a low Spectral Efficiency table (for increased reliability), a 64QAM table for Transform Precoding with the option to use π/2 BPSK and a low Spectral Efficiency table for Transform Precoding with the option to use π/2 BPSK. Each table has 32 rows so this field requires 5 bits

★ New Data Indicator (NDI): indicates if the resource allocation is to be used for a re-transmission, or a new transmission. This field occupies a single bit. In the case of dynamic resource allocations, a re-transmission is triggered if the NDI has the same value as that used for the previous transmission of the relevant HARQ process. A new transmission is triggered if the NDI is toggled. In the case of Configured Grants, a re-transmission is triggered if the NDI has a value of 1

★ Redundancy Version (RV): indicates the puncturing pattern to be used after channel coding. Incremental Redundancy relies upon different puncturing patterns between transmissions and re-transmissions. Chase Combining relies upon the same puncturing pattern for both transmissions and re-transmissions

- HARQ Process Number: indicates the HARQ process which is to use the resource allocation. A UE supports 16 HARQ processes per cell in the uplink so this field occupies 4 bits
- TPC Command for Scheduled PUSCH is used for closed loop power control, i.e. the Base Station provides the UE with Transmit Power Control (TPC) commands which instruct the UE to increase, decrease or maintain its transmit power. Interpretation of the 2 bits depends upon whether or not TPC command accumulation has been configured. Transmit Power Control is described within section 13.3.1
- Padding: is added if the size of DCI Format 0_0 is less than the size of DCI Format 1_0. Padding is added until the two DCI Formats have equal size
- Uplink / Supplemental Uplink Indicator: is a single bit flag used to indicate whether the resource allocation is for the normal uplink carrier or the Supplemental Uplink carrier. This flag is only included if the UE is configured with a Supplemental Uplink carrier and the size of DCI Format 1_0 is greater than the size of DCI Format 0_0
- 3GPP Reference: TS 38.212

3.5.5 DCI FORMAT 0_1

- Downlink Control Information (DCI) Format 0_1 is used to provide resource allocations for the PUSCH. A UE can be addressed by its C-RNTI, CS-RNTI, MCS-C-RNTI or SP-CSI-RNTI when receiving DCI Format 0_1. The UE is addressed by using the RNTI to scramble the CRC bits which are added to the DCI payload
- The fields belonging to DCI Format 0_1 are presented in Table 76

	Number of Bits within DCI
DCI Format Identifier	1
Carrier Indicator	0 or 3
Uplink / Supplemental Uplink Indicator	0 or 1
Bandwidth Part Indicator	0, 1 or 2
Frequency Domain Resource Assignment	'x' bits = N_{RBG} or 'y' bits = $\lceil Log_2(N_{RB}^{UL,BWP} \times (N_{RB}^{UL,BWP} + 1) / 2) \rceil$ or 'z' bits = max (x, y) + 1
Time Domain Resource Assignment	0, 1, 2, 3 or 4
Frequency Hopping Flag	0 or 1
Modulation and Coding Scheme (MCS)	5
New Data Indicator (NDI)	1
Redundancy Version (RV)	2
HARQ Process Number	4
1st Downlink Assignment Index	1 or 2
2nd Downlink Assignment Index	0 or 2
TPC Command for Scheduled PUSCH	2
SRS Resource Indicator	$\lceil Log_2(N_{SRS}) \rceil$ bits for codebook based transmission $\left\lceil Log_2\left(\sum_{k=1}^{\min\{L_{max},N_{SRS}\}} \binom{N_{SRS}}{k}\right)\right\rceil$ bits for non-codebook based transmission
Precoding Information & Number of Layers	0, 1, 2, 3, 4, 5 or 6
Antenna Ports	2, 3, 4 or 5
SRS Request	2 or 3
CSI Request	0, 1, 2, 3, 4, 5 or 6
CBG Transmission Information (CBGTI)	0, 2, 4, 6 or 8
PTRS-DMRS	0 or 2
Beta Offset Indicator	0 or 2
DMRS Sequence Initialisation	0 or 1
UL-SCH Indicator	1
Padding	depends upon use of Supplemental Uplink

Table 76 – Content of DCI Format 0_1

* Underlined DCI Format Identifier: is a flag used to differentiate between DCI Formats 0_1 and 1_1. These two DCI Formats may include an equal number of bits. In this case, the DCI Format Identifier is used to determine which of the two DCI Formats has been received (a value of 0 indicates DCI Format 0_1)

* Carrier Indicator: is applicable when cross carrier scheduling is configured, i.e. the PDCCH is received on carrier 'x', while the resource allocation is for carrier 'y'. The set of 3 bits allows the cell upon which the PDCCH was received, and up to 7 other cells to be addressed. The Carrier Indicator field is absent if cross carrier scheduling has not been configured

* Uplink / Supplemental Uplink Indicator: is a single bit flag used to indicate whether the resource allocation is for the normal uplink carrier or the Supplemental Uplink carrier. This flag is excluded if the UE is not configured with a Supplemental Uplink carrier or the UE is configured with a Supplemental Uplink carrier but the PUSCH is configured to only use the carrier configured with the PUCCH

* Bandwidth Part Indicator: identifies the Bandwidth Part within which the frequency domain resource allocation is located. The number of bits occupied by this field depends upon the number of Bandwidth Parts which have been configured. A UE is permitted to ignore this field if it does not support active Bandwidth Part changes based upon DCI

* Frequency Domain Resource Assignment: allocates a set of Resource Blocks for the PUSCH. DCI Format 0_1 can allocate Resource Blocks using either Resource Allocation Type 0 or Type 1. A UE can be configured to use a specific resource allocation type, or to allow dynamic switching between resource allocation types. The Base Station uses the *resourceAllocation* information element within the *PUSCH-Config* parameter structure to configure the UE. The size of the Frequency Domain Resource Assignment field within the DCI depends upon the configuration of this information element. The field has a size of 'x' bits if *resourceAllocation* is set equal to 'resourceAllocationType0', whereas the field has a size of 'y' bits if *resourceAllocation* is set equal to 'resourceAllocationType1'. If *resourceAllocation* is set equal to 'dynamicSwitch' then the field has a size of max(x, y) + 1. The additional bit is used to indicate which resource allocation type is being used within a specific DCI transmission. Resource Allocation Types 0 and 1 are described in section 7.4.4.2

* If Frequency Hopping is enabled, then 1 or 2 of the Most Significant Bits (MSB) from the Frequency Domain Resource Assignment are used to select the Frequency Hopping Offset. 1 MSB is used if the RRC layer has configured 2 frequency offsets. 2 MSB are used if the RRC layer has configured 4 frequency offsets. Using the MSB for the purposes of Frequency Hopping means that there are fewer bits available to signal the frequency domain resource assignment. This is acceptable because Frequency Hopping is applicable to smaller Resource Block allocations, i.e. the benefit of Frequency Hopping diminishes as the number of allocated Resource Blocks approaches the total number of Resource Blocks within the Bandwidth Part

* Time Domain Resource Assignment: defines a pointer towards a row within a look-up table (either a 3GPP standardised look-up table, or an RRC configured look-up table). The look-up table defines the slot offset, the PUSCH Mapping Type, the starting symbol and the number of allocated symbols. The look-up tables have up to 16 rows so this field requires up to 4 bits

* Frequency Hopping Flag: indicates whether or not Frequency Hopping is to be applied to the resource allocation

* Modulation and Coding Scheme (MCS): defines a pointer towards a row within the relevant MCS look-up table. 3GPP has specified 5 MCS tables for the PUSCH – a 64QAM table; a 256QAM table, a low Spectral Efficiency table (for increased reliability), a 64QAM table for Transform Precoding with the option to use $\pi/2$ BPSK and a low Spectral Efficiency table for Transform Precoding with the option to use $\pi/2$ BPSK. Each table has 32 rows so this field requires 5 bits

* New Data Indicator (NDI): indicates if the resource allocation is to be used for a re-transmission, or a new transmission. This field occupies a single bit. In the case of dynamic resource allocations, a re-transmission is triggered if the NDI has the same value as that used for the previous transmission of the relevant HARQ process. A new transmission is triggered if the NDI is toggled. In the case of Configured Grants, a re-transmission is triggered if the NDI has a value of 1

* Redundancy Version (RV): indicates the puncturing pattern to be used after channel coding. Incremental Redundancy relies upon different puncturing patterns between transmissions and re-transmissions. Chase Combining relies upon the same puncturing pattern for both transmissions and re-transmissions

* HARQ Process Number: indicates the HARQ process which is to use the resource allocation. A UE supports 16 HARQ processes per cell in the uplink so this field occupies 4 bits

* 1st Downlink Assignment Index: occupies 1 bit if a semi-static HARQ-ACK codebook has been configured for acknowledging downlink data, and 2 bits if a dynamic HARQ-ACK codebook has been configured. In the case of the semi-static codebook, the 1 bit is used to indicate whether or not a HARQ-ACK codebook should be multiplexed and transmitted with the PUSCH. In the case of the dynamic codebook, the 2 bits are used to signal the 'Total' Downlink Assignment Index (DAI) for the first sub-codebook. The first sub-codebook is applicable to carriers which are not using Codeblock Groups (CBG). The 'Total' DAI provides information regarding the total number of HARQ Acknowledgements which should be returned to the Base Station. The HARQ acknowledgement procedure is described in section 13.5

* 2nd Downlink Assignment Index: occupies 0 bits if a semi-static HARQ-ACK codebook has been configured for acknowledging downlink data, and either 0 or 2 bits if a dynamic HARQ-ACK codebook has been configured. 2 bits are included if 2 sub-codebooks have been configured for the dynamic HARQ-ACK codebook. These 2 bits are used to signal the 'Total' Downlink Assignment Index (DAI) for the second sub-codebook. The second sub-codebook is applicable to carriers which are using Codeblock Groups (CBG)

* TPC Command for Scheduled PUSCH: is used for closed loop power control, i.e. the Base Station provides the UE with Transmit Power Control (TPC) commands which instruct the UE to increase, decrease or maintain its transmit power. Interpretation of the 2 bits

depends upon whether or not TPC command accumulation has been configured. Transmit Power Control is described within section 13.3.1

★ SRS Resource Indicator (SRI): occupies a number of bits which is dependent upon the uplink transmission scheme. In the case of codebook based transmission, the SRI is used to select between SRS Resources belonging to different antenna panels. There can be up to 2 SRS Resources (2 antenna panels) and so the SRI occupies only a single bit. The value of N_{SRS} corresponds to the number of SRS Resources. In the case of non-codebook based transmission, the SRI is used to select one or more SRS Resources from a set of N_{SRS} resources. The number of SRS Resources selected corresponds to the number of layers (rank) to be transmitted. Codebook and non-codebook based transmission schemes are described in section 8

★ Precoding Information & Number of Layers: is only applicable to codebook based transmission. This field occupies 0 bits for non-codebook based transmission. It also occupies 0 bits for codebook based transmission using a single antenna port. This represents a special case of codebook based transmission because a precoding matrix is not required and the number of layers is always 1. Otherwise, this field is used to signal both the Transmitted Precoding Matrix Indicator (TPMI) and the number of layers. The size of the field depends upon the number of layers and the configured maximum rank. An example look-up table specified by 3GPP TS 38.212 is presented as Table 77. This example is applicable to a UE which has 2 antenna ports and has been configured to use a maximum rank of 2. If the UE has fully coherent antenna ports then values from 0 to 8 can be signalled requiring 4 bits. If the UE has non-coherent antenna ports then values 0 to 2 can be signalled and only 2 bits are required

Value in DCI	Fully Coherent
0	1 layer: TPMI = 0
1	1 layer: TPMI = 1
2	2 layers: TPMI = 0
3	1 layer: TPMI = 2
4	1 layer: TPMI = 3
5	1 layer: TPMI = 4
6	1 layer: TPMI = 5
7	2 layers: TPMI = 1
8	2 layers: TPMI = 2

Value in DCI	Non-Coherent
0	1 layer: TPMI = 0
1	1 layer: TPMI = 1
2	2 layers: TPMI = 0

Table 77 – Precoding Information & Number of Layers for 2 antenna ports and a maximum rank of 2

★ Antenna Ports: is used to indicate 'which' logical antenna ports the UE should use to transmit the PUSCH and the corresponding Demodulation Reference Signal (DMRS). For example, when using PUSCH DMRS Configuration Type 1, with a double symbol DMRS, there are 8 logical antenna ports available for transmission. In the case of Multi-User MIMO, one UE could be instructed to use antenna ports 0 and 1, while another UE could be instructed to use antenna ports 2 and 3. This example is illustrated by DCI 'Antenna Port' values 1 and 2 within Table 78. 3GPP TS 38.212 specifies 18 different look-up tables to cater for all combinations of Transform Precoding, DMRS Configuration, Rank and DMRS length

Value in DCI	DMRS Ports	Number of DMRS CDM Groups without Data	Number of Front Loaded Symbols
0	0, 1	1	1
1	0, 1	2	1
2	2, 3	2	1
3	0, 2	2	1
4	0, 1	2	2
5	2, 3	2	2
6	4, 5	2	2
7	6, 7	2	2
8	0, 4	2	2
9	2, 6	2	2

Table 78 – Antenna Port information for Transform Precoding disabled, DMRS Configuration Type 1, Rank 2 and Max DMRS Length 2

★ The 'Antenna Ports' field also indicates whether or not the UE is permitted to frequency multiplex the PUSCH with the DMRS (3rd column within Table 78). A single DMRS antenna port occupies 1 out of every 2 subcarriers when using Configuration Type 1, and 2 out of every 6 subcarriers when using Configuration Type 2. Subcarriers which are not used by the DMRS can potentially be used by the PUSCH. The UE must be informed explicitly whether or not frequency multiplexing is permitted because other UE may be allocated the DMRS antenna ports which occupy the unused subcarriers, i.e. the UE cannot deduce the use of all subcarriers based upon only its own resource allocation. Table 78 expresses this permission to frequency multiplex by specifying the number of Code Division

Multiplexing (CDM) Groups which are not available for data transfer, i.e. not available for the PUSCH. When using DMRS Configuration Type 1, there are 2 CDM groups (Figure 285 in section 7.5.1). Indicating that 1 CDM Group is without data means that frequency multiplexing is permitted, whereas 2 CDM Groups without data means that frequency multiplexing is not permitted. When using DMRS Configuration Type 2, there are 3 CDM groups (Figure 286 in section 7.5.1) so the number of groups without data can be 1, 2 or 3. Tables which are applicable to Transform Precoding enabled always indicate that all CDM groups are without data because the DFT spreading operation generates an output which occupies the complete set of subcarriers

★ In addition, the 'Antenna Ports' field indicates whether the UE should transmit single symbol DMRS or double symbol DMRS (as illustrated in Figure 285 and Figure 286 in section 7.5.1)

★ SRS Request: is used to trigger SRS Resource Sets which have been configured for aperiodic triggering (section 7.5.3). The field has a size of 2 bits for UE which are not configured with a Supplemental Uplink carrier. In this case, the 2 bits are used to signal 4 values. The '00' value indicates that no SRS Resource Sets are triggered. The remaining 3 values are used to trigger SRS Resource Sets which have been configured with *aperiodicSRS-Resourcetrigger* values of 1, 2 and 3. Multiple SRS Resource Sets can be configured with each value so a single PDCCH transmission can trigger multiple SRS Resource Sets. The 'SRS Request' field has a size of 3 bits for UE which are configured with a Supplemental Uplink carrier. In this case, the first bit indicates whether the request is applicable to the Normal Uplink or the Supplemental Uplink

★ CSI Request: has a size between 0 and 6 bits, which is configured by the *reportTriggerSize* information element within the *CSI-MeasConfig* parameter structure. A UE can be configured with up to 128 aperiodic CSI 'Trigger States'. The 'CSI Request' field is used to select one of these Trigger States. The number of bits occupied by the CSI Request field depends upon the number of Trigger States which have been configured. The maximum of 6 bits is able to select between 64 Trigger States. If more than 64 Trigger States have been configured, an 'Aperiodic CSI Trigger State Subselection' MAC Control Element can be used to identify a subset of Trigger States which are candidates for selection

★ CBG Transmission Information (CBGTI): is applicable when a UE is configured to transmit uplink data using Code Block Groups (CBG). The length of this field is determined by the maximum number of Code Block Groups that the UE is configured to transmit, i.e. based upon the value of the *maxCodeBlockGroupsPerTransportBlock* information element which can be signaled using values of 2, 4, 6 or 8. There is a single bit included within the CBGTI field for each Code Block Group so the field can have lengths of 2, 4, 6 or 8 bits (or 0 bits if the UE is not configured to use CBG). A UE expects that all bits are set to '1' for a first transmission so the UE transmits all Code Block Groups. In the case of re-transmissions, the Base Station determines which Code Block Groups must be re-transmitted and sets the corresponding bits to '1'. The use of Code Block Groups in the uplink direction is described in section 13.5.2

★ PTRS-DMRS Association: is used to link a Phase Tracking Reference Signal (PTRS) to a Demodulation Reference Signal (DMRS). This allows the pair of Reference Signals to be used in combination, i.e. channel estimates derived from both and interpolated between them. If Transform Precoding is enabled or if the configured maximum uplink rank is 1 (based upon the *maxRank* information element), then the PTRS-DMRS Association field is not required and is excluded from the DCI. In these cases, there is only a single DMRS and the PTRS is linked to that DMRS by default. Otherwise, the PTRS-DMRS Association field occupies 2 bits and these bits are used to identify either 1 or 2 DMRS. If the UE transmits a single PTRS then the 2 bits are able to select between 4 DMRS. If the UE transmits 2 PTRS then the first bit is used to select between 2 DMRS for the first PTRS, while the second bit is used to select between 2 DMRS for the second PTRS

★ Beta Offset Indicator: can be used to configure the set of weights to be applied during the rate matching of uplink control information on the PUSCH. These weights impact the quantity of air-interface resources allocated to HARQ Acknowledgements and CSI Reports. If the UE has been configured with *betaOffsets* = 'semiStatic' then this field is not included and the UE applies a fixed set of configured weights. If the UE has been configured with *betaOffsets* = 'dynamic' then this field uses 2 bits to identify 1 out of 4 sets of configured weights. Each set of weights includes 3 weights which are applicable to HARQ Acknowledgements, 2 weights which are applicable to CSI Part 1 reports and 2 weights which are applicable to CSI Part 2 reports. Specific individual weights are subsequently selected based upon the payload size. For example, HARQ Acknowledgement weight 1 is selected if there are up to 2 HARQ Acknowledgements to transfer; weight 2 is selected if there are 3 to 11 HARQ Acknowledgements to transfer; and weight 3 is selected if there are more than 11 HARQ Acknowledgements to transfer

★ DMRS Sequence Initialisation: is a 1 bit field which is applicable when Transform Precoding is disabled. It is used as an input when initialising the pseudo random sequence which populates the Resource Elements allocated to the DMRS. The field is not applicable when Transform Precoding is enabled because the pseudo random sequence is replaced by a Zadoff-Chu sequence which has a lower Peak to Average Power Ratio (PAPR) and is better suited to the poor coverage conditions associated with the use of DFT-S-OFDM

★ UL-SCH Indicator: is a 1 bit field which instructs the UE whether or not the UL-SCH should be transmitted on the PUSCH. The PUSCH can be used to transfer Uplink Control Information (UCI) without any application data nor higher layer signalling when the UL-SCH is excluded. A value of '0' indicates that the UL-SCH should not be transmitted.

★ Padding: is added if a UE is configured for PUSCH transmission on both a Supplemental Uplink and a Normal Uplink and the size of DCI Format 0_1 for transmission on the Supplemental Uplink is not equal to the size of DCI Format 0_1 for transmission on the normal uplink. In this case, padding is added to the smaller DCI Format 0_1 until they both have equal size

★ 3GPP Reference: TS 38.212

3.5.6 DCI FORMAT 1_0

★ Downlink Control Information (DCI) Format 1_0 is used to provide resource allocations for the PDSCH. It is known as a 'Fallback' DCI Format which can be used to maintain a connection when coverage deteriorates. It has a smaller payload than DCI Format 1_1 so can benefit from increased channel coding redundancy. It may also be used to support communication during reconfigurations

★ DCI Format 1_0 supports single layer transmission on the PDSCH

★ 3GPP has specified a range of payloads for DCI Format 1_0. Each payload has been specified to match the requirements associated with a particular type of PDSCH transmission:

- o MSG2 transmission during the Random Access procedure using an RA-RNTI to address the UE
- o MSG4 transmission during the Random Access procedure using an TC-RNTI to address the UE
- o System Information (SI) transmission using the SI-RNTI to address the population of UE
- o Paging message transmission using the P-RNTI to address the population of UE
- o PDCCH Order to initiate the Random Access procedure using the C-RNTI to address the UE
- o Dynamic Grant and Semi-Persistent Scheduling (SPS) transmissions using the C-RNTI, MCS-C-RNTI and CS-RNTI to address the UE

★ The fields belonging to DCI Format 1_0 are presented in Table 79. A subset of the fields is applicable to each use case

	Number of Bits within DCI when UE is addressed using a specific RNTI					
	C-RNTI, CS-RNTI, MCS-C-RNTI	C-RNTI PDCCH Order	TC-RNTI	P-RNTI	SI-RNTI	RA-RNTI
DCI Format Identifier	1	1	1	-		
Short Messages Indicator	-	-	-	2	-	-
Short Messages				8		
Frequency Domain Resource Assignment	$\lceil Log_2(N_{RB}^{DL,BWP} \times (N_{RB}^{DL,BWP}+1)/2) \rceil$					
Time Domain Resource Assignment	4		4	4	4	4
VRB-to-PRB Mapping	1		1	1	1	1
Modulation and Coding Scheme (MCS)	5		5	5	5	5
TB Scaling	-		-	2	-	2
New Data Indicator (NDI)	1		1			
Redundancy Version (RV)	2	-	2		2	
HARQ Process Number	4		4			
Downlink Assignment Index	2		2			
TPC Command for Scheduled PUCCH	2		2			
PUCCH Resource Indicator	3		3	-		-
PDSCH to HARQ Feedback Timing Indicator	3		3		-	
Random Access Preamble Index		6	-			
UL/SUL Indicator		1				
SS/PBCH Index		6				
PRACH Mask Index	-	4				
System Information Indicator		-			1	
Reserved Bits		10		6	15	16
Padding	depends upon size of DCI Format 1_0					

Table 79 – Content of DCI Format 1_0

★ DCI Format Identifier: is a flag used to differentiate between DCI Formats 0_0 and 1_0. These two DCI Formats have been specified to include an equal number of bits. This helps to simplify the UE decoding procedure by reducing the number of block sizes which the UE attempts to decode. Once the UE has obtained a positive CRC result, the DCI Format Identifier is used to determine which of the two DCI Formats has been received (a value of 1 indicates DCI Format 1_0)

★ Short Messages Indicator: is only applicable to PDCCH transmissions using the P-RNTI. This field has a length of 2 bits and is used to indicate whether the DCI includes only scheduling information for a Paging transmission on the PDSCH (value 01), only a short message (value 10), or both scheduling information for a Paging transmission on the PDSCH and a short message (value 11)

★ Short Messages: is only applicable to PDCCH transmissions using the P-RNTI. This field has a length of 8 bits and is used to provide the population of UE with a message regarding the content of the BCCH. If the 1st bit is set to '1' then it indicates that the BCCH content (excluding SIB6, SIB7 and SIB8) has been modified. This triggers the population of UE to re-acquire the System Information at the start of the next modification period. If the 2nd bit is set to '1' then it indicates that there is an Earthquake and Tsunami Warning System (ETWS) primary notification on SIB6, or an ETWS secondary notification on SIB7, or a Commercial Mobile Alert System (CMAS) notification on SIB8. In this case, UE which support these notifications re-acquire SIB1 to check for scheduling information applicable to these SIB. UE then proceed with the acquisition of the relevant SIB if scheduling information is found. Bits 3 to 8 of the Short Messages field remain unused within the release 15 version of the 3GPP specifications

★ Frequency Domain Resource Assignment: allocates a set of Resource Blocks for the PDSCH. DCI Format 1_0 always uses Resource Allocation Type 1. This means that it always allocates a set of contiguous interleaved or non-interleaved Virtual Resource Blocks (VRB). The mapping from VRB to Physical Resource Blocks (PRB) is completed by the Physical layer before generating the CP-OFDM signal. A non-interleaved mapping means that VRB 'n' is mapped onto PRB 'n', whereas an interleaved mapping uses a function to map VRB 'n' onto PRB 'm'. The number of bits required by the Frequency Domain Resource Assignment field depends upon the number of Resource Blocks within the downlink Bandwidth Part

★ The Frequency Domain Resource Assignment field is also used to identify a PDCCH Order. If all bits are set to '1' and the CRC bits have been scrambled using a C-RNTI then the UE deduces that the remaining fields within the DCI Format are applicable to a PDCCH Order. The PDCCH Order triggers the UE to initiate a Random Access procedure

★ Time Domain Resource Assignment: defines a pointer towards a row within a look-up table (either a 3GPP standardised look-up table, or an RRC configured look-up table). The look-up table defines the slot offset, the PDSCH Mapping Type, the starting symbol and the number of allocated symbols. The look-up tables have up to 16 rows so this field requires 4 bits

★ VRB to PRB Mapping: is a single bit field which indicates whether the PDSCH uses a non-interleaved VRB to PRB mapping (value 0), or an interleaved VRB to PRB mapping (value 1)

★ Modulation and Coding Scheme (MCS): defines a pointer towards a row within the relevant MCS look-up table. 3GPP has specified 3 MCS tables for the PDSCH – a 64QAM table; a 256QAM table and a low Spectral Efficiency table (for increased reliability). Each table has 32 rows so this field requires 5 bits

★ Transport Block (TB) Scaling: configures a scaling factor which is applied when determining the Transport Block Size (TBS) for either a paging message or a MSG2 transmission. 3GPP has specified scaling factors of 1, 0.5 and 0.25 so this field requires 2 bits within the payload of the DCI Format. The scaling factors of 0.5 and 0.25 reduce the resultant Transport Block Size which leads to a lower coding rate, i.e. increased redundancy improves the reliability of these transmissions. Section 3.6.2 describes the process used to determine the Transport Block Size

★ New Data Indicator (NDI): indicates if the resource allocation is being used for a re-transmission, or a new transmission. This field occupies a single bit. In the case of dynamic resource allocations, a re-transmission is triggered if the NDI has the same value as that used for the previous transmission of the relevant HARQ process. A new transmission is triggered if the NDI is toggled. In the case of Semi-Persistent Scheduling, a re-transmission is triggered if the NDI has a value of 1. The NDI is only applicable to transmissions which use the HARQ re-transmission protocol, i.e. PDCCH Orders, Paging messages, System Information and random access MSG2 transmissions do not use the HARQ protocol

★ Redundancy Version (RV): indicates the puncturing pattern to be used after channel coding. Incremental Redundancy relies upon different puncturing patterns between transmissions and re-transmissions. Chase Combining relies upon the same puncturing pattern for both transmissions and re-transmissions. A Redundancy Version is not signalled for Paging and MSG2 resource allocations because these transmissions do not benefit from HARQ re-transmissions, i.e. there is no scope to change Redundancy Version between a first transmission and a re-transmission. Instead, a fixed Redundancy Version is used for all transmissions

★ HARQ Process Number: indicates the HARQ process which is to use the resource allocation. A UE supports 16 HARQ processes per cell in the downlink so this field occupies 4 bits. This field is only included for resource allocations which use multiple HARQ processes

★ Downlink Assignment Index (DAI): provides the Counter DAI which is applicable when using the dynamic HARQ-ACK codebook. The Counter DAI informs the UE of the accumulated number of transmissions which require acknowledgement up to the current {serving cell, PDCCH monitoring occasion}. If the UE is configured with multiple serving cells then the UE can receive multiple Counter DAI values within the same PDCCH monitoring occasion, i.e. the Counter DAI value is incremented with each resource allocation. A UE can detect missed resource allocations if it receives non-consecutive values for the Counter DAI. The Counter DAI can use values 0, 1, 2 and 3 so requires 2 bits. The values wrap from 3 to 0, so four consecutive missed resource allocations would be undetected. The HARQ acknowledgement procedure is described in section 13.5

★ TPC Command for Scheduled PUCCH: is used for closed loop power control, i.e. the Base Station provides the UE with Transmit Power Control (TPC) commands which instruct the UE to increase, decrease or maintain its transmit power. Interpretation of the 2 bits is based upon a standardised look-up table which maps the 2 bits onto values of -1, 0, 1 and 3 dB. Transmit Power Control is described within section 13.3.2

★ PUCCH Resource Indicator: is used to instruct the UE to use a specific PUCCH Resource when returning HARQ acknowledgements. If the UE has not been configured with dedicated PUCCH resources then the PUCCH Resource Indicator is used in combination with the index of the first CCE used by the PDCCH to calculate a pointer to a row within a 3GPP standardised look-up table. If the UE has been configured with dedicated PUCCH resources then the PUCCH Resource Indicator points to one of those resources. The PUCCH

Resource Indicator has a length of 3 bits so is able to point towards 1 out of 8 PUCCH resources. If the UE has been configured with more than 8 PUCCH resources then the PUCCH Resource Indicator is used in combination with the index of the first CCE used by the PDCCH to determine the appropriate PUCCH resource

* PDSCH to HARQ Feedback Timing Indicator: determines the number of slots between reception of the PDSCH and transmission of the HARQ Acknowledgement. In the case of DCI Format 1_0, this field has a length of 3 bits and the set of 8 values map onto delays of {1,2,3,4,5,6,7,8} slots. For example, the Timing Indicator value of '000' maps onto a delay of 1 slot so the HARQ acknowledgement is sent during slot 'n + 1', assuming the PDSCH was received during slot 'n'. The set of delays does not include the value of 0 slots. This means that DCI Format 1_0 does not support the transmission of a HARQ acknowledgement during the same slot as the PDSCH reception, i.e. a 'self contained' slot is not supported
* Random Access Preamble Index: is applicable when using DCI Format 1_0 to provide a PDCCH Order. A PDCCH Order triggers the UE to initiate the Random Access procedure. The Random Access Preamble Index field has a length of 6 bits which provides a range from 0 to 63. The value of '0' is treated as a special case and this triggers the UE to complete a 'Contention Based' random access procedure with its own selection of PRACH Preamble and SS/PBCH. Values > 0 are used to allocate a specific dedicated PRACH preamble allowing the UE to complete a 'Contention Free' Random Access procedure
* UL/SUL Indicator: is applicable if the UE is configured with a Supplemental Uplink (SUL) carrier and if the 'Random Access Preamble Index' was not set to '0'. The 'UL/SUL Indicator' field is a 1 bit flag which indicates whether the UE should complete the random access procedure using the Normal Uplink carrier or the Supplemental Uplink carrier
* SS/PBCH Index: is applicable if the 'Random Access Preamble Index' was not set to '0'. This field has a length of 6 bits which provides a range from 0 to 63. The value points towards a specific SS/PBCH Block (a specific Base Station beam) which can then be used to determine the PRACH occasion for the Random Access procedure
* PRACH Mask Index: is applicable if the 'Random Access Preamble Index' was not set to '0'. This field has a length of 4 bits which provides a range from 0 to 15. The value points towards a row within a look-up table standardised by 3GPP TS 38.321. The look-up table determines which PRACH occasions associated with the specified SS/PBCH Block can be used for transmission. A value of '0' indicates that all occasions are available. Values 1 to 8 indicate that PRACH occasions 1 to 8 are available. A value of '9' indicates that even numbered PRACH occasions are available, while a value of '10' indicates that odd numbered PRACH occasions are available
* System Information Indicator: is applicable when using DCI Format 1_0 to allocate PDSCH resources for the transmission of System Information. This 1 bit flag is used to indicate whether the resource allocation is for SIB1, or for another SIB
* Reserved Bits: are added to ensure that all variants of DCI Format 1_0 have equal size. Table 79 illustrates that all variants have a size of 28 bits after including the Reserved Bits (and ignoring the Frequency Domain Resource Assignment which is common across all variants)
* Padding: is added if the size of DCI Format 1_0 is less than the size of DCI Format 0_0. Padding is added until the two DCI Formats have equal size
* 3GPP References: TS 38.212, TS 38.211, TS 38.213, TS 38.321

3.5.7 DCI FORMAT 1_1

* Downlink Control Information (DCI) Format 1_1 is used to provide resource allocations for the PDSCH. A UE can be addressed by its C-RNTI, CS-RNTI or MCS-C-RNTI when receiving DCI Format 1_1. The UE is addressed by using the RNTI to scramble the CRC bits which are added to the DCI payload
* The fields belonging to DCI Format 1_1 are presented in Table 80
* DCI Format Identifier: is a flag used to differentiate between DCI Formats 0_1 and 1_1. These two DCI Formats may include an equal number of bits. In this case, the DCI Format Identifier is used to determine which of the two DCI Formats has been received (a value of 1 indicates DCI Format 1_1)
* Carrier Indicator: is applicable when cross carrier scheduling is configured, i.e. the PDCCH is received on carrier 'x', while the resource allocation is for carrier 'y'. The set of 3 bits allows the cell upon which the PDCCH was received, and up to 7 other cells to be addressed. The Carrier Indicator field is absent if cross carrier scheduling has not been configured
* Bandwidth Part Indicator: identifies the Bandwidth Part within which the frequency domain resource allocation is located. The number of bits occupied by this field depends upon the number of Bandwidth Parts which have been configured. A UE is permitted to ignore this field if it does not support active Bandwidth Part changes based upon DCI
* Frequency Domain Resource Assignment: allocates a set of Resource Blocks for the PDSCH. DCI Format 1_1 can allocate Resource Blocks using either Resource Allocation Type 0 or Type 1. A UE can be configured to use a specific resource allocation type, or to allow dynamic switching between resource allocation types. The Base Station uses the *resourceAllocation* information element within the *PDSCH-Config* parameter structure to configure the UE. The size of the Frequency Domain Resource Assignment field within the DCI depends upon the configuration of this information element. The field has a size of 'x' bits if *resourceAllocation* is set equal to

'resourceAllocationType0', whereas the field has a size of 'y' bits if *resourceAllocation* is set equal to 'resourceAllocationType1'. If *resourceAllocation* is set equal to 'dynamicSwitch' then the field has a size of max(x, y) + 1. The additional bit is used to indicate which resource allocation type is being used within a specific DCI transmission. Resource Allocation Types 0 and 1 are described in section 3.6.4.2

★ Time Domain Resource Assignment: defines a pointer towards a row within a look-up table (either a 3GPP standardised look-up table, or an RRC configured look-up table). The look-up table defines the slot offset, the PDSCH Mapping Type, the starting symbol and the number of allocated symbols. The look-up tables have up to 16 rows so this field requires up to 4 bits

		Number of Bits within DCI
DCI Format Identifier		1
Carrier Indicator		0 or 3
Bandwidth Part Indicator		0, 1 or 2
Frequency Domain Resource Assignment		'x' bits = N_{RBG} or 'y' bits = $\lceil Log_2(N_{RB}^{DL,BWP} \times (N_{RB}^{DL,BWP} + 1) / 2) \rceil$ or 'z' bits = max (x, y) + 1
Time Domain Resource Assignment		0, 1, 2, 3 or 4
VRB to PRB Mapping		0 or 1
PRB Bundling Size Indicator		0 or 1
Rate Matching Indicator		0, 1 or 2
Zero Power CSI Reference Signal Trigger		0, 1 or 2
Transport Block 1	Modulation and Coding Scheme (MCS)	5
	New Data Indicator (NDI)	1
	Redundancy Version (RV)	2
Transport Block 2	Modulation and Coding Scheme (MCS)	5
	New Data Indicator (NDI)	1
	Redundancy Version (RV)	2
HARQ Process Number		4
Downlink Assignment Index		4, 2 or 0
TPC Command for Scheduled PUCCH		2
PUCCH Resource Indicator		3
PDSCH to HARQ Feedback Timing		0, 1, 2 or 3
Antenna Ports		4, 5 or 6
Transmission Configuration Indication (TCI)		0 or 3
SRS Request		2 or 3
CBG Transmission Information (CBGTI)		0, 2, 4, 6 or 8
CBG Flushing Out Information (CBGFI)		0 or 1
DMRS Sequence Initialisation		1
Padding		depends upon size variations for DCI Format 1_1

Table 80 – Content of DCI Format 1_1

★ VRB to PRB Mapping: is a single bit field which indicates whether the PDSCH uses a non-interleaved VRB to PRB mapping (value 0), or an interleaved VRB to PRB mapping (value 1). Interleaved PRB mapping is only applicable to Resource Allocation Type 1 so this field can be excluded if the UE is configured to use only Resource Allocation Type 0. Similarly, the field can be excluded if the UE is not configured by the RRC layer to use the interleaved mapping with Resource Allocation Type 1

★ The mapping from VRB to Physical Resource Blocks (PRB) is completed by the Physical layer before generating the CP-OFDM signal. A non-interleaved mapping means that VRB 'n' is mapped onto PRB 'n', whereas an interleaved mapping uses a function to map VRB 'n' onto PRB 'm'

★ PRB Bundling Size Indicator: is applicable when *prb-BundlingType* within the *PDSCH-Config* has been set to '*dynamicBundling*'. A UE assumes that the Base Station has applied the same precoding to all contiguous Physical Resource Blocks within a Precoding Resource Block Group (PRG). A large PRG helps to improve the accuracy of the UE channel estimates and reduces the number of separate channel estimates which are required. However, a large PRG also reduces the Base Station flexibility in terms of applying frequency selective precoding. PRB Bundling is described in section 3.6.5. The PRB Bundling Size Indicator dynamically selects between the configured Bundle Size Sets 1 and 2

★ Rate Matching Indicator: is applicable when 'Reserved Resources' have been configured for the PDSCH. Reserved Resources are Resource Elements which are not available for the reception of the PDSCH. The 'Rate Matching' term is used because Reserved Resources puncture the normal PDSCH resources. Physical layer Rate Matching has to adjust the number of bits after channel coding to account for the reduced number of Resource Elements available to the PDSCH. Reserved Resources can be configured with a Resource Block/Symbol resolution, or with a Resource Element resolution. The Rate Matching Indicator within DCI Format 1_1 is applicable to Reserved Resources which have been configured with a Resource Block/Symbol resolution. Up to 4 patterns of Reserved Resources can be configured per serving cell, and per Bandwidth Part. If the Rate Matching Indicator is included within DCI Format 1_1, then its value points towards a specific pattern of Reserved Resources. Reserved Resources are described in section 3.6.7

★ Zero Power CSI Reference Signal Trigger: is applicable to triggering aperiodic Zero Power (ZP) CSI Reference Signal resources. This corresponds to generating Reserved Resources with a Resource Element resolution. Up to 3 aperiodic ZP CSI Reference Signal Resource Sets can be configured per Bandwidth Part. The number of bits occupied by this field within DCI Format 1_1 depends upon the number of Resource Sets which have been configured. The '0' and '00' values indicate that no aperiodic ZP CSI Reference Signal Resource Set is triggered. The values '1' or '01' triggers the Resource Set with identity 1. Similarly, the value '10' triggers the Resource Set with identity 2, and the value '11' triggers the Resource Set with identity 3. Reserved Resources are described in section 3.6.7, while ZP CSI Reference Signals are described in section 3.7.4.2

★ Modulation and Coding Scheme (MCS): defines a pointer towards a row within the relevant MCS look-up table. 3GPP has specified 3 MCS tables for the PDSCH – a 64QAM table; a 256QAM table and a low Spectral Efficiency table (for increased reliability). Each table has 32 rows so this field requires 5 bits

★ New Data Indicator (NDI): indicates if the resource allocation is being used for a re-transmission, or a new transmission. This field occupies a single bit. In the case of dynamic resource allocations, a re-transmission is triggered if the NDI has the same value as that used for the previous transmission of the relevant HARQ process. A new transmission is triggered if the NDI is toggled. In the case of Semi-Persistent Scheduling, a re-transmission is triggered if the NDI has a value of 1

★ Redundancy Version (RV): indicates the puncturing pattern to be used after channel coding. Incremental Redundancy relies upon different puncturing patterns between transmissions and re-transmissions. Chase Combining relies upon the same puncturing pattern for both transmissions and re-transmissions

★ Information regarding Transport Block 2 can only be included if *maxNrofCodeWordsScheduledByDCI* within *PDSCH-Config* has been configured with a value of 2. In the case of New Radio (NR), a second Transport Block is only required when the number of transmission layers is greater than 4, i.e. both 2×2 and 4×4 MIMO operate using only a single Transport Block

★ HARQ Process Number: indicates the HARQ process which is to use the resource allocation. A UE supports 16 HARQ processes per cell in the downlink so this field occupies 4 bits

★ Downlink Assignment Index (DAI): provides both the Counter DAI and Total DAI which are applicable when using the dynamic HARQ-ACK codebook with more than a single serving cell. The Counter DAI (2 Most Significant Bits from the DCI field) informs the UE of the accumulated number of transmissions which require acknowledgement up to the current {serving cell, PDCCH monitoring occasion}. The Total DAI (2 Least Significant Bits from the DCI field) informs the UE of the accumulated number of transmissions which require acknowledgement up to the current PDCCH monitoring occasion, after accounting for all serving cells. If the UE has been configured with only a single serving cell then only the Counter DAI is required and the field has a length of 2 bits. If the UE has been configured with the semi-static HARQ-ACK codebook then this field is not required within the DCI. The HARQ acknowledgement procedure is described in section 13.5

★ TPC Command for Scheduled PUCCH: is used for closed loop power control, i.e. the Base Station provides the UE with Transmit Power Control (TPC) commands which instruct the UE to increase, decrease or maintain its transmit power. Interpretation of the 2 bits is based upon a standardised look-up table which maps the 2 bits onto values of -1, 0, 1 and 3 dB. Transmit Power Control is described within section 13.3.2

★ PUCCH Resource Indicator: is used to instruct the UE to use a specific PUCCH Resource when returning HARQ acknowledgements. If the UE has not been configured with dedicated PUCCH resources then the PUCCH Resource Indicator is used in combination with the index of the first CCE used by the PDCCH to calculate a pointer to a row within a 3GPP standardised look-up table. If the UE has been configured with dedicated PUCCH resources then the PUCCH Resource Indicator points to one of those resources. The PUCCH Resource Indicator has a length of 3 bits so is able to point towards 1 out of 8 PUCCH resources. If the UE has been configured with more than 8 PUCCH resources then the PUCCH Resource Indicator is used in combination with the index of the first CCE used by the PDCCH to determine the appropriate PUCCH resource

★ PDSCH to HARQ Feedback Timing Indicator: determines the number of slots between reception of the PDSCH and transmission of the HARQ Acknowledgement. In the case of DCI Format 1_1, this field provides a pointer towards an entry within the sequence defined by *dl-DataToUL-ACK* within *PUCCH-Config*. Up to 8 values can be configured within this sequence so the pointer requires up to 3 bits. Each entry within the sequence can be allocated a value between 0 and 15. The value of '0' means that DCI Format 1_1 can be used to request a UE to transmit its HARQ acknowledgement during the same slot as the PDSCH reception, i.e. a 'self contained' slot is supported. The field can be excluded if *dl-DataToUL-ACK* is configured with a single value

★ Antenna Ports: defines a pointer to a row within a look-up table. 3GPP TS 38.312 specifies 4 look-up tables to cater for all combinations of DMRS Configuration Types 1 and 2 with DMRS lengths of 1 and 2 symbols. A subset of the rows belonging to the look-up table for DMRS Configuration Type 1 with a DMRS length of 2 symbols is presented as Table 81. The left side of the table is applicable when the UE is allocated a single codeword. A single codeword can be used to transfer up to 4 layers of data, i.e. when using 4×4 MIMO, so this part of the table specifies up to 4 antenna ports. The right side of the table is applicable when the UE is allocated two codewords. Two codewords can be used to transfer up to 8 layers so this part of the table specifies up to 8 antenna ports

★ In the case of Multi-User MIMO, one UE could be instructed to use antenna ports 1000 and 1001, while another UE could be instructed to use antenna ports 1002 and 1003. This example is illustrated by DCI 'Antenna Port' values 7 and 8 within Table 81

1 Codeword			
Value in DCI	Number of DMRS CDM Groups without Data	DMRS Ports (1000 + n)	Number of Front Load Symbols
0	1	0	1
1	1	1	1
2	1	0,1	1
3	2	0	1
4	2	1	1
5	2	2	1
6	2	3	1
7	2	0,1	1
8	2	2,3	1
9	2	0,1,2	1
…	…	…	…
28	2	0,1,4,5	2
29	2	2,3,6,7	2
30	2	0,2,4,6	2

2 Codewords			
Value in DCI	Number of DMRS CDM Groups without Data	DMRS Ports (1000 + n)	Number of Front Load Symbols
0	2	0,1,2,3,4	2
1	2	0,1,2,3,4,6	2
2	2	0,1,2,3,4,5,6	2
3	2	0,1,2,3,4,5,6,7	2

Table 81 – Antenna Port information for DMRS Configuration Type 1 and Max DMRS Length 2 (subset of complete table shown)

★ The look-up tables also indicate whether or not the PDSCH is frequency multiplexed with the DMRS (columns titled 'Number of DMRS CDM Groups without Data'). A single DMRS antenna port occupies 1 out of every 2 subcarriers when using Configuration Type 1, and 2 out of every 6 subcarriers when using Configuration Type 2. Subcarriers which are not used by the DMRS can potentially be used by the PDSCH. The UE must be informed explicitly whether or not frequency multiplexing is being used because other UE may be allocated the DMRS antenna ports which occupy the unused subcarriers, i.e. the UE cannot deduce the use of all subcarriers based upon only its own resource allocation

★ The look-up tables indicate whether or not the PDSCH is frequency multiplexed with the DMRS by specifying the number of Code Division Multiplexing (CDM) Groups which are not available for data transfer, i.e. not available for the PDSCH. When using DMRS Configuration Type 1, there are 2 CDM groups (Figure 180 in section 3.7.3). Indicating that 1 CDM Group is without data means that frequency multiplexing is permitted, whereas 2 CDM Groups without data means that frequency multiplexing is not permitted. When using DMRS Configuration Type 2, there are 3 CDM groups (Figure 181 in section 3.7.3) so the number of groups without data can be 1, 2 or 3

★ In addition, the 'Antenna Ports' field indicates whether the UE should transmit single symbol DMRS or double symbol DMRS

★ Transmission Configuration Indication (TCI): can be used to dynamically change the Quasi Co-Location (QCL) assumptions for the PDSCH. QCL refers to the PDSCH sharing some large scale propagation channel characteristics with either an SS/PBCH Block or CSI Reference Signal. Knowledge of these common characteristics helps the UE to decode the PDSCH. QCL is described in section 2.6. The Transmission Configuration Indication field is only included within DCI Format 1_1 if *tci-PresentInDCI* has been configured with a value of 'enabled'. This information element can be included as part of the *ControlResourceSet* parameter structure so different configurations can exist for different CORESET. The field has a size of 3 bits within DCI Format 1_1 so is able to select between up to 8 TCI states (up to 8 QCL relationships)

★ SRS Request: is used to trigger SRS Resource Sets which have been configured for aperiodic triggering (section 7.5.3) The field has a size of 2 bits for UE which are not configured with a Supplemental Uplink carrier. In this case, the 2 bits are used to signal 4 values. The '00' value indicates that no SRS Resource Sets are triggered. The remaining 3 values are used to trigger SRS Resource Sets which have been configured with *aperiodicSRS-Resourcetrigger* values of 1, 2 and 3. Multiple SRS Resource Sets can be configured with each value so a single PDCCH transmission can trigger multiple SRS Resource Sets. The 'SRS Request' field has a size of 3 bits for UE which are configured with a Supplemental Uplink carrier. In this case, the first bit indicates whether the request is applicable to the Normal Uplink or the Supplemental Uplink

★ CBG Transmission Information (CBGTI): is applicable when a UE is configured to receive downlink data using Code Block Groups (CBG). The length of this field is determined by the maximum number of Code Block Groups that the UE is configured to receive, i.e. based upon the value of the *maxCodeBlockGroupsPerTransportBlock* information element which can be signaled using values of 2, 4, 6 or 8. There is a single bit included within the CBGTI field for each Code Block Group so the field can have lengths of 2, 4, 6 or 8 bits (or 0 bits if the UE is not configured to use CBG). A UE expects that all bits are set to '1' for a first transmission so the UE receives all

Code Block Groups. In the case of re-transmissions, the Base Station determines which Code Block Groups must be re-transmitted and sets the corresponding bits to '1'. The use of Code Block Groups in the downlink direction is described in section 13.5.1.1

★ CBG Flushing Out Information (CBGFI): is used as a flag to indicate whether or not the set of Code Block Groups (CBG) being re-transmitted can be combined with previous transmissions. In general, a UE applies combining between an original downlink transmission and all re-transmissions. This combining helps to improve the decoding success rate. However, there are scenarios where re-transmissions should not be combined. In these cases, the UE should discard previously received downlink data and should attempt decoding using only the re-transmission. This scenario can be caused by the pre-emption of downlink air-interface resources. For example, a Base Station may receive some high priority downlink data which requires immediate transmission. The Base Station may have already allocated all air-interface resources so pre-emption of one or more existing allocations is required. This pre-emption means that one or more UE will receive some Resource Blocks which include downlink data belonging to another UE. Those UE will not have immediate knowledge of the pre-emption so decoding will be attempted with the data which has been sent to the high priority UE. Assuming that decoding fails, the UE will buffer the received data so it can be combined with any subsequent re-transmissions. However, the downlink buffers are now corrupt and they should be emptied rather than used for combining. Inclusion of the CBGFI flag within DCI Format 1_1 is enabled using the *codeBlockGroupFlushIndicator* information element which can be provided to the UE when configuring the use of CBG, i.e. within the *PDSCH-CodeBlockGroupTransmission* parameter structure. If the flag is set to '0' then the UE should discard any existing buffered data associated with the CBG being re-transmitted. Pre-emption is described in section 3.6.6

★ DMRS Sequence Initialisation: can be used to dynamically switch between the scrambling identities which initialize the pseudo random sequence which populates the Resource Elements belonging to the PDSCH DMRS. A UE can be configured with values for *scramblingID0* and *scramblingID1* within the *DMRS-DownlinkConfig* parameter structure. The 1 bit DMRS Sequence Initialisation field within DCI Format 1_1 allows selection between these two values

★ Padding: can be included if a UE is configured to receive DCI Format 1_1 in multiple search spaces associated with multiple CORESET within a specific Bandwidth Part. Padding is included if those instances of DCI Format 1_1 have different sizes, i.e. padding is added to ensure that all instances of DCI Format 1_1 within a Bandwidth Part have equal size

★ 3GPP References: TS 38.212, TS 38.213, TS 38.214, TS 38.331, TS 38.211

3.5.8 DCI FORMAT 2_0

★ Downlink Control Information (DCI) Format 2_0 is used to provide Slot Format Indicators (SFI). The fields belonging to DCI Format 2_0 are presented in Table 82

★ A UE is addressed by its SFI-RNTI when receiving DCI Format 2_0. The UE is addressed by using the RNTI to scramble the CRC bits which are added to the DCI payload. A UE is configured with an SFI-RNTI using the *SlotFormatIndicator* parameter structure that belongs to the *PDCCH-ServingCellConfig*

★ DCI Format 2_0 is used for 'UE Group' common signalling so multiple UE can be allocated the same SFI-RNTI. This means that multiple UE will decode the same PDCCH payload but will extract only the information which is relevant to that specific UE. A UE is provided with a *positionInDCI* information element as part of the *SlotFormatCombinationsPerCell* configuration. This information element indicates the starting position of the information which is relevant to that UE

★ The number of bits extracted from the DCI payload depends upon the range of values which have been configured for the *slotFormatCombinationId*. This identity has a maximum value of 511 so a maximum of 9 bits are extracted from the payload. The actual number of bits extracted is given by MAX{ROUNDUP[LOG$_2$(maximum value allocated to *slotFormatCombinationId* + 1)], 1}

	Number of Bits within DCI
Slot Format Indicator 1	1 to 9 bits
Slot Format Indicator 2	1 to 9 bits
Slot Format Indicator 3	1 to 9 bits
...	...
Slot Format Indicator n	1 to 9 bits

Table 82 – Content of DCI Format 2_0

★ The SFI acts as a pointer towards a specific *slotFormatCombinationId* which identifies a slot format combination which has been configured for the UE. This Slot Format Combination is able to dynamically reconfigure Flexible Symbols and Flexible Slots which may have already been allocated by SIB1 or by dedicated RRC signalling. Slot Formats are described in section 2.2

★ The maximum size of DCI Format 2_0 is 128 bits. The UE is informed of the actual size of DCI Format 2_0 using the *dci-PayloadSize* information element within the *SlotFormatIndicator* parameter structure

★ 3GPP References: TS 38.212, TS 38.213, TS 38.331

3.5.9 DCI FORMAT 2_1

- Downlink Control Information (DCI) Format 2_1 is used to provide Pre-emption Indications. The fields belonging to DCI Format 2_1 are presented in Table 83
- A UE is addressed by its Interruption RNTI (INT-RNTI) when receiving DCI Format 2_1. The UE is addressed by using the RNTI to scramble the CRC bits which are added to the DCI payload. A UE is configured with an INT-RNTI using the *DownlinkPreemption* parameter structure that belongs to the *PDCCH-Config*
- DCI Format 2_1 is used for 'UE Group' common signalling so multiple UE can be allocated the same INT-RNTI. This means that multiple UE will decode the same PDCCH payload but will extract only the information which is relevant to that specific UE. A UE is provided with a *positionInDCI* information element as part of the *DownlinkPreemption* configuration. This information element indicates the starting position of the information which is relevant to that UE

	Number of Bits within DCI
Pre-emption Indication 1	14
Pre-emption Indication 2	14
...	...
Pre-emption Indication n	14

Table 83 – Content of DCI Format 2_1

- A Pre-emption Indication occupies 14 bits within the DCI payload so each UE extracts a set of 14 bits. The maximum size of DCI Format 2_1 is 126 bits so a maximum of 9 Pre-emption Indications can be accommodated. The UE is informed of the actual size of DCI Format 2_1 using the *dci-PayloadSize* information element within the *DownlinkPreemption* parameter structure
- Each bit within the Pre-emption Indication corresponds to a specific time/frequency resource. The period between instances of the Search Space for DCI Format 2_1 can be divided into 14 time intervals. If a bit is set to '1' then it indicates that pre-emption has occurred during the corresponding time interval and the UE should ignore the associated downlink data. Alternatively, the period between instances of the Search Space for DCI Format 2_1 can be divided into 7 time intervals, and the downlink Bandwidth Part can be divided into 2 halves. In that case, each Pre-emption Indication corresponds to a specific time interval and half of the Bandwidth Part. The use of Pre-emption Indications is described in section 3.6.6
- 3GPP References: TS 38.212, TS 38.213, TS 38.331

3.5.10 DCI FORMAT 2_2

- Downlink Control Information (DCI) Format 2_2 is used to provide Transmit Power Control (TPC) commands for the PUSCH and PUCCH. The fields belonging to DCI Format 2_2 are presented in Table 84
- A UE is addressed by its TPC-PUSCH-RNTI or TPC-PUCCH-RNTI when receiving DCI Format 2_2. The UE is addressed by using the RNTI to scramble the CRC bits which are added to the DCI payload. A UE is configured with a TPC-PUSCH-RNTI and/or TPC-PUCCH-RNTI within the *PhysicalCellGroupConfig* parameter structure that belongs to the *CellGroupConfig*

	Number of Bits within DCI
Block Number 1	2 or 3
Block Number 2	2 or 3
...	...
Block Number n	2 or 3
Padding	depends upon size of DCI Format 1_0

Table 84 – Content of DCI Format 2_2

- DCI Format 2_2 is used for 'UE Group' common signalling so multiple UE can be allocated the same RNTI. This means that multiple UE will decode the same PDCCH payload but will extract only the information which is relevant to that specific UE. Each UE is provided with a TPC Index which points towards a specific 'Block' within DCI Format 2_2. The TPC Index can have a value from 1 to 15 indicating that DCI Format 2_2 can accommodate up to 15 Blocks
- In the case of PDCCH reception using the TPC-PUSCH-RNTI, the UE can be provided with TPC Indices for both a Normal Uplink (NUL) carrier and a Supplemental Uplink (SUL) carrier (*tpc-Index* and *tpc-IndexSUL* within *PUSCH-TPC-CommandConfig*)
- In the case of PDCCH reception using the TPC-PUCCH-RNTI, the UE can be provided with TPC Indices for the Primary Cell (PCell) and the Primary SCG Cell (PSCell) (*tpc-IndexPCell* and *tpc-IndexPUCCH-SCell* within *PUCCH-TPC-CommandConfig*). The PCell index is also applicable to the Special Cell (SpCell) when using the EN-DC Non-Standalone Base Station architecture

★ The TPC Index is translated into a bit position within the DCI payload based upon an assumption regarding the size of each Block. A Block has a size of 3 bits when using two power control adjustment states, and a size of 2 bits when using one power control adjustment state. In both cases, the actual TPC command occupies 2 bits. The third bit is used to identify the power control adjustment state when using two states. A UE assumes that all Blocks have equal size based upon its own configuration, i.e. a UE assumes that all UE are using a single adjustment state, or all UE are using two adjustment states

★ The configuration and maintenance of two power control adjustment states can be beneficial when switching between uplink beam pairs. The Base Station can dynamically request the UE to change uplink beam pairs using the SRS Resource Indicator (SRI) within DCI Format 0_1. This can impact the uplink link loss and consequently impact the appropriate UE transmit power. Maintaining two power control adjustment states allows the UE to switch between power control calculations at the same time as switching between beams. This helps to ensure that the UE always transmits with an appropriate power. Uplink power control is described in section 13.3

★ A UE signals its support for two power control adjustment states when providing its UE capability information, i.e. using the *twoDifferentTPC-Loop-PUSCH* and *twoDifferentTPC-Loop-PUCCH* information elements. The Base Station can subsequently configure the use of two adjustment states using *twoPUSCH-PC-AdjustmentStates* and *twoPUCCH-PC-AdjustmentStates*

★ It is not necessary to signal the size of DCI Format 2_2 because the Base Station adds padding to ensure that DCI Format 2_2 has the same size as DCI Format 1_0 in the Common Search Space of the same serving cell, i.e. the UE calculates the size of DCI Format 1_0 and assumes the same size for DCI Format 2_2

★ 3GPP References: TS 38.212, TS 38.213, TS 38.331

3.5.11 DCI FORMAT 2_3

★ Downlink Control Information (DCI) Format 2_3 is used to provide Transmit Power Control (TPC) commands for the SRS. In addition, it can be used to request the transmission of an aperiodic SRS

★ It is not always necessary to use DCI Format 2_3 to provide TPC commands for the SRS. A UE can be configured to apply the PUSCH TPC commands to both the PUSCH and SRS. The *srs-PowerControlAdjustmentStates* information element within the *SRS-ResourceSet* parameter structure is used to indicate whether or not the UE should apply the same TPC commands to both the PUSCH and SRS. Alternatively, a UE may be configured to transmit the SRS within a cell where the UE is not configured to transmit the PUSCH nor PUCCH. In this case, the UE requires dedicated TPC commands for the SRS

★ A UE is addressed by its TPC-SRS-RNTI when receiving DCI Format 2_3. The UE is addressed by using the RNTI to scramble the CRC bits which are added to the DCI payload. A UE is configured with a TPC-SRS-RNTI within the *PhysicalCellGroupConfig* parameter structure that belongs to the *CellGroupConfig*

★ DCI Format 2_3 is used for 'UE Group' common signalling so multiple UE can be allocated the same RNTI. This means that multiple UE will decode the same PDCCH payload but will extract only the information which is relevant to that specific UE. A UE is provided with a *startingBitOfFormat2-3* information element as part of the *SRS-TPC-CommandConfig*. This information element indicates the starting position of the information which is relevant to that UE

★ The fields belonging to DCI Format 2_2 are presented in Table 85

	Number of Bits within DCI
Block Number 1	2, 4, 6, ..
Block Number 2	2, 4, 6, ..
...	...
Block Number n	2, 4, 6, ..
Padding	depends upon size of DCI Format 1_0

Table 85 – Content of DCI Format 2_3

★ Each Block can include an SRS Request and one or more TPC commands. An SRS Request occupies 2 bits and each TPC Command occupies 2 bits. A UE is configured in advance for the inclusion of an SRS Request. The *fieldTypeFormat2-3* within *SRS-TPC-CommandConfig* is used to indicate whether or not an SRS Request will be included. Inclusion of an SRS Request does not mean that an SRS transmission will always be requested (SRS Request value '00' means that no SRS transmission is requested, while other values trigger specific SRS Resource Sets)

★ The Base Station uses the *srs-TPC-PDCCH-Group* information element to configure a UE to receive either 'Type A' or 'Type B' TPC commands. Type B means that the UE is configured to decode one or more Blocks from within the DCI payload and each Block provides a single TPC command for a specific uplink carrier. Type A means that the UE is configured to decode one Block from within the DCI payload but that Block can provide multiple TPC commands for multiple uplink carriers

★ It is not necessary to signal the size of DCI Format 2_3 because the Base Station adds padding to ensure that DCI Format 2_3 has the same size as DCI Format 1_0 in the Common Search Space of the same serving cell, i.e. the UE calculates the size of DCI Format 1_0 and assumes the same size for DCI Format 2_3

★ 3GPP References: TS 38.212, TS 38.213, TS 38.331

3.6 PHYSICAL DOWNLINK SHARED CHANNEL

★ The Physical Downlink Shared Channel (PDSCH) is used to transfer end-user application data, Signalling Radio Bearer (SRB) messages, System Information and Paging messages. Application data belongs to the user plane, while SRB messages, System Information and Paging messages belong to the control plane

★ In addition, the PDSCH can be used to transfer control information generated by the set of radio network protocol stack layers. For example, the MAC layer can add a range of MAC Control Elements (MAC CE) including Timing Advance Commands and Secondary Cell Activation/Deactivation Commands. The MAC Control Elements which can be transferred using the PDSCH are listed in Table 86

UE Contention Resolution Identity	TCI State Indication for UE-specific PDCCH
Timing Advance Command	TCI States Act./Deact. for UE-specific PDSCH
SP SRS Act./Deact.	DRX Command
SP ZP CSI-RS Resource Set Act./Deact.	PUCCH Spatial Relation Act./Deact.
SP CSI-RS / CSI-IM Resource Set Act./Deact.	Duplication Act./Deact.
SP CSI reporting on PUCCH Act./Deact.	SCell Act./Deact.
Aperiodic CSI Trigger State Subselection	Recommended Bit Rate

Table 86 – MAC Control Elements which can be transferred using the PDSCH

★ In the case of the uplink, the Physical layer can add Uplink Control Information (UCI) to the PUSCH. This UCI includes HARQ Acknowledgements and Channel State Information (CSI). In contrast, the Physical layer does not add Downlink Control Information (DCI) to the PDSCH

★ Figure 158 summarises the content transferred by the PDSCH

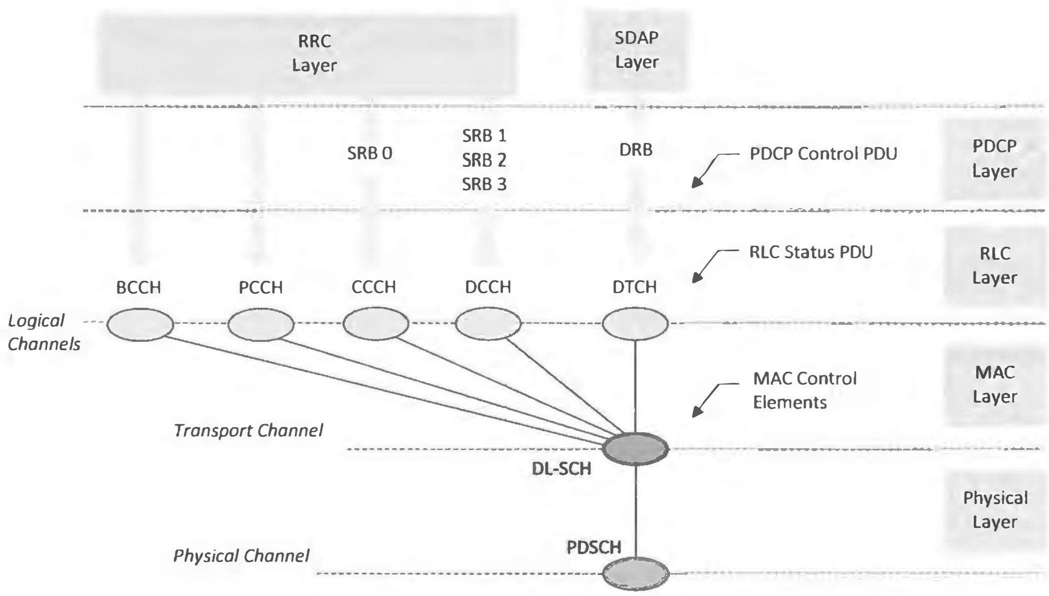


Figure 158 – Content transferred by the PDSCH

★ The PDSCH can use the QPSK, 16QAM, 64QAM and 256QAM modulation schemes. Modulation schemes are described in section 2.7. The Base Station transmits the PDSCH using a CP-OFDM waveform. This is in contrast to the PUSCH which supports both CP-OFDM and DFT-S-OFDM. Waveforms are described in section 2.9.

★ The PDSCH uses antenna ports 1000 to 1011. These are the same as those used by the Demodulation Reference Signal (DMRS). An individual UE can use up to 8 ports to transfer 8 layers of downlink data, i.e. 8×8 MIMO. The full set of ports can be utilised when using Multi-User MIMO

★ The PDSCH is always transmitted in combination with a DMRS. It may also be configured to be transmitted in combination with a Phase Tracking Reference Signal (PTRS) or a Tracking Reference Signal (TRS). The concept of Quasi Co-Location (QCL) can be used to help support PDSCH reception. The Base Station can inform the UE that the PDSCH is Quasi Co-Located with either an SS/PBCH Block or a CSI Reference Signal. This allows the UE to use the SS/PBCH Block or CSI Reference Signal to deduce specific large scale properties associated with the radio propagation channel, e.g. Doppler Shift; Doppler Spread; Average Delay, Delay Spread. This information can then be used to help decode the content of the PDSCH. Quasi Co-Location is described in section 2.6

★ Cell specific configuration information for the PDSCH is broadcast within System Information Block 1 (SIB1) using the *PDSCH-ConfigCommon* parameter structure presented in Table 87.

PDSCH-ConfigCommon		
pdsch-TimeDomainAllocationList	SEQUENCE (1 to 16 instances)	
	k0	0 to 32
	mappingType	typeA, typeB
	startSymbolAndLength	0 to 127

Table 87 – *PDSCH-ConfigCommon* parameter structure

★ The *pdsch-TimeDomainAllocationList* defines a look-up table with rows which can be selected when making a time domain resource allocation. Each row specifies a slot offset (K_0), a PDSCH Mapping Type, a starting symbol and a number of allocated symbols (the length). This look-up table is used in combination with other similar tables – Default tables 'A', 'B' and 'C' standardised by 3GPP within TS 38.214, and another table within the *pdsch-Config* parameter structure which can be provided using dedicated signalling. Selection between these look-up tables and their subsequent use is described in section 3.6.4.1

★ UE specific configuration information for the PDSCH can be provided using the *PDSCH-Config* parameter structure presented in Table 88. The Base Station uses dedicated signalling to forward this parameter structure to the UE

<table>
<tr><th colspan="5">PDSCH-Config</th></tr>
<tr><td>dataScramblingIdentityPDSCH</td><td colspan="4">0 to 1023</td></tr>
<tr><td>dmrs-DownlinkForPDSCH-MappingTypeA</td><td colspan="4">SetupRelease { DMRS-DownlinkConfig }</td></tr>
<tr><td>dmrs-DownlinkForPDSCH-MappingTypeB</td><td colspan="4">SetupRelease { DMRS-DownlinkConfig }</td></tr>
<tr><td>tci-StatesToAddModList</td><td colspan="4">SEQUENCE {1 to 128 instances of TCI-State}</td></tr>
<tr><td>tci-StatesToReleaseList</td><td colspan="4">SEQUENCE {1 to 128 instances of TCI-StateId}</td></tr>
<tr><td>vrb-ToPRB-Interleaver</td><td colspan="4">n2, n4</td></tr>
<tr><td>resourceAllocation</td><td colspan="4">resourceAllocationType0, resourceAllocationType1, dynamicSwitch</td></tr>
<tr><td rowspan="4">pdsch-TimeDomainAllocationList</td><td colspan="4">SEQUENCE (1 to 16 instances)</td></tr>
<tr><td colspan="2">k0</td><td colspan="2">0 to 32</td></tr>
<tr><td colspan="2">mappingType</td><td colspan="2">typeA, typeB</td></tr>
<tr><td colspan="2">startSymbolAndLength</td><td colspan="2">0 to 127</td></tr>
<tr><td>pdsch-AggregationFactor</td><td colspan="4">n2, n4, n8</td></tr>
<tr><td>rateMatchPatternToAddModList</td><td colspan="4">SEQUENCE {1 to 4 instances of RateMatchPattern}</td></tr>
<tr><td>rateMatchPatternToReleaseList</td><td colspan="4">SEQUENCE {1 to 4 instances of RateMatchPatternId}</td></tr>
<tr><td>rateMatchPatternGroup1</td><td colspan="4">SEQUENCE {1 to 8 instances of cellLevel or bwpLevel RateMatchPatternId }</td></tr>
<tr><td>rateMatchPatternGroup2</td><td colspan="4">SEQUENCE {1 to 8 instances of cellLevel or bwpLevel RateMatchPatternId }</td></tr>
<tr><td>rbg-Size</td><td colspan="4">config1, config2</td></tr>
<tr><td>mcs-Table</td><td colspan="4">qam256, qam64LowSE</td></tr>
<tr><td>maxNrofCodeWordsScheduledByDCI</td><td colspan="4">n1, n2</td></tr>
<tr><td rowspan="4">prb-BundlingType</td><td colspan="4">CHOICE</td></tr>
<tr><td colspan="2">staticBundling</td><td colspan="2">dynamicBundling</td></tr>
<tr><td rowspan="2">bundleSize</td><td rowspan="2">n4, wideband</td><td>bundleSizeSet1</td><td>n4, wideband, n2-wideband, n4-wideband</td></tr>
<tr><td>bundleSizeSet2</td><td>n4, wideband</td></tr>
<tr><td>zp-CSI-RS-ResourceToAddModList</td><td colspan="4">SEQUENCE {1 to 32 instances of ZP-CSI-RS-Resource}</td></tr>
<tr><td>zp-CSI-RS-ResourceToReleaseList</td><td colspan="4">SEQUENCE {1 to 32 instances of ZP-CSI-RS-ResourceId}</td></tr>
<tr><td>aperiodic-ZP-CSI-RS-ResourceSetsToAddModList</td><td colspan="4">SEQUENCE {1 to 3 instances of ZP-CSI-RS-ResourceSet}</td></tr>
<tr><td>aperiodic-ZP-CSI-RS-ResourceSetsToReleaseList</td><td colspan="4">SEQUENCE {1 to 3 instances of ZP-CSI-RS-ResourceSetId}</td></tr>
<tr><td>sp-ZP-CSI-RS-ResourceSetsToAddModList</td><td colspan="4">SEQUENCE {1 to 16 instances of ZP-CSI-RS-ResourceSet}</td></tr>
<tr><td>sp-ZP-CSI-RS-ResourceSetsToReleaseList</td><td colspan="4">SEQUENCE {1 to 16 instances of ZP-CSI-RS-ResourceSetId}</td></tr>
<tr><td>p-ZP-CSI-RS-ResourceSet</td><td colspan="4">SetupRelease { ZP-CSI-RS-ResourceSet }</td></tr>
</table>

Table 88 – *PDSCH-Config* parameter structure

★ *dataScramblingIdentityPDSCH* can be used to initialise the pseudo random sequence which scrambles the PDSCH payload prior to modulation. *dataScramblingIdentityPDSCH* is applicable if the RNTI used to address the UE on the PDCCH is a C-RNTI, MCS-C-RNTI or CS-RNTI, and if the PDSCH is not scheduled using DCI Format 1_0 in a Common Search Space. Otherwise, the PCI is used to initialise the pseudo random sequence. Scrambling uses the pseudo random sequence to 'randomly' change some bits from '1' to '0' and other bits from '0' to '1'. The order of the bits is not changed. The objective of scrambling is to randomise the bit stream and thus randomise the intercell interference experienced by neighbouring cells. The impact of intercell interference is reduced if the interference appears random

★ *dmrs-DownlinkForPDSCH-MappingTypeA* and *dmrs-DownlinkForPDSCH-MappingTypeB* provide configuration information for DMRS Types A and B. The DMRS Type is indicated for each PDSCH transmission using the 'Time Domain Resource Assignment' field within the PDCCH Downlink Control Information. The 'Time Domain Resource Assignment' field points to a row within a look-up table which includes a column for the DMRS Type. The parameter sets belonging to *dmrs-DownlinkForPDSCH-MappingTypeA* and *dmrs-DownlinkForPDSCH-MappingTypeB* are described in section 3.7.3

★ *tci-StatesToAddModList* configures the UE with a set of Transmission Configuration Indicator (TCI) States. These TCI States are used for the purposes of Quasi Co-Location (QCL) described in section 2.6. The parameter set configured by *tci-StatesToAddModList* is presented in Table 89. Up to two QCL relationships can be configured for each TCI State. In each case, either a CSI Reference Signal or an SS/PBCH Block within a specific Bandwidth Part and belonging to a specific cell is identified for the QCL relationship. The type of QCL relationship is then specified as either 'A', 'B', 'C' or 'D'. The type of QCL relationships defines the set of large scale radio channel properties which are shared with the PDSCH when the TCI State is activated and selected. Activation is completed using the '*TCI States Act/Deact. for UE-specific PDSCH*' MAC Control Element presented in Table 86. Subsequent selection is completed using the TCI field within DCI Format 1_1

TCI-State					
tci-StateId	0 to 127				
qcl-Type1	cell	0 to 31			
	bwp-Id	0 to 4			
	referenceSignal	CHOICE			
		csi-rs		ssb	
		NZP-CSI-RS-ResourceId	0 to 191	SSB-Index	0 to 63
	qcl-Type	typeA, typeB, typeC, typeD			
qcl-Type2	cell	0 to 31			
	bwp-Id	0 to 4			
	referenceSignal	CHOICE			
		csi-rs		ssb	
		NZP-CSI-RS-ResourceId	0 to 191	SSB-Index	0 to 63
	qcl-Type	typeA, typeB, typeC, typeD			

Table 89 – *TCI-State* parameter structure

★ *tci-StatesToReleaseList* can be used to release any TCI States which have been previously configured

★ *vrb-ToPRB-Interleaver* is used to configure the Resource Block Bundle (RBB) size which is applicable to the 'interleaved' mapping between Virtual Resource Blocks (VRB) and Physical Resource Blocks (PRB). The 'interleaved' mapping can be used when either DCI Format 1_0 or 1_1 provides a Resource Allocation Type 1 (the VRB to PRB Mapping field within the DCI payload indicates whether or not an interleaved mapping is to be applied). The 'interleaved' mapping function itself is described in section 3.6.4.2.2

★ *resourceAllocation* configures the UE to expect either a specific Resource Allocation Type or a dynamic switching between Resource Allocation Types within DCI Format 1_1. DCI Format 1_0 always uses Resource Allocation Type 1 so does not require any configuration. When using DCI Format 1_1 with dynamic switching, an additional bit is included within the Frequency Domain Resource Assignment field to indicate the Resource Allocation Type

★ *pdsch-TimeDomainAllocationList* provides a look-up table which has the same format as the look-up table provided by *PDSCH-ConfigCommon* (presented in Table 87). Each row specifies a slot offset (K_0), a PDSCH Mapping Type, a starting symbol and a number of allocated symbols (the length). These two tables are used in combination with Default tables 'A', 'B' and 'C' standardised by 3GPP within TS 38.214. Selection between these look-up tables and their subsequent use is described in section 3.6.4.1

★ *pdsch-AggregationFactor* defines the number of repetitions applied to the transmission of a downlink Transport Block on the PDSCH. When the aggregation factor is configured with a value of 'n' which is > 1, the Transport Block transmission is repeated in 'n' consecutive slots. The same symbol allocation is assumed for all repetitions and the PDSCH is limited to a single layer. The redundancy version applied during the Physical layer processing of the PDSCH is changed for each repetition to help maximise the incremental redundancy combining gain at the UE receiver

★ *rateMatchPatternToAddModList* is used to configure up to four Rate Matching Patterns. Each Rate Matching Pattern defines a set of Resource Blocks belonging to specific symbols which are not available for PDSCH transmission, i.e. Reserved Resources. The 'Rate

Matching' term is used because Reserved Resources puncture the normal PDSCH resources. Physical layer Rate Matching has to adjust the number of bits after channel coding to account for the reduced number of Resource Elements available to the PDSCH. The set of Rate Matching Patterns are used to generate either one or two Rate Matching Pattern Groups (*rateMatchPatternGroup1* and *rateMatchPatternGroup2*). A specific Rate Matching Pattern Group is subsequently activated using the 'Rate Matching Indicator' field within DCI Format 1_1. This field has a maximum length of 2 bits where each bit corresponds to a specific Rate Matching Pattern Group. Reserved resources and Rate Matching Patterns are described in section 3.6.7

★ *rbg-Size* defines the size of the Resource Block Groups (RBG) used for downlink Resource Allocation Type 0. Resource Allocation Type 0 uses a bitmap to allocate specific RBG. The size of the bitmap is equal to the number of RBG within the downlink Bandwidth Part. *rbg-Size* represents a pointer to a column belonging to a look-up table standardised by 3GPP TS 38.214. This look-up table is presented as Table 90. Configuration 1 corresponds to smaller RBG sizes which provide the Base Station with increased scheduling flexibility but these smaller RBG increase the size of the bitmap within DCI Format 1_1 when using Resource Allocation Type 0. PDSCH resource allocations are described in section 3.6.4

Bandwidth Part Size	Configuration 1	Configuration 2
1 to 36	2	4
37 to 72	4	8
73 to 144	8	16
145 to 275	16	16

Table 90 – Resource Block Group (RBG) sizes

★ *mcs-Table* specifies the Modulation and Coding Scheme (MCS) table to be used for the PDSCH. 3GPP has specified 3 MCS tables for the PDSCH – 64QAM table, 256QAM table and a low spectral efficiency table. The low spectral efficiency table has been specified for applications which require lower coding rates for reliable data transfer, e.g. applications belonging to the Ultra Reliable Low Latency Communications (URLLC) category. The *mcs-Table* information element can be configured with values of 'qam256' and 'qam64LowSE'. These values correspond to the 256QAM and low spectral efficiency MCS tables. The 64QAM table is configured by excluding the *mcs-Table* information element from the parameter structure. The set of MCS tables are presented in section 3.6.1. The 'Modulation and Coding Scheme' field within DCI Format 1_0 and 1_1 provides a pointer to a row within these tables

★ *maxNrofCodeWordsScheduledByDCI* defines the maximum number of code words which can be scheduled using a single resource allocation on the PDCCH. The UE uses this information to determine the expected content and payload size of DCI Format 1_1

★ *prb-BundlingType* configures the use of either 'static' or 'dynamic' Bundling. PRB Bundles correspond to Precoding Resource Block Groups (PRG). The Resource Blocks belonging to a PRG are assumed to experience similar channel conditions and have the same precoding applied by the Base Station, i.e. a UE can generate a single channel estimate from a PRG. In the case of the static configuration, the UE can be instructed to assume a PRG size of 4 Resource Blocks, or a wideband set of Resource Blocks. It is not necessary to have the option to configure a PRG size of 2 Resource Blocks because that is the default assumption, i.e. the UE assumes a PRG size of 2 Resource Blocks if the Base Station does not provide the '*prb-BundlingType*' information. The 'wideband' value indicates that the UE should assume that all of the allocated Resource Blocks belong to a single PRG. When using a dynamic configuration, 2 Bundle Size Sets can be configured. The 'PRB Bundling Size Indicator' field within DCI Format 1_1 is used to switch between the Bundle Size Sets. Resource Block Bundling is described in section 3.6.5

★ *zp-CSI-RS-ResourceToAddModList* configures the UE with a set of Zero Power (ZP) CSI Reference Signal Resources. A ZP CSI Reference Signal defines a set of Resource Elements which do not contain any transmission for the UE. These Resource Elements may however contain transmissions for other UE so the name 'Zero Power' can be misleading. The important point is that these Resource Elements puncture the PDSCH so the UE does not expect to receive any downlink data within them, i.e. ZP CSI Reference Signals are used to configure a Resource Element puncturing pattern for the PDSCH when some Resource Elements are allocated for other purposes. Reserved resources are described in section 3.6.7, while ZP CSI Reference Signal Resources are described in section 3.7.4

★ *aperiodic-ZP-CSI-RS-ResourceSetsToAddModList* uses the ZP CSI Reference Signal Resources to generate up to 3 Resource Sets which can be triggered aperiodically. DCI Format 1_1 includes a 'ZP CSI-RS Trigger' field to trigger an aperiodic Resource Set. This field occupies up to 2 bits to allow the 3 Resource Sets to be addressed

★ *sp-ZP-CSI-RS-ResourceSetsToAddModList* uses the ZP CSI Reference Signal Resources to generate up to 16 Resource Sets which can be triggered for the semi-persistent reservation of resources. Semi-persistent Resource Sets are triggered using the 'SP ZP CSI-RS Resource Set Act./Deact' MAC Control Element presented in Table 86. This MAC Control Element is used for both activation and deactivation purposes so it includes a 1 bit flag to differentiate between commands. The MAC Control Element includes a 4 bit field to address a specific Resource Set

★ *p-ZP-CSI-RS-ResourceSet* uses the ZP CSI Reference Signal Resources to generate a Resource Set for the periodic reservation of resources. The Base Station can configure a single periodic Resource Set which is always allocated identity 0

★ 3GPP References: TS 38.331, TS 38.214, TS 38.212, TS 38.321

3.6.1 MODULATION AND CODING SCHEME

★ The Modulation and Coding Scheme (MCS) is allocated by the Link Adaptation algorithm belonging to the Base Station. The allocated MCS is signalled to the UE on the PDCCH using DCI Format 1_0 or 1_1

★ 3GPP has specified three MCS tables for the PDSCH (presented below as Table 91):

- o 64QAM table which may be used when 256QAM is not supported by the Base Station or UE. It may also be used for UE which are in moderate to poor coverage, i.e. unable to benefit from 256QAM. This table is preferred for poor coverage conditions because it provides greater resolution for QPSK. It also provides slightly higher resolution for 16QAM and 64QAM
- o 256QAM table which is required whenever 256QAM is to be allocated
- o low spectral efficiency table which is suitable for applications which require lower coding rates for reliable data transfer, e.g. applications belonging to the Ultra Reliable Low Latency Communications (URLLC) category. This table includes entries which have low Spectral Efficiency (SE), i.e. a reduced coding rate which corresponds to increased channel coding redundancy

MCS Index Table 1 (64QAM Table)			
MCS Index	Modulation Order	Target Code Rate	Spectral Efficiency
0	2 (QPSK)	0.117	0.2344
1	2 (QPSK)	0.153	0.3066
2	2 (QPSK)	0.188	0.3770
3	2 (QPSK)	0.245	0.4902
4	2 (QPSK)	0.301	0.6016
5	2 (QPSK)	0.370	0.7402
6	2 (QPSK)	0.438	0.8770
7	2 (QPSK)	0.514	1.0273
8	2 (QPSK)	0.588	1.1758
9	2 (QPSK)	0.663	1.3262
10	4 (16QAM)	0.332	1.3281
11	4 (16QAM)	0.369	1.4766
12	4 (16QAM)	0.424	1.6953
13	4 (16QAM)	0.479	1.9141
14	4 (16QAM)	0.540	2.1602
15	4 (16QAM)	0.602	2.4063
16	4 (16QAM)	0.643	2.5703
17	6 (64QAM)	0.428	2.5664
18	6 (64QAM)	0.455	2.7305
19	6 (64QAM)	0.505	3.0293
20	6 (64QAM)	0.554	3.3223
21	6 (64QAM)	0.602	3.6094
22	6 (64QAM)	0.650	3.9023
23	6 (64QAM)	0.702	4.2129
24	6 (64QAM)	0.754	4.5234
25	6 (64QAM)	0.803	4.8164
26	6 (64QAM)	0.853	5.1152
27	6 (64QAM)	0.889	5.3320
28	6 (64QAM)	0.926	5.5547
29	2 (QPSK)	Reserved	
30	4 (16QAM)	Reserved	
31	6 (64QAM)	Reserved	

MCS Index Table 2 (256QAM Table)			
MCS Index	Modulation Order	Target Code Rate	Spectral Efficiency
0	2 (QPSK)	0.117	0.2344
1	2 (QPSK)	0.188	0.3770
2	2 (QPSK)	0.301	0.6016
3	2 (QPSK)	0.438	0.8770
4	2 (QPSK)	0.588	1.1758
5	4 (16QAM)	0.369	1.4766
6	4 (16QAM)	0.424	1.6953
7	4 (16QAM)	0.479	1.9141
8	4 (16QAM)	0.540	2.1602
9	4 (16QAM)	0.602	2.4063
10	4 (16QAM)	0.643	2.5703
11	6 (64QAM)	0.455	2.7305
12	6 (64QAM)	0.505	3.0293
13	6 (64QAM)	0.554	3.3223
14	6 (64QAM)	0.602	3.6094
15	6 (64QAM)	0.650	3.9023
16	6 (64QAM)	0.702	4.2129
17	6 (64QAM)	0.754	4.5234
18	6 (64QAM)	0.803	4.8164
19	6 (64QAM)	0.853	5.1152
20	8 (256QAM)	0.667	5.3320
21	8 (256QAM)	0.694	5.5547
22	8 (256QAM)	0.736	5.8906
23	8 (256QAM)	0.778	6.2266
24	8 (256QAM)	0.821	6.5703
25	8 (256QAM)	0.864	6.9141
26	8 (256QAM)	0.895	7.1602
27	8 (256QAM)	0.926	7.4063
28	2 (QPSK)	Reserved	
29	4 (16QAM)	Reserved	
30	6 (64QAM)	Reserved	
31	8 (256QAM)	Reserved	

MCS Index Table 3 (Low Spectral Efficiency Table)			
MCS Index	Modulation Order	Target Code Rate	Spectral Efficiency
0	2 (QPSK)	0.029	0.0586
1	2 (QPSK)	0.039	0.0781
2	2 (QPSK)	0.049	0.0977
3	2 (QPSK)	0.063	0.1250
4	2 (QPSK)	0.076	0.1523
5	2 (QPSK)	0.097	0.1934
6	2 (QPSK)	0.117	0.2344
7	2 (QPSK)	0.153	0.3066
8	2 (QPSK)	0.188	0.3770
9	2 (QPSK)	0.245	0.4902
10	2 (QPSK)	0.301	0.6016
11	2 (QPSK)	0.370	0.7402
12	2 (QPSK)	0.438	0.8770
13	2 (QPSK)	0.514	1.0273
14	2 (QPSK)	0.588	1.1758
15	4 (16QAM)	0.332	1.3281
16	4 (16QAM)	0.369	1.4766
17	4 (16QAM)	0.424	1.6953
18	4 (16QAM)	0.479	1.9141
19	4 (16QAM)	0.540	2.1602
20	4 (16QAM)	0.602	2.4063
21	6 (64QAM)	0.428	2.5664
22	6 (64QAM)	0.455	2.7305
23	6 (64QAM)	0.505	3.0293
24	6 (64QAM)	0.554	3.3223
25	6 (64QAM)	0.602	3.6094
26	6 (64QAM)	0.650	3.9023
27	6 (64QAM)	0.702	4.2129
28	6 (64QAM)	0.754	4.5234
29	2 (QPSK)	Reserved	
30	4 (16QAM)	Reserved	
31	6 (64QAM)	Reserved	

Table 91 – MCS Tables for the PDSCH

★ The 'Target Code Rate' represents the ratio between the number of information bits at the top of the Physical layer and the number of bits which are mapped onto the PDSCH at the bottom of the Physical layer, i.e. it provides a measure of the redundancy which is added by the Physical layer. A low coding rate corresponds to increased redundancy

- The 'Spectral Efficiency' is calculated as the product of the 'Modulation Order' and the 'Target Code Rate'. The Spectral Efficiency increases with MCS. This corresponds to larger transport block sizes and transferring more information bits across the air-interface. This Spectral Efficiency does not account for the number of MIMO layers, i.e. it represents the Spectral Efficiency per layer.
- The Spectral Efficiency figures within the 64QAM table remain approximately constant when the modulation order changes, e.g. MCS 9 (QPSK) and MCS 10 (16QAM) have approximately equal Spectral Efficiencies. This allows the modulation scheme to be changed without having to change the Spectral Efficiency
- The highest MCS values within each table are associated with specific modulation schemes but are shown as 'Reserved'. These MCS values are used for re-transmissions. For example, a UE being requested to complete a re-transmission using 16QAM within the 64QAM table will be allocated MCS 30
- The Base Station instructs the UE to select a specific MCS table using a combination of RRC signalling and Physical layer signalling. RRC signalling is used to configure the *mcs-Table* information elements within the *PDSCH-Config* and *SPS-Config* parameter structures. This corresponds to a semi-static configuration which requires further RRC signalling for modification. Physical layer signalling uses a dynamic selection of the RNTI which scrambles the CRC bits belonging to the PDCCH payload, e.g. switching between the C-RNTI and MCS-C-RNTI can influence the selection of the MCS table. The decision process for selecting the appropriate MCS table is presented in Figure 159

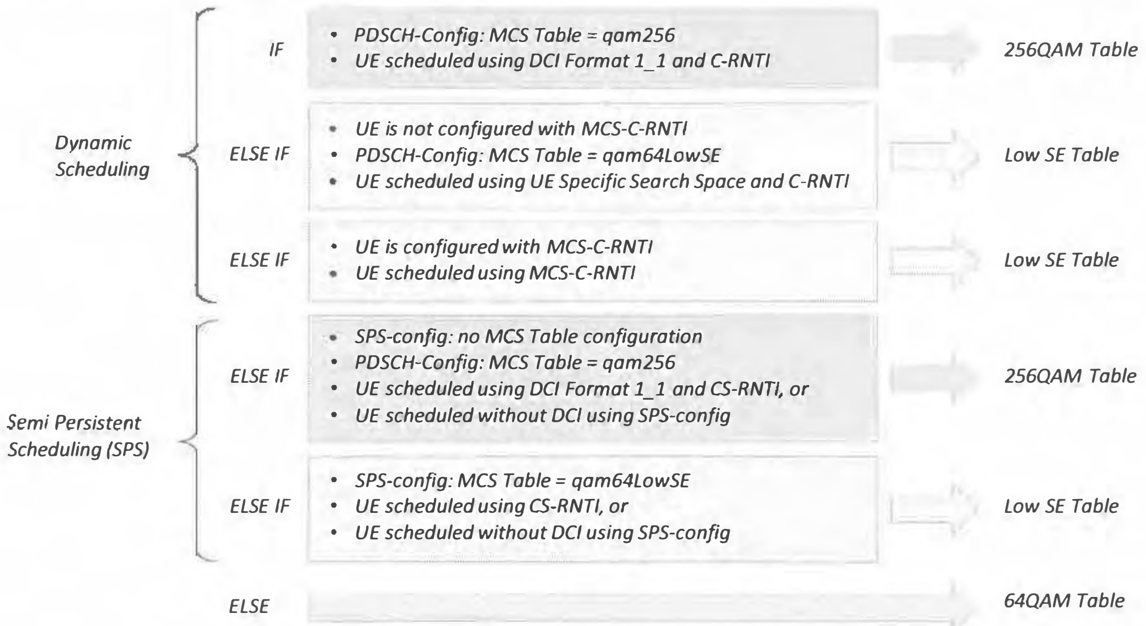


Figure 159 – Selection of MCS table for the PDSCH

- For example, consider a UE which is configured with *mcs-Table* = 'qam256' within *PDSCH-Config* and assume that the UE has been allocated an MCS-C-RNTI in addition to a C-RNTI. If the UE receives a PDSCH resource allocation using DCI Format 1_1 with the C-RNTI, then the UE will select the 256QAM MCS table. If the same UE receives a PDSCH resource allocation using DCI Format 1_0 with the C-RNTI, then the UE will select the 64QAM MCS table. If the same UE receives a PDSCH resource allocation using either DCI Format 1_1 or 1_0 with the MCS-C-RNTI, then the UE will select the Low Spectral Efficiency MCS table. This example illustrates that MCS table selection can be controlled using only Physical layer signalling once the initial RRC signalling has been completed
- 3GPP References: TS 38.214, TS 38.331

3.6.2 TRANSPORT BLOCK SIZE

- A Transport Block is a packet of data which is passed between the MAC and Physical layers. It is passed downwards at the transmitter and upwards at the receiver. A Transport Block undergoes Physical layer processing at the transmitter before being mapped onto the PDSCH for transfer across the air-interface
- A UE receiving data on the PDSCH has to determine the Transport Block Size (TBS) before attempting to decode the data. The UE uses a combination of semi-static information provided by RRC signalling and dynamic information provided by Downlink Control Information (DCI) on the PDCCH

★ The UE starts by quantifying the number of Resource Elements which are available for data transfer within the bandwidth of a single Resource Block. This is done using the following equation which is standardised by 3GPP TS 38.214:

$$N'_{RE} = 12 \times N^{sh}_{symb} - N^{PRB}_{DMRS} - N^{PRB}_{oh}$$

where,

N'_{RE} is the number of Resource Elements per Resource Block available for data transfer

N^{sh}_{symb} is the number of symbols per slot which have been allocated to the UE. This information is extracted from the Downlink Control Information (DCI) on the PDCCH, i.e. it is part of the PDSCH resource allocation

N^{PRB}_{DMRS} is the number of Resource Elements per Resource Block allocated to the Demodulation Reference Signal (DMRS). This includes the impact of the DMRS which are allocated to other UE when using multi-user MIMO, i.e. as indicated by the 'Number of DMRS CDM Groups without Data' column within the relevant DCI Format 'Antenna Ports' look-up table (example presented as Table 81 in section 3.5.7)

N^{PRB}_{oh} represents any additional overhead which reduces the number of Resource Elements available for data transfer, e.g. the CSI Reference Signal. The Base Station provides the value of this additional overhead using the *Xoh-PDSCH* RRC information element. This information element can have values of 0, 6, 12 or 18 Resource Elements. The UE assumes a value of 0 if it is not provided with a value

★ If the value of N'_{RE} is greater than 156 then N'_{RE} is rounded down to 156, i.e. the UE never assumes a resource allocation of more than 156 Resource Elements within the bandwidth of a single Resource Block. The total number of Resource Elements within the bandwidth of a single Resource Block is 12 × 14 = 168 when assuming the normal cyclic prefix

★ The resultant value of N'_{RE} is multiplied by the number of allocated Resource Blocks to generate a value for N_{RE}. The number of allocated Resource Blocks is extracted from the DCI on the PDCCH, i.e. it is part of the PDSCH resource allocation. The value of N_{RE} represents the total number of Resource Elements available for data transfer

★ The total number of Resource Elements available for data transfer is then converted into a corresponding number of information bits. The number of information bits depends upon the modulation scheme, the coding rate and the number of layers, i.e. the use of MIMO. The UE uses the following equation standardised by 3GPP:

$$N_{info} = N_{RE} \times Modulation\ Order \times Target\ Code\ Rate \times Number\ of\ Layers$$

★ The *Modulation Order* and *Target Code Rate* are both extracted from an MCS table. The set of MCS tables are presented in section 3.6.1. Table selection is based upon both RRC and Physical layer signalling. The 'MCS' field within the DCI on the PDCCH determines the appropriate row within the MCS table. A high *Modulation Order* means that each Resource Element can transfer an increased number of bits. A high *Target Code Rate* means that the Physical layer adds less redundancy so there is increased capacity for actual information bits

★ The *Number of Layers* is fixed to '1' if the PDSCH resource allocation has been received using DCI Format 1_0. Otherwise, the *Number of Layers* is obtained from the 'DMRS Ports' column within the 'Antenna Ports' look-up table used by DCI Format 1_1. The number of layers is equal to the number of allocated DMRS Ports. An example of the 'Antenna Ports' look-up table is presented as Table 81 in section 3.5.7

★ If PDSCH resources are allocated for a Paging message or a Random Access Response (DCI Format 1_0 using the P-RNTI or an RA-RNTI), then a scaling factor is applied to the value of N_{info}. The scaling factor is based upon the value of the 'Transport Block Scaling' field within DCI Format 1_0. This field defines a pointer to a row within Table 92. The scaling factors of 0.5 and 0.25 reduce the resultant Transport Block Size which leads to a lower coding rate, i.e. increased redundancy improves the reliability of these transmissions

Transport Block Scaling Field	Scaling Factor
00	1
01	0.5
10	0.25
11	reserved

Table 92 – Scaling factor applied to N_{info} when DCI Format 1_0 addresses the UE using P-RNTI or RA-RNTI

★ The remaining steps depend upon the value of N_{info}. If $N_{info} \leq 3824$ bits, then one routine is applied. Otherwise, another routine is applied. The threshold of 3824 is based upon the maximum code block size of 3840 bits which can be processed by the Low Density Parity Check (LDPC) channel coding when using 'Base Graph 2'. CRC bits are added prior to channel coding. Transport blocks which have a size ≤ 3824 bits have a 16 bit CRC added, i.e. the total size after CRC addition can be up to 3840 bits. LDPC 'Base Graph 1' can process a maximum code block size of 8448 bits, so transport blocks ≤ 3824 bits will not require segmentation prior to channel coding for both 'Base Graph 1' and 'Base Graph 2'

★ If $N_{info} \le 3824$ then the value of N'_{info} is calculated as:

$$N'_{info} = max\left(24,\ 2^n \times \left\lfloor \frac{N_{info}}{2^n} \right\rfloor\right) \qquad \text{where, } n = max(3, \lfloor LOG_2\,(N_{info}) \rfloor - 6)$$

This equation generates a result which is a multiple of 8, i.e. the result contains an integer number of bytes. It also generates a step size which is dependent upon the value of N_{info} ('n' determines the step size). A step size of 8 bits is generated for small values of N_{info} ('n' = 3); a step size of 16 bits is generated for intermediate values of N_{info} ('n' = 4); and a step size of 32 bits is generated for high values of N_{info} ('n' = 5). The value of 'n' does not exceed 5 because the maximum value of N_{info} is 3824 and $\lfloor LOG_2\,(N_{info}) \rfloor = 11$. The UE completes the procedure by selecting the closest Transport Block Size from Table 93 which is not smaller than N'_{info}

Index	TBS	Index	TBS	Index	TBS	Index	TBS	Index	TBS
1	24	21	184	41	552	61	1288	81	2600
2	32	22	192	42	576	62	1320	82	2664
3	40	23	208	43	608	63	1352	83	2728
4	48	24	224	44	640	64	1416	84	2792
5	56	25	240	45	672	65	1480	85	2856
6	64	26	256	46	704	66	1544	86	2976
7	72	27	272	47	736	67	1608	87	3104
8	80	28	288	48	768	68	1672	88	3240
9	88	29	304	49	808	69	1736	89	3368
10	96	30	320	50	848	70	1800	90	3496
11	104	31	336	51	888	71	1864	91	3624
12	112	32	352	52	928	72	1928	92	3752
13	120	33	368	53	984	73	2024	93	3824
14	128	34	384	54	1032	74	2088		
15	136	35	408	55	1064	75	2152		
16	144	36	432	56	1128	76	2216		
17	152	37	456	57	1160	77	2280		
18	160	38	480	58	1192	78	2408		
19	168	39	504	59	1224	79	2472		
20	176	40	528	60	1256	80	2536		

Table 93 – Transport Block Size Table for $N_{info} \le 3824$

★ If $N_{info} > 3824$ then a 24 bit CRC will be added rather than a 16 bit CRC. In addition, segmentation may be required prior to channel coding. When segmentation is applied, an additional 24 bit CRC is added to each segment. The following calculations account for these 24 bit CRC. N'_{info} is calculated as:

$$N'_{info} = max\left(3840,\ 2^n \times round\left(\frac{N_{info}-24}{2^n}\right)\right) \qquad \text{where, } n = \lfloor LOG_2\,(N_{info} - 24) \rfloor - 5$$

This equation generates a result which contains an integer number of bytes. It also generates a step size which is dependent upon the value of N_{info}. A step size of 64 bits is generated for smaller values of N_{info}, this increases to 128, 256, 512, … bits as the value of N_{info} increases. The transport block size is then calculated using one of three equations:

- if *Target Code Rate* ≤ 0.25 then LDPC 'Base Graph 2' will be used (maximum code block size of 3816 + 24 = 3840 bits) and the following equation is applied:

$$TBS = 8 \times C \times \lceil (N'_{info} + 24) / (8 \times C) \rceil - 24 \qquad \text{where, } C = \lceil (N'_{info} + 24) / 3816 \rceil$$

- Else if $N'_{info} > 8424$ bits then LDPC 'Base Graph 1' will be used (maximum code block size of 8424 + 24 = 8448 bits) and the following equation is applied:

$$TBS = 8 \times C \times \lceil (N'_{info} + 24) / (8 \times C) \rceil - 24 \qquad \text{where, } C = \lceil (N'_{info} + 24) / 8424 \rceil$$

- Else the following equation is applied:

$$TBS = 8 \times \lceil (N'_{info} + 24) / 8 \rceil - 24$$

★ 3GPP References: TS 38.214, TS 38.212

3.6.3 PHYSICAL LAYER PROCESSING

★ The Physical layer processes either 1 or 2 Transport Blocks for each resource allocation. In the downlink direction, a maximum of 8 layers can be generated for MIMO. Resource allocations using DCI Format 1_0 always allocate a single layer, whereas resource allocations using DCI Format 1_1 can allocate 1 to 8 layers. A single Transport Block is processed if 1 to 4 layers are allocated, whereas two Transport Blocks are processed if 5 to 8 layers are allocated

★ This section describes the Physical layer processing for the PDSCH in two parts. The first part (illustrated in Figure 160) is based upon the multiplexing and channel coding specified within 3GPP TS 38.212. The second part (illustrated in Figure 167) is based upon the subsequent physical channel processing and modulation specified within 3GPP TS 38.211

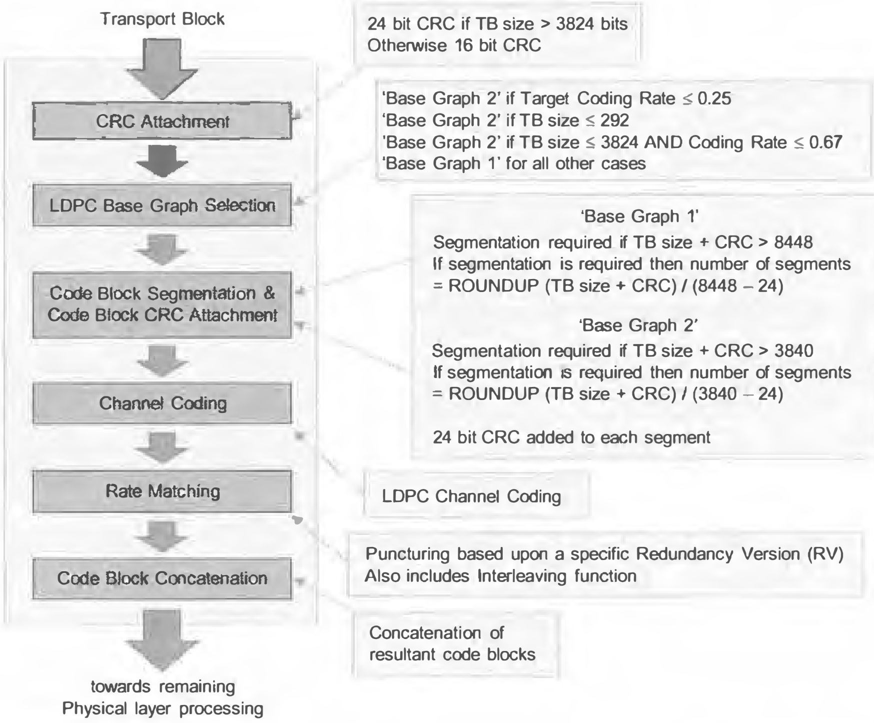


Figure 160 – Physical layer processing for the PDSCH (part 1)

★ Cyclic Redundancy Check (CRC) bits are attached to provide an error detection capability at the UE. They do not provide an error correction capability. The UE uses the CRC bits to determine whether or not the received Transport Block includes any bit errors. A negative HARQ acknowledgement is returned if any errors are detected. For a specific number of CRC bits, the probability of an undetected error increases as the Transport Block size increases. This provides the justification for using a larger set of CRC bits for larger Transport Block sizes. The PDSCH uses a 24 bit CRC for Transport Block sizes > 3824 bits, and a 16 bit CRC for Transport Block sizes ≤ 3824 bits. In contrast, the 4G PDSCH always uses a 24 bit CRC

★ The Physical layer then completes 'Base Graph' selection for the Low Density Parity Check (LDPC) channel coding. This selection is necessary prior to the channel coding itself because it determines the maximum code block size and thus impacts the requirement for segmentation. The maximum code block size is the maximum number of bits which the channel coding algorithm can accept. Blocks of data larger than this upper limit must be segmented before channel coding. Channel coding is then applied individually to each segment. Restricting the code block size handled by the channel coding algorithm helps to limit the decoding complexity at the UE

★ 'Base Graph' selection uses a combination of coding rate and Transport Block size thresholds. These thresholds are illustrated in Figure 161. Base Graph 2 is selected if the target coding rate is less than 0.25, or if the transport block size is less than 292 bits, or if the transport block size is less than 3824 bits AND the target coding rate is less than 0.67. Otherwise, Base Graph 1 is selected

★ The combination of Transport Block and CRC bits is then segmented if necessary. When segmentation is required, additional sets of CRC bits are attached to each segment. This allows the UE to complete error detection for each individual segment. Each additional CRC has a length of 24 bits. Base Graph 1 supports a maximum code block size of 8448 bits, whereas Base Graph 2 supports a maximum code block size of 3840 bits. If the Transport Block and CRC is less than the maximum code block size then segmentation is not required. If segmentation is required then the number of segments is given by ROUNDUP [(Transport Block size + CRC) / (maximum code block size – 24)]. The value of 24 is subtracted from the maximum code block size to provide capacity for the additional CRC to be added after segmentation

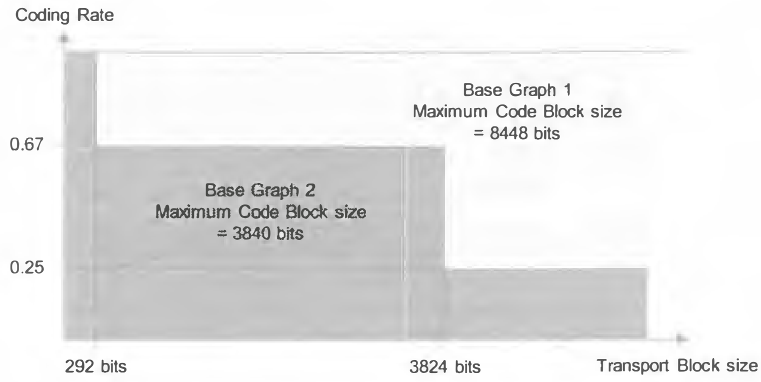


Figure 161 – Base Graph selection for LDPC channel coding

★ The code block segmentation phase is also responsible for ensuring that each code block has an appropriate number of bits for channel coding, i.e. in addition to requiring that the maximum code block size is not exceeded, channel coding also requires that code blocks have specific sizes. This may require the addition of filler bits, which are flagged as being 'NULL' entries. These 'NULL' entries are subsequently removed after channel coding. At the start of this operation, a variable K' is set equal to the segment size

- if segmentation has not been required then there is a single segment which has a size equal to (Transport Block size + CRC size)
- if segmentation has been required then each segment has a size equal to [(Transport Block size + CRC size) / Number of Segments] + Additional CRC size of 24

★ A table of 'Lifting Sizes' are used to identify an allowed code block size. These 'Lifting Sizes' are used during the channel coding process to increase the dimensions of the parity check matrix. The table of 'Lifting Sizes' is presented as Table 94. At this stage, the rows are not differentiated and all 'Lifting Sizes' within the table are considered to belong to a single group

★ If Base Graph 1 has been selected then the minimum Lifting Size (Z) which satisfies: $22 \times Z \geq K'$, is selected. The final code block size is then set equal to $22 \times Z$

★ If Base Graph 2 has been selected then the minimum Lifting Size (Z) which satisfies: $K_b \times Z \geq K'$ is selected. The final code block size is then set equal to $10 \times Z$. The value of K_b depends upon (Transport Block size + CRC size). If greater than 640 bits then $K_b = 10$, else if greater than 560 bits then $K_b = 9$, else if greater than 192 bits then then $K_b = 8$, else $K_b = 6$

LDPC Lifting Set Index	Set of Lifting Sizes (Z)	LDPC Lifting Set Index	Set of Lifting Sizes (Z)
0	2, 4, 8, 16, 32, 64, 128, 256	4	9, 18, 36, 72, 144, 288
1	3, 6, 12, 24, 48, 96, 192, 384	5	11, 22, 44, 88, 176, 352
2	5, 10, 20, 40, 80, 160, 320	6	13, 26, 52, 104, 208
3	7, 14, 28, 56, 112, 224	7	15, 30, 60, 120, 240

Table 94 – Sets of Lifting Sizes for LDPC channel coding

★ The code block segmentation stage is complete once the 'NULL' entries have been added to generate a code block size which can be processed by the channel coding stage. Figure 162 summarises the code block segmentation stage

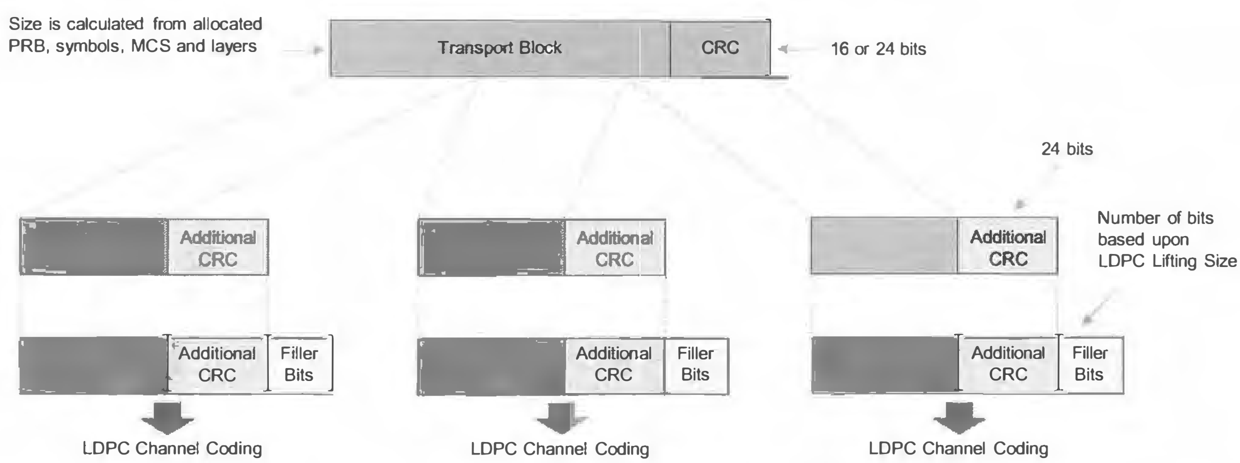


Figure 162 – Code Block segmentation and Code Block CRC attachment

★ 3GPP selected Low Density Parity Check (LDPC) coding for the PDSCH. This was selected as an alternative to Turbo coding which has been used for the PDSCH in 4G and HSDPA in 3G. LDPC channel coding is characterised by its sparse parity check matrix. This means that the matrix used to generate the set of parity bits has a relatively small number of '1's, i.e. it has a Low Density of 1's. This Low Density characteristic helps to reduce the complexity of both encoding and decoding. Reduced complexity translates to lower power consumption and a smaller area of silicon. The LDPC solution selected by 3GPP is scalable to support a wide range of code block sizes and a wide range of coding rates. LDPC and Turbo coding offer similar performance in terms of their error correction capabilities

★ The principle of the LDPC channel coding used for the PDSCH is illustrated in Figure 163. The 'Base Graph' defines a matrix which has dimensions of 46 rows × 68 columns when using Base Graph 1, and 42 rows × 52 columns when using Base Graph 2. This matrix is expanded by a factor equal to the selected 'Lifting Size' (Z). Each '0' within the Base Graph is replaced by a Z × Z matrix of '0's. Each '1' within the Base Graph is replaced by a circularly shifted Z × Z identity matrix. This leads to a Parity Check matrix which has dimensions of 46Z rows × 68Z columns when using Base Graph 1, and 42Z rows × 52Z columns when using Base Graph 2

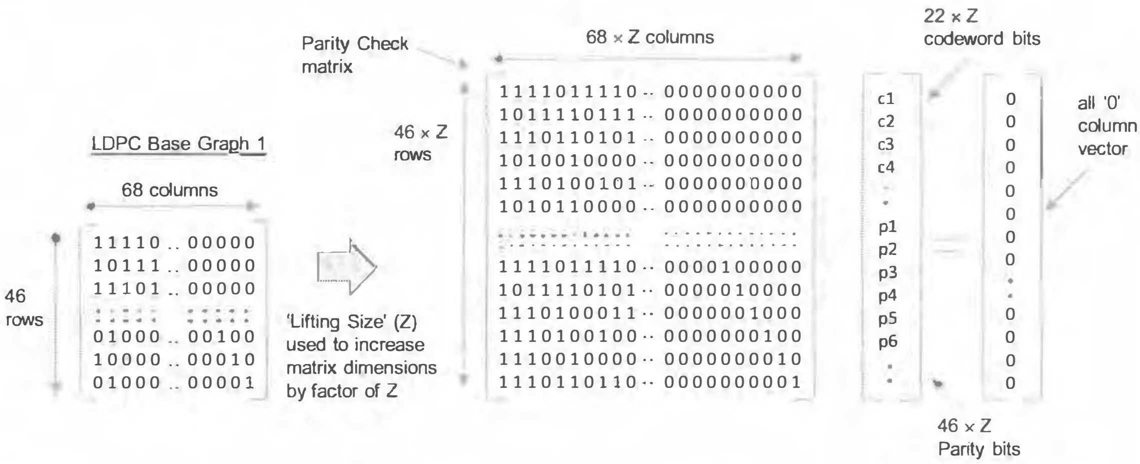


Figure 163 – Low Density Parity Check matrix used to generate Parity bits (shown for Base Graph 1)

★ The parity bits are calculated such that the product of the Parity Check matrix with the codeword/parity bit vector generates an all '0' vector. Any codeword bits which were previously flagged as 'NULL' are translated into '0's for the purposes of calculating the parity bits. However, these codeword bits remain flagged as 'NULL' within the output codeword/parity bit vector

★ In the case of Base Graph 1, there are 22Z codeword bits so 46Z parity bits are generated (the sum must equal the number of columns within the Parity Check matrix). In the case of Base Graph 2, there are 10Z codeword bits so 42Z parity bits are generated

★ When using Base Graph 1, the output from the channel coding has 66Z bits after providing an input of 22Z bits, i.e. a coding rate of 0.33. It should be noted that the codeword/parity bit vector has a length of 68Z bits. The first 2Z bits from the codeword are punctured to reduce the size to 66Z bits

★ When using Base Graph 2, the output from the channel coding has 50Z bits after providing an input of 10Z bits, i.e. a coding rate of 0.20. Similar to Base Graph 1, the first 2Z bits from the codeword are punctured to reduce the length of the codeword/parity bit vector from 52Z to 50Z

★ The output from Channel Coding is forwarded to the Rate Matching function. The Rate Matching function processes each channel coded segment separately. Rate Matching is completed in 2 stages: Bit Selection and Bit Interleaving. Bit Selection reduces the number of channel coded bits to match the capacity of the allocated air-interface resources. Bit Interleaving re-orders the bit sequence

★ Bit Selection starts by writing the set of 'N' bits belonging to a specific channel coded segment into a circular buffer. The size of the circular buffer is based upon a Limited Buffer Rate Matching (LBRM) calculation. LBRM is always applied for PDSCH Rate Matching (LBRM can be enabled/disabled for the PUSCH). 3GPP has specified the concept of LBRM to help reduce the requirement for buffering large code blocks. This helps to reduce the cost of the device by reducing the requirement for memory. The drawback is a potentially reduced performance when transferring large code blocks. LBRM does not impact performance when transferring smaller code blocks, i.e. these code blocks can be fully accommodated by the circular buffer

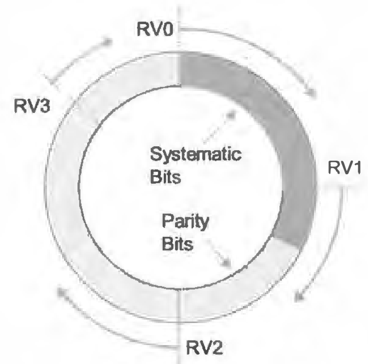
★ LBRM uses a circular buffer size given by $N_{cb} = \min(N, N_{ref})$, where N_{ref} = ROUND DOWN [TB_Size$_{\text{LBRM}}$ / (Number_of_Segments$_{\text{LBRM}}$ × 0.67)]. TB_Size$_{\text{LBRM}}$ and Number_of_Segments$_{\text{LBRM}}$ are calculated assuming a maximum number of layers, a maximum modulation order, a maximum coding rate and a maximum Resource Block allocation

★ If the circular buffer size is limited by 'N_{ref}' then only a subset of the channel coded bits are written into the circular buffer. The bits which are excluded are never transmitted across the air-interface. This reduces the scope for gains from HARQ incremental redundancy

★ Figure 164 illustrates the concept of the circular buffer. The Systematic Bits are written into the buffer first, followed by the Parity Bits. Systematic Bits correspond to the original codeword prior to channel coding, whereas Parity Bits correspond to the additional bits generated by channel coding. Transferring large codewords while using LBRM leads to the exclusion of the last section of Parity Bits

★ The Bit Selection process extracts a subset of bits from the circular buffer using a specific starting position. The starting position depends upon the Redundancy Version (RV). The Redundancy Version is indicated within the Downlink Control Information (DCI) on the PDCCH

★ 3GPP TS 38.212 specifies the starting position for each Redundancy Version, as presented in Figure 164. RV0, RV1 and RV2 have starting positions which are 0, 25 and 50 % around the circular buffer. RV3 has a starting position which is ~85 % around the circular buffer. The starting position for RV3 has been moved towards the starting position for RV0 to increase the number of Systematic Bits which are captured by an RV3 transmission. This approach has been adopted to allow 'self-decoding' when either RV0 or RV3 is transmitted, i.e. the receiver can decode the original transport block after receiving only a single standalone transmission of RV0 or RV3. RV1 and RV2 do not allow 'self-decoding'. These RV require another transmission using a different RV to allow decoding of the transport block



Redundancy Version (RV)	Starting Positions for reading bits out of buffer: Base Graph 1	Base Graph 2
0	0	0
1	$\left\lfloor \frac{17N_{cb}}{66Z} \right\rfloor \times Z$	$\left\lfloor \frac{13N_{cb}}{50Z} \right\rfloor \times Z$
2	$\left\lfloor \frac{33N_{cb}}{66Z} \right\rfloor \times Z$	$\left\lfloor \frac{25N_{cb}}{50Z} \right\rfloor \times Z$
3	$\left\lfloor \frac{56N_{cb}}{66Z} \right\rfloor \times Z$	$\left\lfloor \frac{43N_{cb}}{50Z} \right\rfloor \times Z$

Figure 164 – Reading bits from the circular buffer using the Redundancy Versions (RV)

★ The bits transmitted by each Redundancy Version will overlap to some extent, e.g. the bits extracted using RV0 will pass the starting position for RV1. The number of bits which are extracted depends upon the quantity of allocated Resource Elements, the modulation scheme and the number of layers. The 'NULL' entries which were added during code block segmentation remain present within the circular buffer but these entries are now skipped when extracting the set of bits for transmission

★ Bit Interleaving is applied once the set of bits have been extracted from the circular buffer. Bit Interleaving involves the stream of bits being read into a table row-by-row, and then being read out of the table column-by-column. The number of rows belonging to the table is set equal to the modulation order. This means that each column corresponds to a single modulation symbol. The concept of interleaving is illustrated in Figure 165

Data read in row-by-row

1, 2, 3, 4, 5, 6, 7, 8,...

1	2	3	4	5	6	7	8	9	10
11	12	13	14	15	16	17	18	19	20
21	22	23	24	25	26	27	28	29	30
31	32	33	34	35	36	37	38	39	40

Number of rows is equal to the modulation order, i.e. each column maps onto a single modulation symbol

Data read out column-by-column

1, 11, 21, 31, 2, 12, 22, 32, 3, 13, 23, ...

Figure 165 – Row-In Column-Out table used for Bit Interleaving

★ Interleaving helps to avoid bursts of contiguous bit errors at the input of the channel decoder at the receiver. The performance of the decoder is improved when bit errors are distributed at random rather than in contiguous groups. Figure 166 illustrates an example of a single modulation symbol being received in error due to the fading channel conditions. This example is based upon 16QAM so there are 4 bits associated with the modulation symbol. It is possible that there is only a single bit error when this modulation symbol is received in error. Gray coding is used to ensure that there is only a single bit error when a modulation symbol is mis-detected as a neighbouring modulation symbol. The concept of Gray coding for 16QAM is illustrated in Figure 124 (section 2.7). However, for the purposes of this example, it is assumed that the modulation symbol is completely mis-detected and all 4 bits are received in error. Figure 166 illustrates that after de-interleaving at the receiver, the set of 4 bit errors are distributed across the code block. This helps to improve the error correction capability of the LDPC decoder

★ Code Block Concatenation is applied after Rate Matching. This simply involves concatenating the set of code blocks into a single larger code block

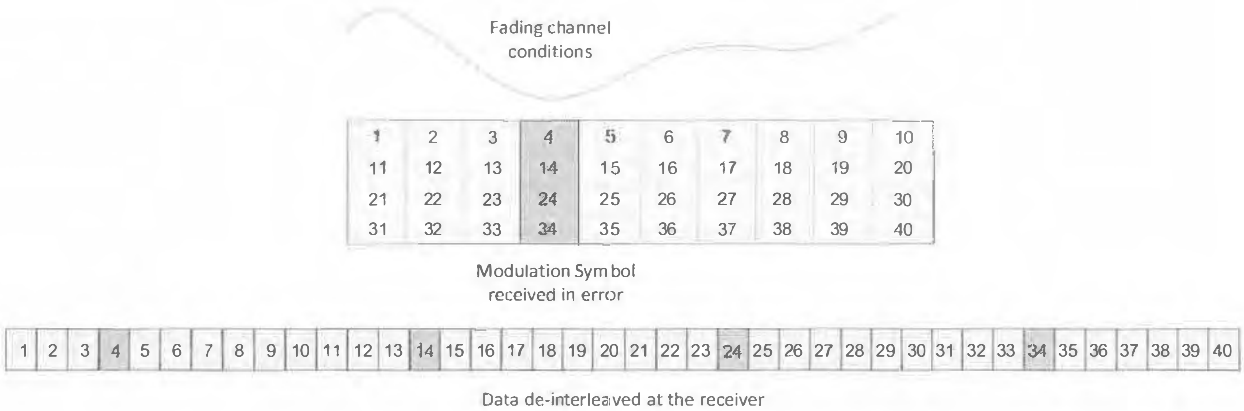


Figure 166 – Distribution of bit errors after de-interleaving

- The second part of the Physical layer processing for the PDSCH is illustrated in Figure 167. This part is based upon procedures specified by 3GPP TS 38.211
- The scrambling operation does not change the order of the bits. Instead, it switches some of the '1's into '0's and some of the '0's into '1's. The switching is done using a modular 2 summation between the original bit stream and a pseudo random sequence. A '1' in the pseudo random sequence causes the corresponding bit to switch, whereas a '0' leaves the bit with its original value. The objective of scrambling is to randomise the bit sequence and thus randomise the interference generated by the PDSCH. Interference has less impact when it is randomised and appears closer to white noise
- The pseudo random sequence used to complete the scrambling procedure is initialised using the *dataScramblingIdentityPDSCH* if it has been configured, and the UE has been addressed using a C-RNTI, MCS-C-RNTI or CS-RNTI, and the resource allocation was not provided using DCI Format 1_0 in a Common Search Space. Otherwise, the pseudo random sequence is initialised using the PCI. The *dataScramblingIdentityPDSCH* belongs to the *PDSCH-Config* parameter structure presented in Table 88

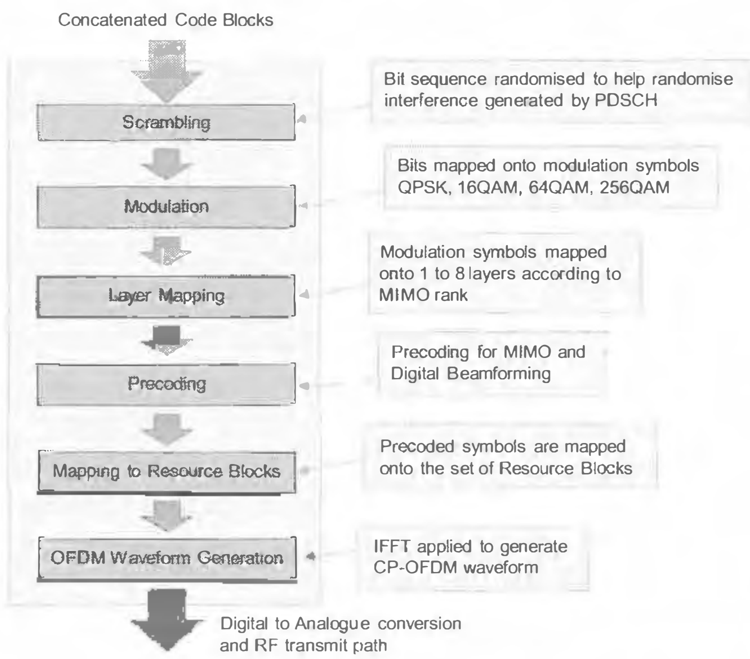


Figure 167 – Physical layer processing for the PDSCH (part 2)

- Modulation changes the bit sequence ('1's and '0's) into a modulation symbol sequence (complex numbers representing the set of modulation symbols). QPSK maps 2 bits onto each modulation symbol; 16QAM maps 4 bits onto each modulation symbol; 64QAM maps 6 bits onto each modulation symbol; and 256QAM maps 8 bits onto each modulation symbol. The appropriate modulation scheme is identified by selecting a row within a specific MCS table. The row is selected using the MCS field within DCI Format 1_0 or 1_1. The MCS table is selected using a combination of RRC configuration information and the type of RNTI used to address the UE when providing the resource allocation. Modulation is described in section 2.7 while the MCS tables are presented in section 3.6.1
- Layer mapping is used to distribute the set of modulation symbols across the layers which are used for MIMO. If the resource allocation has been provided using DCI Format 1_0 then there is only a single transmission layer and layer mapping is not required. In contrast, DCI Format 1_1 uses the 'Antenna Ports' field to allocate between 1 and 8 MIMO layers (the number of layers is equal to the

number of allocated DMRS Ports. An example look-up table is presented in Table 81, section 3.5.7). The layer mapping procedure is illustrated in Figure 168. The procedure distributes the stream of modulation symbols across the layers in a round robin fashion

★ The use of 1 to 4 layers requires a single codeword as an input, i.e. the Physical layer has processed a single Transport Block. The use of 5 to 8 layers requires two codewords as an input, i.e. the Physical layer has processed two Transport Blocks. In the case of 4G, 3GPP release 8 requires 2 codewords when generating more than 2 layers. 3GPP release 10 allows 4G to generate 1 to 4 layers using a single codeword. The number of codewords determines the trade-off between the HARQ acknowledgement signalling load and the volume of data which must be re-transmitted when a codeword is received in error. For example, if 2 codewords are used to generate 4 layers then the receiver must return 2 HARQ acknowledgements (ignoring the use of Code Block Groups). If there is a single bit error then it is necessary to re-transmit only 1 of the codewords. Alternatively, a single large codeword could be used to generate the same 4 layers and in this case, the receiver only has to return 1 HARQ acknowledgement. But a single bit error means that the whole of the larger codeword must be re-transmitted. The use of Code Block Groups (described in section 13.5.1.1) moves this trade-off in the direction of using only a single codeword because groups of codeword segments can be re-transmitted rather than whole codewords. But HARQ acknowledgements must be sent for each group of segments so there is an impact upon the HARQ signalling overhead

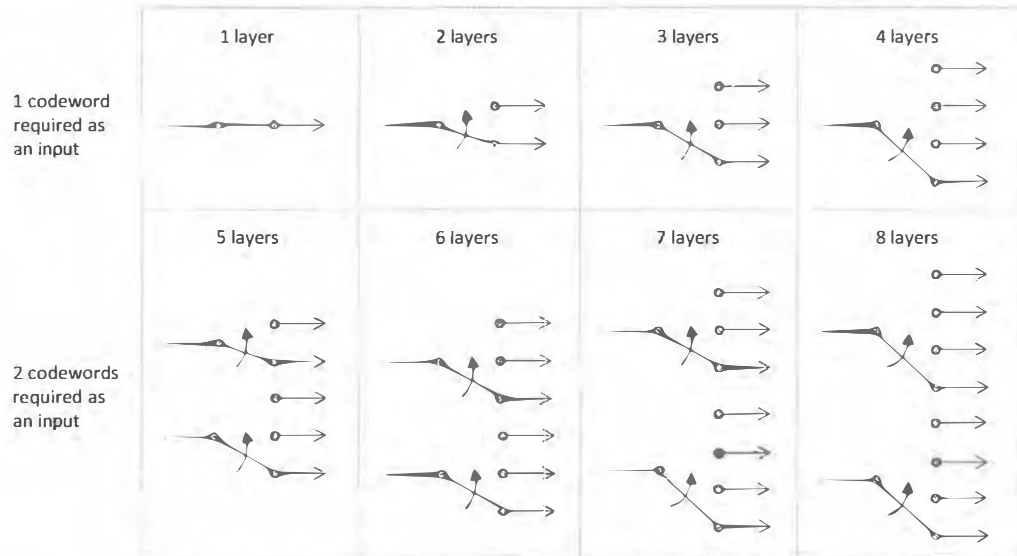


Figure 168 – Layer Mapping for the PDSCH

★ The number of layers should match the current channel conditions between the set of transmit antenna and the set of receive antenna. Low correlation propagation paths between the transmit and receive antenna allow an increased number of layers. This corresponds to a propagation channel with increased rank. Precoding can be used to reduce the correlation between the propagation paths so the precoding procedure should be taken into account when selecting an appropriate number of layers. The UE uses the Rank Indicator (RI) within its Channel State Information (CSI) reporting to indicate the number of layers which it believes can be supported across the air-interface. The Base Station may also account for buffer occupancy when selecting the number of layers. It is not necessary to allocate a high number of layers if the UE has only a small volume of data to be transferred

★ The precoding illustrated in Figure 167 is not standardised by 3GPP. Network vendors are free to select and implement their own proprietary solutions for precoding. The UE does not require explicit knowledge of the precoding weights which have been applied by the Base Station. This is made possible by the transmission of the Demodulation Reference Signal (DMRS). The DMRS is precoded in the same way as the PDSCH so the UE can deduce the composite propagation channel (precoding weights plus air-interface radio channel) from the DMRS. This composite channel estimate can then be used to support decoding

★ This approach differs from 4G Transmission Modes 3 and 4 which support open loop and closed loop spatial multiplexing. These transmission modes do not use a DMRS so the UE requires explicit knowledge of the precoding which has been applied to the downlink data. In the case of open loop spatial multiplexing, the precoding weights are standardised and follow a pre-defined pattern. In the case of closed loop spatial multiplexing, the precoding weights are standardised and the PDCCH is used to provide the UE with information regarding the weights which have been applied. In contrast, 4G Transmission Modes 8 and 9 use a DMRS so the UE is not provided with explicit information regarding the precoding weights

★ Figure 169 illustrates an example of the precoding which may be applied to the 5G PDSCH when using digital beamforming. In this case, the precoding is divided into two phases. The first phase applies the precoding for MIMO, while the second phase applies the precoding for digital beamforming

★ Figure 169 assumes the use of 2×2 MIMO with the transmission of 2 layers (rank 2). These 2 layers would be generated from a single Transport Block. 2×2 MIMO requires the use of 2 antenna ports so there are 2 DMRS. These DMRS are precoded in the same way as the PDSCH data. The precoding weights used for MIMO are updated at a relatively high rate because they are sensitive to the changing radio conditions. These weights are also frequency selective so different weights can be applied to different Resource Blocks. 3GPP has specified the use of Resource Block Bundles to provide the UE with information regarding the frequency domain resolution of the precoding applied by the Base Station, i.e. the same precoding weights are applied to all Resource Blocks within a Bundle. This information helps the UE to improve its channel estimates. Resource Block Bundling is described in section 3.6.5. The precoding weights applied for MIMO are often referred to as 'Short Term' weights because their values change rapidly over time. For example, they could change 100 times per second. Updating these weights at a high rate requires increased quantities of computation and the resultant weights may be more susceptible to errors due to less averaging

★ The MIMO precoding mixes the data streams and DMRS such that both data streams and both DMRS contribute to each output. This means that each of the beams generated by the physical antenna elements include contributions from both logical antenna ports, i.e. there is not a one-to-one mapping between logical antenna port and beam

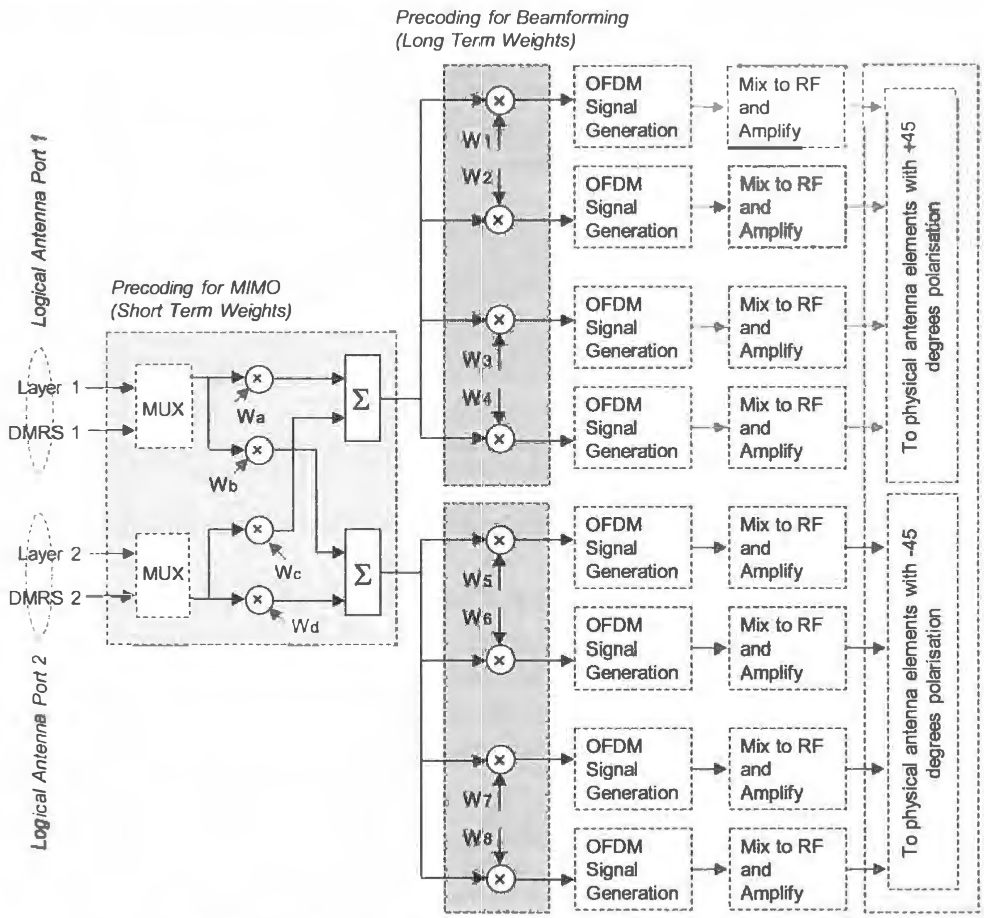


Figure 169 – Precoding for the PDSCH (digital beamforming)

★ The outputs from the MIMO precoding are used as inputs to the beamforming precoding. There is a one-to-one mapping between the MIMO precoding output and the beam transmitted across the air-interface. The first beam is used to transfer the first output from the MIMO precoding and this beam is generated using the +45° antenna elements. The second beam is used to transfer the second output from the MIMO precoding and this beam is generated using the -45° antenna elements

★ Figure 169 is based upon an example which illustrates 8 transceivers connected to 8 physical antenna elements. The number of antenna elements has been kept small to simplify the diagram. In practice, an active antenna is likely to use more than 8 antenna elements. An active antenna for Frequency Range 1 (450 MHz to 6 GHz) may support 64 transceivers connected to 128 antenna elements, i.e. 32 transceivers for each polarisation and 2 antenna elements connected to each transceiver. Each transceiver could provide an output power of 0.625 W per carrier leading to a total of 40 W per carrier

★ The solution for updating the beamforming weights will depend upon the type of beamforming that has been implemented:

- o 'Eigen based Beamforming' (EBB) relies upon the weights being updated dynamically to allow the beams to follow the UE as the UE moves around the cell. This type of solution is suitable for TDD which can take advantage of channel reciprocity to generate the downlink beamforming weights from uplink measurements of the Sounding Reference Signal (SRS). Generating beams which follow the population of UE around the cell requires significant quantities of baseband processing

- o 'Grid of Beams' (GoB) uses a set of fixed beam positions which means that each beam is generated using a fixed set of beamforming weights. The best beam changes as a UE moves around the cell so the Base Station switches between the fixed sets of beamforming weights. This type of solution is suitable for both FDD and TDD. It avoids the requirement to generate UE specific beamforming weights so requires significantly less baseband processing. The UE is required to provide feedback regarding the best fixed beam at any point in time. There are 2 general solutions for providing this feedback:

- a 'Grid of Beams' solution can use a set of beamformed SS/PBCH Blocks. The UE is able to measure and select the best SS/PBCH Block which is then reported using an SS/PBCH Block Resource Indicator (SSBRI). This solution may also use a set of beamformed CSI Reference Signals for beam refinement, i.e. the beams belonging to the CSI Reference Signals would be narrower and more directional than the beams belonging to the SS/PBCH Blocks. The UE measures and selects the best CSI Reference Signal which is then reported using a CSI Reference Signal Resource Indicator (CRI)
- a 'Grid of Beams' solution can use a set of non-beamformed CSI Reference Signals transmitted from a set of physical antenna elements. The UE is able to measure these CSI Reference Signals and determine the Precoding Matrix which would create the best beam towards the UE. The UE uses Precoding Matrix Indicator (PMI) reports to inform the Base Station of the selected Precoding Matrix (which corresponds to the selected beam)

★ Figure 170 illustrates the 'Eigen based Beamforming' and 'Grid of Beams' solutions. The precoding weights for beamforming are often referred to as 'Long Term' weights because their values change less frequently, e.g. they may be updated once per second. Their values depend upon the UE location which does not normally change very rapidly

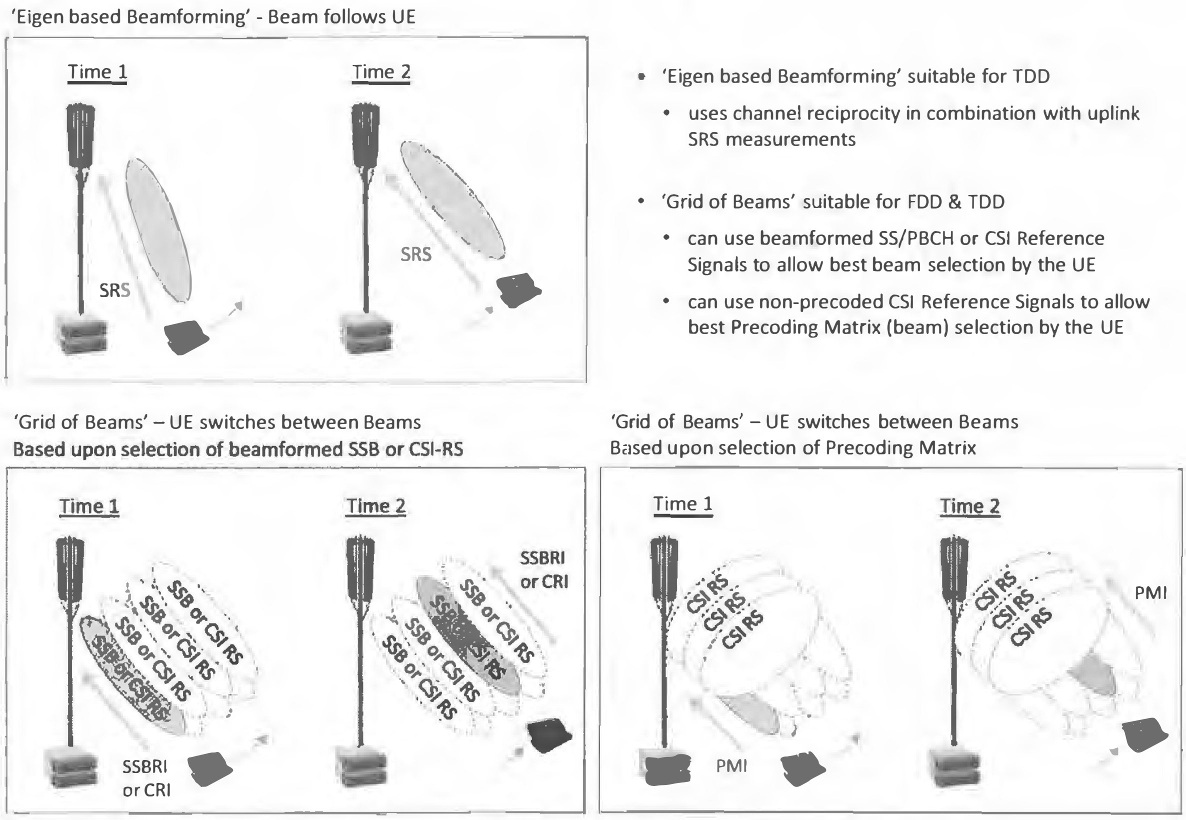


Figure 170 – Comparison between 'Eigen based Beamforming' and 'Grid of Beams'

★ As already stated, 3GPP has not standardised the precoding weights for the PDSCH, nor has 3GPP standardised a mechanism for the Base Station to provide the UE with the values of the precoding weights. However, 3GPP has standardised a set of precoding weights for the purposes of CSI reporting from the UE. This allows the UE to provide feedback to the Base Station regarding a preferred set of precoding weights selected from tables standardised by 3GPP. The Base Station can use this information when determining the weights to be applied for both the MIMO and beamforming precoding phases

★ Returning to Figure 167, the precoded modulation symbols are mapped onto the Resource Elements which belong to the allocated Virtual Resource Blocks within each of the allocated symbols. Each output from the precoding has its own set of Virtual Resource Blocks. The example in Figure 169 illustrates 2 outputs from the precoding so there will be 2 sets of Virtual Resource Blocks

★ If frequency domain Resource Allocation Type 0 has been used, the Virtual Resource Blocks (VRB) are mapped directly onto Physical Resource Blocks (PRB) using a 'non-interleaved' function, i.e. VRB 'n' is mapped onto PRB 'n'. If Resource Allocation Type 1 has been used then the Base Station can configure *vrb-ToPRB-Interleaver* within the *PDSCH-Config* shown in Table 88 to enable the use of an interleaved VRB to PRB mapping. The 'VRB to PRB Mapping' field within DCI Format 1_0 and 1_1 can then be used to activate the 'non-interleaved' mapping for each individual transmission. An interleaved mapping uses a function to map VRB 'n' onto PRB 'm'. Frequency domain resource allocations and the 'interleaved' mapping function are presented in section 3.6.4

★ The set of Physical Resource Blocks are then used to generate the CP-OFDM waveform. Each column of Resource Elements generates a CP-OFDM symbol. The process used to generate the waveform is described in section 2.9.1

★ 3GPP References: TS 38.211, TS 38.212, TS 38.214

3.6.4 RESOURCE ALLOCATIONS

★ There are 2 categories of resource allocation in the downlink:

- o Dynamic Grant allocations: which rely upon a PDCCH transmission prior to every PDSCH transmission. The PDCCH transfers Downlink Control Information (DCI) Format 1_0 or 1_1 to specify the allocated resources. The resources can be changed with every transmission so dynamic allocations are very adaptive to the current radio conditions, user requirements and network load. Dynamic allocations have the drawback of increased PDCCH signalling load which creates an overhead towards the PDSCH

- o Semi Persistent Scheduling (SPS) allocations: which do not require a PDCCH transmission prior to every PDSCH transmission (PDCCH transmissions are still used to request re-transmissions). The resource allocation is partially configured using RRC signalling but is subsequently activated and deactivated using PDCCH transmissions. The PDCCH provides the time and frequency resource allocation so this can change with each activation. Once activated, the UE has a set of periodic opportunities for PDSCH transmission. Semi Persistent Scheduling can be used for applications such as the voice service, i.e. the PDCCH can be used to activate a periodic resource allocation while a user is speaking and then deactivate those resources when the user is listening

★ Both Dynamic Grant and Semi Persistent Scheduling categories use the time and frequency domain resource allocations described in sections 3.6.4.1 and 3.6.4.2. These resource allocations are included within the DCI on the PDCCH. DCI content is presented within sections 3.5.6 and 3.5.7. Semi Persistent Scheduling is further described in section 3.6.4.3

3.6.4.1 TIME DOMAIN RESOURCE ALLOCATION

★ PDSCH time domain resources can be allocated using Downlink Control Information (DCI) Formats 1_0 and 1_1. DCI is transferred to the UE using the PDCCH physical channel. The '*Time Domain Resource Assignment*' field within these DCI Formats is used to specify the slot offset, the starting symbol, the number of allocated symbols and the PDSCH Mapping Type

★ The '*Time Domain Resource Assignment*' field defines a pointer towards a row within a look-up table. This look-up table can be either a 3GPP standardised table or an RRC configured table. 3GPP has standardised default tables 'A', 'B' and 'C' which can be used without having to provide the UE with information regarding their content, i.e. these tables are standardised so the UE already knows the content of each table. RRC configured tables can be provided to the UE within SIB1 or by using dedicated signalling

★ A standardised table is always used when receiving a downlink resource allocation for the transmission of SIB1. This approach means that the UE can always interpret the '*Time Domain Resource Assignment*' field without having received any prior configuration information from the Base Station. The standardised default tables 'A', 'B' and 'C' have been designed for use with SS/PBCH - COREST multiplexing patterns '1', '2' and '3' respectively. These multiplexing patterns are described in section 3.5.3. Default tables 'A', 'B' and 'C' are presented within that section as Table 71, Table 73 and Table 74

- o operating bands within Frequency Range 1 always use multiplexing pattern '1'. This means that PDSCH resource allocations applicable to SIB1 within Frequency Range 1 always use default table 'A'

- o operating bands within Frequency Range 2 can use multiplexing patterns '1', '2' or '3'. This means that PDSCH resource allocations applicable to SIB1 within Frequency Range 2 can use default tables 'A', 'B' or 'C'

★ SIB1 can be used to provide an RRC configured look-up table within the *pdsch-ConfigCommon* parameter structure. In that case, the UE uses the RRC configured look-up table when receiving PDSCH resource allocations for Other System Information (OSI), i.e. SIB2, SIB3, SIB4, etc. The *pdsch-ConfigCommon* parameter structure can also be provided to the UE using dedicated signalling if the UE has already entered RRC Connected mode. If the UE has not been provided with an RRC configured look-up table within the *pdsch-ConfigCommon* parameter structure then the UE uses a standardised table for the reception of OSI. The standardised table is selected based upon the SS/PBCH - COREST multiplexing pattern (pattern '1' => table 'A'; pattern '2' => table 'B'; pattern '3' => table 'C')

★ The same rules are applied when receiving PDSCH resource allocations for paging messages, i.e. the UE will use an RRC configured look-up table if one has been provided within *pdsch-ConfigCommon*, otherwise the UE will use a standardised table 'A', 'B' or 'C' dependent upon the SS/PBCH - COREST multiplexing pattern '1', '2' or '3'

★ In the case of receiving PDSCH resource allocations for MSG2 or MSG4 belonging to the random access procedure, the UE will use an RRC configured look-up table if one has been provided within *pdsch-ConfigCommon*, otherwise the UE will use standardised table 'A'. In this case there is no dependency upon the SS/PBCH - COREST multiplexing pattern

★ The Base Station can also use dedicated signalling to provide the UE with an RRC configured look-up table within the *pdsch-Config* parameter structure. When a UE receives PDSCH resource allocations on the PDCCH within the 'UE specific Search Space' then the UE will use the look-up table from within *pdsch-Config* if it has been provided. Otherwise, the UE will use the look-up table from within *pdsch-ConfigCommon* if it has been provided. Otherwise, the UE will use the standardised default table 'A'

★ As an example, Table 95 presents four rows from the standardised look-up table 'A'. The rows are indexed using a combination of the 'Index' and 'dmrs-TypeA-Position' columns. The 'Index' corresponds to the '*Time Domain Resource Assignment*' field within the DCI whereas the 'dmrs-TypeA-Position' corresponds to the '*dmrs-TypeA-Position*' field within the Master Information Block (MIB)

Index	dmrs-TypeA-Position	PDSCH Mapping Type	Slot Offset (K_0)	Starting Symbol (S)	Length (L)
1	2	Type A	0	2	12
	3			3	11
6	2	Type B		9	4
	3			10	4

Table 95 – 3GPP standardised Default PDSCH Time Domain Resource Allocation 'A' (only four rows are shown)

★ The PDSCH Mapping Type can be set to either 'Type A' or 'Type B'. Selection between Type A and Type B has an impact upon the allowed combinations of the Starting Symbol (S) and Length (L). These allowed combinations are presented in Table 96. Mapping Type B limits the maximum resource allocation to 7 symbols when using the normal cyclic prefix and 6 symbols when using the extended cyclic prefix, i.e. half of a slot. In contrast, Mapping Type A allows a complete slot of symbols to be allocated. In the case of Mapping Type A, the resource allocation always starts relatively soon after the start of the slot (symbols 0 to 3). Mapping Type B allows a minimum resource allocation of only 2 symbols, whereas Mapping Type A allows a minimum resource allocation of 3 symbols

PDSCH Mapping Type	Normal Cyclic Prefix (14 symbols per slot)			Extended Cyclic Prefix (12 symbols per slot)		
	S	L	S + L	S	L	S + L
Type A	0 to 3	3 to 14	3 to 14	0 to 3	3 to 12	3 to 12
Type B	0 to 12	2, 4, 7	2 to 14	0 to 10	2, 4, 6	2 to 12

Table 96 – Allowed combinations of Starting Symbol (S) and Length (L)

★ The PDSCH Mapping Type also has an impact upon the Resource Elements allocated to the Demodulation Reference Signal (DMRS). The DMRS is always present within the first allocated symbol when using Mapping Type B. This corresponds to a 'Front Loaded' configuration which allows the UE receiver to estimate the downlink channel response in advance of receiving the downlink data. When using Mapping Type A, the DMRS can be configured to be located within either symbol 2 or symbol 3. Section 3.7.3 provides greater detail regarding the impact of the PDSCH Mapping Type upon the DMRS

★ The Slot Offset (K_0) within Table 95 is used to determine the PDSCH slot number where the resource allocation applies. The 'Slot Offset' allows the resource allocation to be scheduled a specific number of slots in the future ($K_0 > 0$), or for the resource allocation to be scheduled within the current slot ($K_0 = 0$). The PDSCH slot number is calculated using the following expression:

$$PDSCH\ Slot\ Number = \left\lfloor n \times \frac{2^{\mu\_PDSCH}}{2^{\mu\_PDCCH}} \right\rfloor + K_0$$

★ 'n' is the PDCCH slot number during which the resource allocation was received. The value of 'n' is scaled according to the relative PDCCH and PDSCH numerologies. This scaling maps the PDCCH slot number onto the corresponding PDSCH slot number. For example, if the PDCCH and PDSCH are transmitted using the same numerology then the scaling factor equals 1 because the PDCCH and PDSCH share the same slot numbering. If the PDCCH numerology is 0 (15 kHz subcarrier spacing) while the PDSCH numerology is 1 (30 kHz subcarrier spacing) then the scaling factor is 2 because the PDSCH slots have half the duration of the PDCCH slots. If the PDCCH numerology is 1 (30 kHz subcarrier spacing) while the PDSCH numerology is 0 (15 kHz subcarrier spacing) then the scaling factor is 0.5 because the PDSCH slots have twice the duration of the PDCCH slots. In this case, the ROUNDDOWN function is important to ensure that the scaled slot number is an integer. The value of K_0 is added to the scaled slot number to determine the PDSCH slot number

★ The Starting Symbol (S) within Table 95 specifies the first symbol of the resource allocation. This first symbol is used by the DMRS for 'Front Loaded' configurations. The Length (L) determines the number of allocated symbols. The combination of the Starting Symbol and Length is always configured such that the resource allocation remains within the boundaries of a specific slot and does not overlap into the next slot

★ Table 97 presents the set of columns belonging to the look-up tables which can be configured by the Base Station, i.e. within *pdsch-ConfigCommon* and *pdsch-Config*. These tables are indexed using only the first column which corresponds to the '*Time Domain Resource Assignment*' field within the DCI

Time Domain Resource Assignment	PDSCH Mapping Type	Slot Offset (K_0)	Start and Length Indicator Value (SLIV)
1 to 16	Type A or B	0, 1, 2 or 3	14 to 104

Table 97 – Look-up table configured by the Base Station for time domain resource allocation (*PDSCH-TimeDomainResourceAllocationList*)

★ The PDSCH Mapping Type and Slot Offset columns are interpreted in the same way as the standardised tables

★ The Starting Symbol (S) and Length (L) are not explicitly shown within the configured look-up table. Instead they a jointly coded as the 'Start and Length Indicator Value' (SLIV). The SLIV is coded according to the following rules:

$$\text{if } (L-1) \leq 7 \quad \text{then} \quad SLIV = 14 \times (L-1) + S$$
$$\text{else} \quad SLIV = 14 \times (14 - L + 1) + (14 - 1 - S) \qquad \text{where } 0 < L \leq 14 - S$$

★ The coding of the SLIV has been designed to minimise the range of numerical values, i.e. to minimise the number of bits required to signal its value. The set of values associated with the SLIV is presented in Table 98

		Length (L)													
		1	2	3	4	5	6	7	8	9	10	11	12	13	14
Starting Symbol (S)	0	0	14	28	42	56	70	84	98	97	83	69	55	41	27
	1	1	15	29	43	57	71	85	99	96	82	68	54	40	
	2	2	16	30	44	58	72	86	100	95	81	67	53		
	3	3	17	31	45	59	73	87	101	94	80	66			
	4	4	18	32	46	60	74	88	102	93	79				
	5	5	19	33	47	61	75	89	103	92					
	6	6	20	34	48	62	76	90	104						
	7	7	21	35	49	63	77	91							
	8	8	22	36	50	64	78								
	9	9	23	37	51	65									
	10	10	24	38	52										
	11	11	25	39											
	12	12	26												
	13	13													

Table 98 – Coding of Start and Length Indicator Value (SLIV)

★ 3GPP References: TS 38.214, TS 38.212, TS 38.331

3.6.4.2 FREQUENCY DOMAIN RESOURCE ALLOCATION

★ PDSCH frequency domain resources can be allocated using Downlink Control Information (DCI) Formats 1_0 and 1_1. DCI is transferred to the UE using the PDCCH physical channel. The '*Frequency Domain Resource Assignment*' field within these DCI Formats is used to specify the set of allocated Virtual Resource Blocks (VRB)

★ 3GPP has specified two downlink resource allocation schemes – Type 0 and Type 1

- o DCI Format 1_0: always uses Type 1
- o DCI Format 1_1: uses either Type 0 or Type 1. The Base Station can use the *PDSCH-Config* parameter structure to configure '*resourceAllocation*' with a value of 'resourceAllocationType0', 'resourceAllocationType1' or 'dynamicSwitch'. The 'dynamicSwitch' option allows the Base Station to use the content of the DCI to dynamically change between resource allocation schemes. In this case, the Most Significant Bit (MSB) of the '*Frequency Domain Resource Assignment*' field within the DCI indicates the resource allocation type

★ The frequency domain resource allocation is applicable to a specific Bandwidth Part. The Base Station can use RRC signalling to configure up to 4 Bandwidth Parts per serving cell. If the resource allocation is received using DCI Format 1_0 within the Common Search Space for CORESET 0, then the resource allocation is applicable to the initial Bandwidth Part. Otherwise, resource allocations received using DCI Format 1_0 are applicable to the current active Bandwidth Part

★ DCI Format 1_1 can use the 'Bandwidth Part Indicator' field to identify a specific Bandwidth Part for the resource allocation. This can be used as a mechanism to change the active Bandwidth Part, if the UE has signalled its support for dynamic switching between Bandwidth Parts. The UE assumes that the resource allocation is applicable to the current active Bandwidth Part if the 'Bandwidth Part Indicator' field is not included within DCI Format 1_1

3.6.4.2.1 DOWNLINK RESOURCE ALLOCATION TYPE 0

★ Downlink resource allocation type 0 can be signalled on the PDCCH using DCI Format 1_1. This type of resource allocation uses a bitmap to indicate a set of allocated Resource Block Groups (RBG), i.e. resources are allocated in terms of RBG rather than individual Resource Blocks

★ A Resource Block Group (RBG) is a set of contiguous Virtual Resource Blocks (VRB) within a Bandwidth Part. The number of Resource Blocks within an RBG is dependent upon the Bandwidth Part size and the '*rbg-Size*' information element provided within the *PDSCH-Config* shown in Table 88. The '*rbg-Size*' can be configured with values of either 'config1' or 'config2'. The relationship between the Bandwidth Part size, the value of '*rbg-Size*' and the resultant RBG size is presented in Table 99

Bandwidth Part Size (Resource Blocks)	Configuration 1 RBG Sizes (Resource Blocks)	Configuration 2 RBG Sizes (Resource Blocks)
1 to 36	2	4
37 to 72	4	8
73 to 144	8	16
145 to 275	16	16

Table 99 – Resource Block Group (RBG) Sizes

★ Resource allocation type 0 always uses a 'non-interleaved' Virtual Resource Block (VRB) to Physical Resource Block (PRB) mapping. This means that VRB 'n' is mapped onto PRB 'n', i.e. the UE is effectively allocated PRB directly

★ The length of the bitmap used to provide the resource allocation depends upon the number of RBG within the Bandwidth Part. There is 1 bit for each RBG. The RBGs at the lower and upper ends of the Bandwidth Part may contain fewer Resource Blocks. This depends upon the position of the Bandwidth Part within the set of Common Resource Blocks. Figure 171 presents some example Bandwidth Part positions to illustrate the possibility of having smaller RBG at each end of the Bandwidth Part. Smaller RBG are generated when the end of the Bandwidth Part does not coincide with an integer multiple of the RBG size from the perspective of Common Resource Block numbering

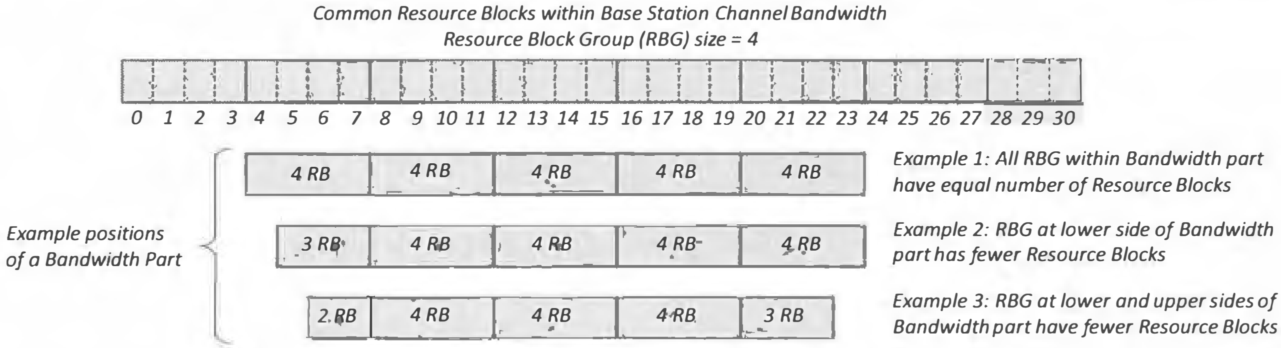


Figure 171 – Example sets of RBG within a Bandwidth Part

★ Figure 172 illustrates an example bitmap allocating a set of RBG when the RBG size is 4. This example has a smaller RBG at the upper end of the Bandwidth Part. The allocated RBG do not need to be contiguous

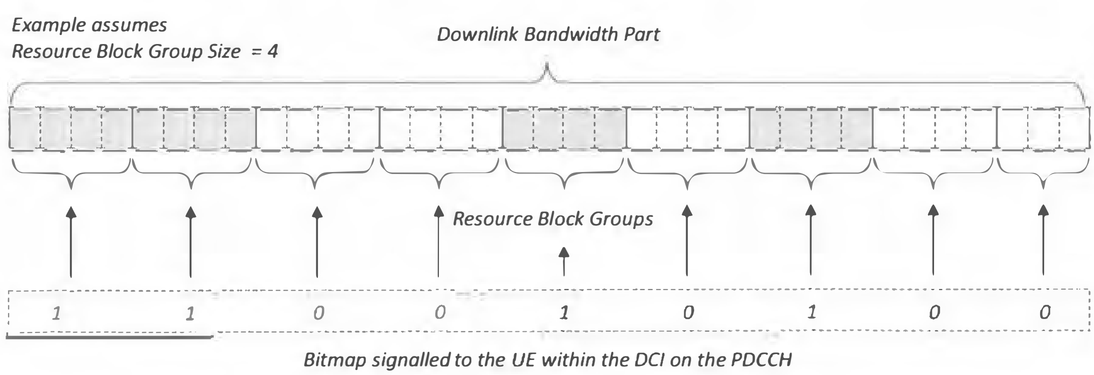


Figure 172 – Use of a bitmap to allocate Resource Block Groups (RBG) within the active Bandwidth Part

★ 3GPP References: TS 38.214, TS 38.331, TS 38.211, TS 38.212

3.6.4.2.2 DOWNLINK RESOURCE ALLOCATION TYPE 1

★ Downlink resource allocation type 1 can be signalled on the PDCCH using either DCI Format 1_0 or Format 1_1. This type of resource allocation uses a Resource Indication Value (RIV) to indicate the set of allocated Virtual Resource Blocks (VRB) within the active Bandwidth Part. These Virtual Resource Blocks are subsequently mapped onto a set of Physical Resource Blocks (PRB) using either a 'non-interleaved' or an 'interleaved' mapping

★ The allocated VRB are always contiguous. When using the 'non-interleaved' mapping then the VRB are the same as the PRB and so the allocated PRB are also contiguous. This is known as a 'localised' resource allocation. When using the 'interleaved' mapping then the allocated PRB are deduced from the allocated VRB using an interleaving function. In this case, the allocated PRB are less likely to be contiguous and the resource allocation is known as a 'distributed' resource allocation (the PRB would be contiguous when using an interleaving function if a UE is allocated all VRB within a Bandwidth Part)

★ The Resource Indication Value (RIV) provides the starting Virtual Resource Block (RB_{start}) and the number of consecutive allocated Virtual Resource Blocks (L_{RBs}). The RIV is coded according to the following rules:

$$\text{if } (L_{RBs} - 1) \le \lfloor N_{BWP}^{size} / 2 \rfloor \quad \text{then} \quad RIV = N_{BWP}^{size} \times (L_{RBs} - 1) + RB_{start}$$

$$\text{else} \quad RIV = N_{BWP}^{size} \times (N_{BWP}^{size} - L_{RBs} + 1) + (N_{BWP}^{size} - 1 - RB_{start})$$

$$\text{where } 1 \le L_{RBs} \le N_{BWP}^{size} - RB_{start}$$

★ The RIV coding is similar to the coding used for the 'Start and Length Indicator Value' (SLIV) described in section 3.6.4.1 for the time domain resource allocation. An example of the RIV coding is presented in Table 100. This example assumes that the Bandwidth Part includes 14 Resource Blocks

	Number of Allocated Resource Blocks (L_{RBs})													
Starting Allocated Resource Block (RB_{start})	1	2	3	4	5	6	7	8	9	10	11	12	13	14
0	0	14	28	42	56	70	84	98	97	83	69	55	41	27
1	1	15	29	43	57	71	85	99	96	82	68	54	40	
2	2	16	30	44	58	72	86	100	95	81	67	53		
3	3	17	31	45	59	73	87	101	94	80	66			
4	4	18	32	46	60	74	88	102	93	79				
5	5	19	33	47	61	75	89	103	92					
6	6	20	34	48	62	76	90	104						
7	7	21	35	49	63	77	91							
8	8	22	36	50	64	78								
9	9	23	37	51	65									
10	10	24	38	52										
11	11	25	39											
12	12	26												
13	13													

Table 100 – Example coding of Resource Indication Value (RIV)

★ The UE has to determine the VRB to PRB mapping type after identifying the set of allocated VRB. Both DCI Formats 1_0 and 1_1 include a 1 bit flag to indicate whether the mapping type is 'non-interleaved' or 'interleaved'

★ An interleaved VRB to PRB mapping uses the concept of Resource Block Bundles (RBB). A Resource Block Bundle is a set of contiguous Resource Blocks within the Bandwidth Part. The Resource Block Bundles used for the interleaved mapping from VRB to PRB should be differentiated from those which are used to provide the UE with information regarding the frequency domain granularity of precoding. Resource Block Bundles used within the context of precoding are described in section 3.6.5

★ The Base Station can use the '*vrb-ToPRB-Interleaver*' information element from within the *PDSCH-Config* (Table 88) to configure the Resource Block Bundle size as either 2 or 4 Resource Blocks. If a UE is instructed to use the interleaved mapping without having received the '*vrb-ToPRB-Interleaver*' information element then the UE assumes a Bundle size of 2 Resource Blocks

★ Similar to Resource Block Groups (RBG), the Resource Block Bundles at the lower and upper ends of the Bandwidth Part may contain fewer Resource Blocks. This depends upon the position of the Bandwidth Part within the set of Common Resource Blocks. A smaller Bundle is generated when the end of the Bandwidth Part does not coincide with an integer multiple of the Bundle size from the perspective of Common Resource Block numbering

★ The Virtual Resource Block Bundles at the lower and upper edges of the Bandwidth Part are always mapped onto the Physical Resource Block Bundles at the lower and upper edges of the Bandwidth Part. For example, if the Bandwidth Part includes 60 Resource Blocks and the Bundle size is 4 Resource Blocks then there may be 15 Bundles (depending upon the boundaries of the Bandwidth Part relative to the set of Common Resource Blocks). In this case, Virtual Bundle 0 is mapped onto Physical Bundle 0, and Virtual Bundle 14 is mapped onto Physical Bundle 14

★ The remaining Virtual Bundles are mapped onto Physical Bundles using an interleaving function which is defined as:

Virtual Bundle 'j' is mapped to Physical Bundle '$r \times C + c$'

where, $j = 2 \times c + r$

$r = 0, 1$

$c = 0$ to $C - 1$

$C = \lfloor N_{bundle}/2 \rfloor$

★ As an example, consider the case of a Bandwidth Part which has 15 Bundles (C = 7)

- o Virtual Bundle 1 corresponds to j = 1, i.e. c = 0 and r = 1 => Virtual Bundle 1 maps onto Physical Bundle '1×7 + 0 = 7'
- o Virtual Bundle 2 corresponds to j = 2, i.e. c = 1 and r = 0 => Virtual Bundle 2 maps onto Physical Bundle '0×7 + 1 = 1'
- o Virtual Bundle 3 corresponds to j = 3, i.e. c = 1 and r = 1 => Virtual Bundle 3 maps onto Physical Bundle '1×7 + 1 = 8'
- o and so forth

★ Figure 173 illustrates the mapping of Virtual Bundles onto Physical Bundles for the example of 15 Bundles within the Bandwidth Part

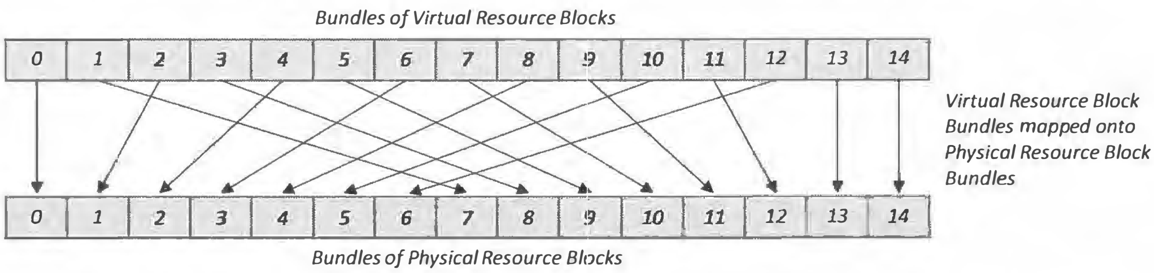


Figure 173 – Mapping of Virtual Resource Block Bundles onto Physical Resource Block Bundles (interleaved mapping)

★ 3GPP References: TS 38.214, TS 38.331, TS 38.211, TS 38.212

3.6.4.3 SEMI PERSISTENT SCHEDULING

★ Semi-Persistent Scheduling (SPS) refers to a combination of persistent and dynamic scheduling:

- o persistent scheduling is used to allocate periodic resources which are intended for the first transmission of Transport Blocks
- o dynamic scheduling is used to allocate resources for re-transmissions, as and when required

★ SPS is suitable for applications like Voice over NR (VoNR) where data arrives in periodic bursts, i.e. VoNR packets arrive once every 20 ms. The use of persistent scheduling reduces the overhead generated by Downlink Control Information (DCI) on the PDCCH. The PDCCH is normally required to allocate uplink and downlink resources every time a connection needs to transfer data. The persistent scheduling component of SPS does not require any PDCCH signalling once SPS has been activated

★ A UE uses the *downlinkSPS* flag within the *Phy-ParametersCommon* part of its UE Capability information to indicate support for SPS

★ SPS uses a combination of RRC signalling and Physical layer signalling on the PDCCH. RRC signalling provides a subset of the resource allocation information. The remaining information is provided by the PDCCH which also acts as an activation trigger. A subsequent PDCCH transmission can be used as a deactivation trigger

★ SPS can be rapidly activated and deactivated by the PDCCH. In the case of a speech call, SPS can potentially be activated when the user starts to talk and deactivated when the user starts to listen

★ The RRC parameter structure used to configure SPS is illustrated in Table 101. This parameter structure does not activate SPS but provides the UE with sufficient information to allow subsequent activation by the PDCCH

SPS-Config		
periodicity	10, 20, 32, 40, 64, 80, 128, 160, 320, 640 ms	
nrofHARQ-Processes	1 to 8	
n1PUCCH-AN	PUCCH-ResourceId	0 to 127
mcs-Table	qam64LowSE	

Table 101 – *SPS-Config* parameter structure

★ The *periodicity* defines the time interval between consecutive persistent resource allocations. Resource allocations are provided within slots which satisfy the following condition:

(Number of Slots Per Frame × SFN + Current Slot Number in the Frame) =

[(Number of Slots Per Frame × SFN_{START} + $Slot_{START}$) + (N × *periodicity* × Number of Slots Per Frame / 10)] modulo

(1024 × Number of Slots Per Frame)

where, SFN_{START} and $Slot_{START}$ correspond to the System Frame Number (0 to 1023) and slot number where the first PDSCH resources are allocated based upon the '*Time Domain Resource Assignment*' field within the DCI. The range of the slot numbering depends upon the numerology. For example, the 15 kHz subcarrier spacing has 10 slots per frame so the slot number ranges from 0 to 9, whereas the 30 kHz subcarrier spacing has 20 slots per frame so the slot number ranges from 0 to 19

★ In the case of dynamic resource allocations, the HARQ process identity is specified within the DCI associated with each individual resource allocation. A UE does not receive DCI for each individual transmission when using persistent scheduling so 3GPP has specified a calculation to determine the HAR Process Identity:

HARQ Process Identity =
[floor (Current Slot Number in the Frame × 10 / (Number of Slots Per Frame × *periodicity*)] modulo *nrofHARQ-Processes*

where, '*periodicity*' and '*nrofHARQ-Processes*' are provided within the *SPS-Config* parameter structure presented in Table 101

★ *n1PUCCH-AN* is used to specify the identity of the PUCCH Resource which is to be used for returning HARQ Acknowledgements to the Base Station. Either PUCCH Format 0 or PUCCH Format 1 can be used for this purpose

★ *mcs-Table* is used to configure the MCS Table for SPS transmissions. If this information element is included then it can only have a single value of 'qam64LowSE' and in this case, the low spectral efficiency table is used. Otherwise if the information element is excluded, and if *mcs-Table* within *PDSCH-Config* is set to 'qam256', and DCI Format 1_1 is used to activate the SPS, then the 256QAM table is used. Otherwise, the 64QAM table is used. The selection rules are summarised in Figure 159 in section 3.6.1

★ The Base Station must also allocate a CS-RNTI to the UE before activating SPS. The CS-RNTI is used to address the UE on the PDCCH when activating or deactivating SPS (or when allocating dynamic resources for re-transmissions). The CS-RNTI is allocated using the *PhysicalCellGroupConfig* parameter structure

★ A UE also validates the content of the DCI after receiving a PDCCH transmission for SPS activation or release. Validation is based upon checking the values assigned to specific fields within the DCI. The fields used for validation are presented in Table 102

	SPS Activation		SPS Deactivation
	DCI Format 1_0	DCI Format 1_1	DCI Format 1_0
HARQ Process Number	'0000'		
Redundancy Version	'00'		
Modulation and Coding Scheme	not used for validation		'11111'
Frequency Domain Resource Assignment	not used for validation		all '1's

Table 102 – DCI payload patterns used to validate SPS activation and deactivation

★ The New Data Indicator (NDI) field within the PDCCH is used to indicate that a re-transmission has been scheduled. Normally, the NDI is toggled between 0 and 1 to indicate that a new transmission has been scheduled, or kept at the same value to indicate that a re-transmission has been scheduled. This approach requires a previous value of NDI so the UE can determine if it has toggled or remained the same. In the case of SPS, there is no previous value because the PDCCH was not used to schedule the original transmission. In the case of SPS, an NDI value of 1 indicates that a re-transmission has been scheduled

★ 3GPP References: TS 38.213, TS 38.214, TS 38.331, TS 38.212, TS 38.321

3.6.5 RESOURCE BLOCK BUNDLING

* UE use the Demodulation Reference Signal (DMRS) to estimate the downlink propagation channel. The resultant channel estimate helps the UE to decode the downlink data. The accuracy of the channel estimate depends upon the density of Resource Elements which are allocated to the DMRS. High densities help to increase accuracy because the UE can increase averaging and reduce the impact of noise. The accuracy of the channel estimate also depends upon the number of Resource Blocks across which the channel estimate is measured. Measuring across a larger number of Resource Blocks also allows increased averaging and leads to a better result

* Air-interface scenarios without any delay spread experience flat fading. This means that all Resource Blocks experience the same fading and there is no frequency dependence. In this case, there is scope to use a large number of Resource Blocks to estimate the propagation channel because all Resource Blocks experience the same channel

* Delay spread introduces frequency selective fading and the concept of coherence bandwidth. A large delay spread corresponds to a small coherence bandwidth. A small coherence bandwidth means that the separation of two frequencies which have uncorrelated fading is small. In contrast, a small delay spread corresponds to a large coherence bandwidth. A large coherence bandwidth means that the separation of two frequencies which have uncorrelated fading is large

* If the delay spread is sufficiently small then fading will appear flat because the coherence bandwidth will be greater than the bandwidth of the transmitted signal. If delay spread is sufficiently large then fading will be frequency selective and the UE will not be able to assume a single channel estimate is applicable across the whole bandwidth of the received signal

* From the UE perspective, precoding applied by the Base Station is part of the propagation channel. This means that the Base Station precoding can also impact the channel estimation procedure at the UE. Figure 174 illustrates an example where the Base Station divides the set of Resource Blocks into groups of 4 and applies a different set of precoding weights to each group. This leads to the UE experiencing a different propagation channel for each group of 4 Resource Blocks, and the UE has to estimate the channel separately for each group

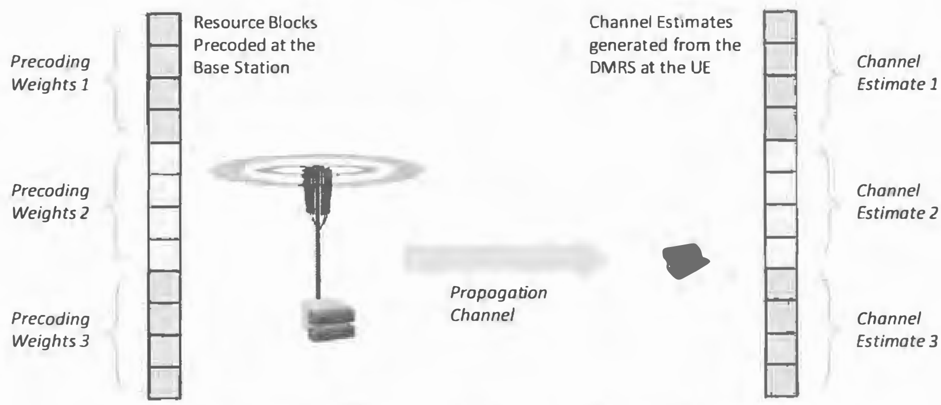


Figure 174 – Use of Precoding Resource Block Groups (PRG) for UE Channel Estimation

* Physical Resource Block (PRB) Bundling allows the UE to assume that all Resource Blocks within a bundle experience a similar propagation channel. For example, if a UE is told that a PRB Bundle includes 8 PRB then the UE can use the DMRS across all 8 PRB to generate a single channel estimate. This allows the UE to generate an accurate channel estimate because the result is based upon a relatively large number of DMRS Resource Elements. If a UE is told that a PRB Bundle includes 2 PRB then the UE is limited to using the DMRS across only 2 PRB. In general, this leads to a less accurate result. It also means that the UE has to generate a larger number of channel estimates to provide results for all received PRB, i.e. the UE processing requirement increases

* The benefit of a small PRB Bundle is that the Base Station can perform frequency selective precoding with increased resolution. This provides the potential for improving the performance of MIMO and beamforming. The drawback of a small PRG size is that channel estimation becomes more challenging for the UE. The loss in channel estimation accuracy may outweigh the gain in MIMO and beamforming performance. In this case, the number of DMRS Resource Elements per Resource Block can be increased to help compensate for a small PRG size

* The transmission scheme can impact the requirement for a specific PRB Bundling size. A transmission scheme which uses beamforming can benefit from a smaller PRB Bundling size because it allows the Base Station to adjust the precoding weights with higher resolution. This helps to improve the antenna beam directivity and gain. Multi-User MIMO (MU-MIMO) transmission schemes can also benefit from a smaller PRB Bundling size because it provides the Base Station with increased flexibility when grouping UE to receive their downlink data on the same time/frequency resources, i.e. it becomes easier to separate the transmissions towards each UE. Transmission schemes using PRB level Precoder Cycling also require small PRB Bundle sizes. Precoder Cycling is applicable to open loop transmission schemes which do not require feedback from the UE. The Base Station cycles through a series of precoding weights which help to randomise the propagation channel and improve the probability of successful reception

* Reciprocity based transmission schemes (typically applicable to TDD) can use larger PRB Bundling sizes. The Base Station uses uplink measurements from the Sounding Reference Signal (SRS) to identify the downlink propagation channel. The SRS allows the

downlink propagation channel to be measured with high resolution. The Base Station can then generate precoding weights for individual subcarriers or groups of subcarriers rather than groups of Resource Blocks. This helps to ensure that the propagation channel viewed by the UE appears continuous in the frequency domain, rather than having step changes between Resource Block Groups where significantly different sets of precoding weights have been applied. This high resolution precoding can reduce delay spread and thus increase the coherence bandwidth, i.e. the propagation channel moves closer to having flat fading. In some cases, there may still be step changes in the precoding weights if the SRS transmissions are not wideband. For example, a UE may be configured to transmit the SRS across a relatively small number of Resource Blocks and then to use multiple transmissions at different times to cover the whole bandwidth. This leads to channel measurements which have a time dependence and so the channel may not appear continuous across the whole bandwidth

★ The PRB Bundling size should also be aligned with the type of resource allocation. If a UE is allocated non-contiguous Resource Blocks, or non-contiguous Resource Block Groups then a small PRB Bundling size is likely to be more appropriate. If a UE is allocated contiguous Resource Blocks then a larger PRB Bundling size may be appropriate

★ UE experiencing high SINR can benefit from a small PRB Bundling size because the additional precoding resolution can provide gains while channel estimation is made easier by the good channel conditions. UE experiencing low SINR can benefit from a large PRB Bundling size because the focus needs to be placed upon improving the channel estimate which becomes relatively challenging when the SINR is poor

★ 3GPP TS 38.214 introduces the concept of Precoding Resource Block Groups (PRG) which correspond to PRB Bundles, i.e. a PRG is a set of contiguous Resource Blocks from which the UE can generate a single channel estimate. The Resource Blocks belonging to a PRG are assumed to experience similar channel conditions and have the same precoding applied by the Base Station

★ 3GPP has specified that when receiving a PDSCH transmission which has been scheduled using an SI-RNTI, RA-RNTI, P-RNTI or TC-RNTI, the UE assumes a PRG size of 2 Resource Blocks

★ For other PDSCH transmissions, the UE assumes a default PRG size of 2 Resource Blocks unless the Base Station has provided '*prb-BundlingType*' information using RRC signalling. '*prb-BundlingType*' information can instruct the UE to use either a static or dynamic PRG size. The options for both cases are presented in Table 103. When using a dynamic configuration, 2 Bundle Size Sets can be configured. Downlink Control Information (DCI) on the PDCCH is used to switch between the dynamic configuration values

prb-BundlingType		
CHOICE		
Static	Dynamic	
	Bundle Size Set 1	Bundle Size Set 2
4, or wideband	4, or wideband, or 2 - wideband, or 4 - wideband	4, or wideband

Table 103 – PRG sizes which can be configured using *prb-BundlingType*

★ In the case of the static configuration, the UE can be instructed to assume a PRG size of 4 Resource Blocks, or a wideband set of Resource Blocks. It is not necessary to have the option to configure a PRG size of 2 Resource Blocks because that is the default assumption, i.e. the UE assumes a PRG size of 2 Resource Blocks if the Base Station does not provide the '*prb-BundlingType*' information. The 'wideband' value indicates that the UE should assume that all of the allocated Resource Blocks belong to a single PRG

★ 3GPP specifies that the UE should always be allocated contiguous Resource Blocks when configured with the 'wideband' PRB Bundle size (applicable to both static and dynamic configurations)

★ In the case of the dynamic configuration, and receiving a PDSCH resource allocation using a C-RNTI or CS-RNTI with:

- o DCI Format 1_0, the UE assumes a PRG size of 2 Resource Blocks
- o DCI Format 1_1, the UE uses the '*PRB bundling size indicator*' from within the DCI to deduce the PRG size

★ The '*PRB bundling size indicator*' occupies 1 bit within DCI Format 1_1 (this 1 bit is only included when using the dynamic configuration)

- o if set to '0' then the UE assumes the PRG size from 'Bundle Size Set 2'. This can be either '4' or 'wideband'
- o if set to '1' and a single value has been configured for 'Bundle Size Set 1' then use that value. This can be either '4' or 'wideband'
- o if set to '1' and two values have been configured for 'Bundle Size Set 1' then use the 'wideband' value if the allocated Resource Blocks are contiguous and they occupy more than half of the Bandwidth Part. Otherwise use the first value, which can be either '2' or '4'

★ 3GPP References: TS 38.214, TS 38.212, TS 38.331

3.6.6 PRE-EMPTION

★ If the utilisation of Resource Blocks within a Bandwidth Part is high, then it may be necessary for high priority services with low latency requirements to pre-empt Resource Blocks which have already been allocated to another connection. This type of pre-emption is illustrated in Figure 175

★ In this example, the Packet Scheduler has allocated a block of Resource Blocks to a mobile broadband connection. The Base Station receives some high priority downlink data for a low latency application during the transfer of the mobile broadband data. The Packet Scheduler recognises the requirement for low latency and immediately schedules resources without waiting for existing resource allocations to complete. Figure 175 illustrates two example resource allocations for the low latency data. The first resource allocation does not impact the existing mobile broadband allocation, whereas the second resource allocation pre-empts some of the mobile broadband resources

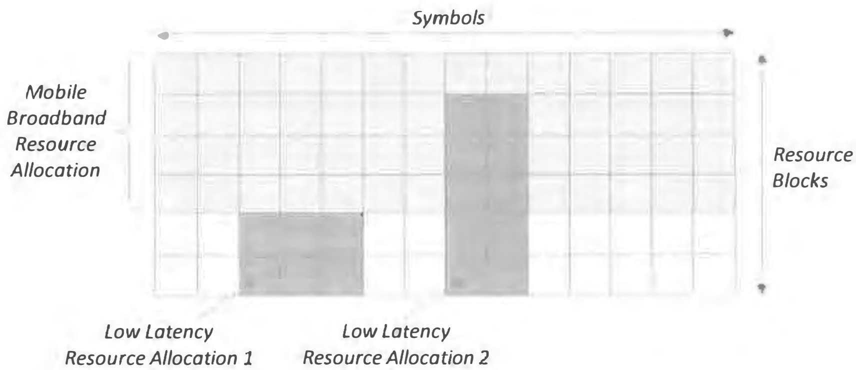


Figure 175 – Existing Mobile Broadband resource allocation pre-empted by a new Low Latency resource allocation

★ Pre-emption is likely to generate bit errors and can also corrupt the contents of the HARQ soft combining buffer. Normally, when a UE detects a bit error, it will buffer the received data and send a negative acknowledgement to trigger a re-transmission. The re-transmission is then combined with the original transmission within the soft combining buffer before attempting to decode a second time. When pre-emption has occurred, the soft combining buffer includes some samples which do not belong to the expected transmission. This means that soft combining is no longer combining two versions of the same signal

★ 3GPP has introduced two solutions to help manage the impact of pre-emption. The first solution is based upon a 'Flush Indicator' within DCI Format 1_1. The second solution is based upon a set of 'Pre-emption Indications' within DCI Format 2_1

★ DCI Format 1_1 can include a Code Block Group (CBG) Flushing out Information (CBGFI) field. It is optional for a UE to support this field so the UE capability information has to be checked. A UE uses the *cbg-FlushIndication-DL* information element within the *Phy-ParametersCommon* parameter structure to indicate whether or not it supports the CBGFI field. In addition, the Base Station has to enable the use of the CBGFI field using RRC signalling. This is done using the *codeBlockGroupFlushIndicator* information element within the *PDSCH-CodeBlockGroupTransmission* parameter structure. This parameter structure and information element are presented in Table 104

PDSCH-CodeBlockGroupTransmission	
maxCodeBlockGroupsPerTransportBlock	2, 4, 6, 8
codeBlockGroupFlushIndicator	BOOLEAN

Table 104 – Information element used to enable the Code Block Group Flush Indicator within DCI Format 1_1

★ If the CBGFI field is included within DCI Format 1_1 when allocating resources for a re-transmission, then a value of '0' indicates that the previously received version(s) of the CBG which are being re-transmitted may be corrupted and so the soft combining buffers should be flushed before populating with the newly received data. In contrast, a value of '1' indicates that the previously received version(s) of the CBG can be combined with the newly received data

★ DCI Format 2_1 is used to signal up to 9 sets of pre-emption indications. A single set uses 14 bits to represent 14 pre-emption indications, i.e. DCI Format 2_1 has a maximum payload size of $9 \times 14 = 126$ bits. DCI Format 2_1 is addressed to one or more UE using an 'interruption' RNTI (int-RNTI). The int-RNTI is used to scramble the CRC bits belonging to DCI Format 2_1. All UE which extract a set of pre-emption indications from a specific DCI Format 2_1 transmission share the same int-RNTI. Similar to DCI Formats 2_0, 2_2 and 2_3, DCI Format 2_1 is categorised as providing 'UE Group' common signalling because a group of UE can extract content from a single transmission

★ The Base Station uses RRC signalling to configure a UE to use DCI Format 2_1. Table 105 presents the *DownlinkPreemption* parameter structure used for this purpose. This parameter structure is used to allocate an int-RNTI. It also specifies the total DCI payload size and the position within the payload where the UE can find its set of 14 pre-emption indications

DownlinkPreemption		
int-RNTI	0 to 65535	
timeFrequencySet	set0, set1	
dci-PayloadSize	0 to 126 bits	
int-ConfigurationPerServingCell	1 to 32 instances	
	servingCellId	0 to 31
	positionInDCI	0 to 125

Table 105 – Parameter structure used to configure Downlink Pre-emption notifications

★ The *timeFrequencySet* information element indicates the method used to interpret the set of 14 pre-emption indications

★ If *timeFrequencySet* = 'set0' then the PDCCH monitoring period is divided into 14 time domain intervals. The PDCCH monitoring period corresponds to the period of the Search Space within which DCI Format 2_1 is transmitted. This is configured using the *monitoringSlotPeriodicityAndOffset* information element within the *SearchSpace* parameter structure. This period can be set to 1, 2 or 4 slots when configuring DCI Format 2_1. This means that each of the 14 time domain intervals can have a duration of 1, 2 or 4 symbols when using the normal cyclic prefix

★ There is a one-to-one mapping between each pre-emption indication and each time interval preceding the Search Space within which DCI Format 2_1 has been received. The pre-emption indication is set to '1' if any of the Resource Blocks within the time interval and within the active downlink Bandwidth Part were pre-empted. The upper half of Figure 176 illustrates example sets of pre-emption indications for *timeFrequencySet* = 'set0' when the Search Space period is 1 and 2 slots. These examples are based upon the pre-emption illustrated in Figure 175. In the case of the 2 slot period, it is assumed that the pre-emptions occurred during the second slot

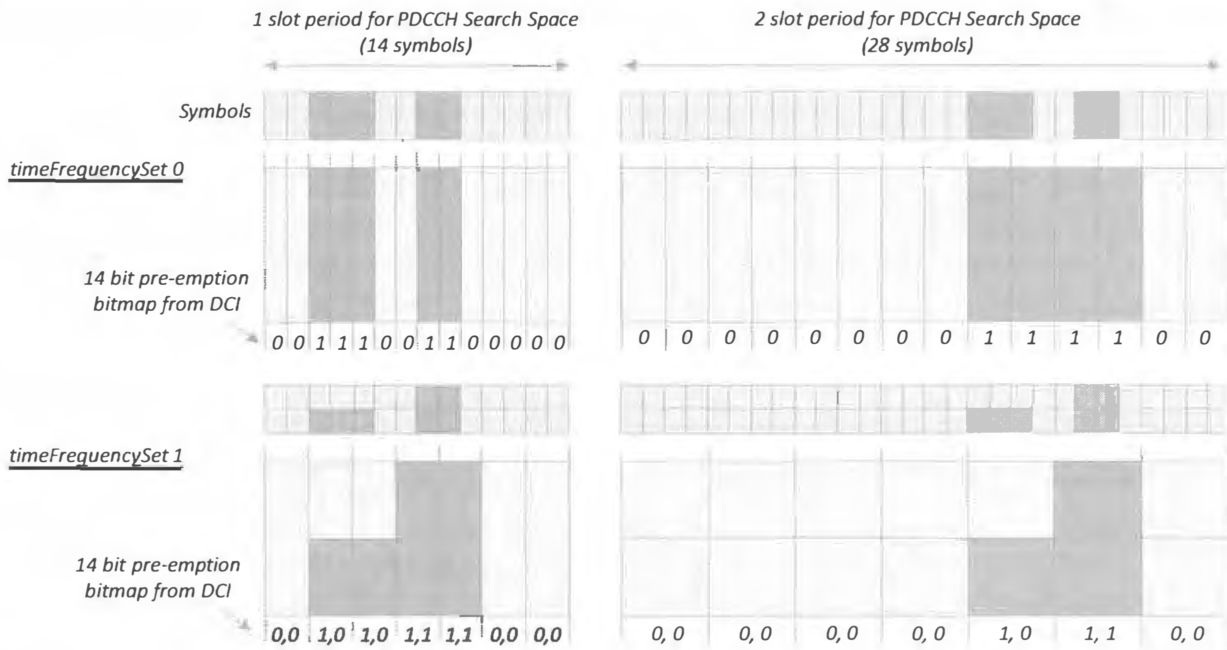


Figure 176 – Example pre-emption indications for Set0 and Set1 assuming 1 or 2 slot search space periods

★ If *timeFrequenytSet* = 'set1' then the PDCCH monitoring period is divided into 7 time domain intervals and 2 frequency domain intervals. Each frequency domain interval corresponds to half of the active downlink Bandwidth Part

★ There is a one-to-one mapping between each pre-emption indication and each time/frequency interval preceding the Search Space within which DCI Format 2_1 has been received. The pre-emption indication is set to '1' if any of the Resource Blocks within the time/frequency interval and within the active downlink Bandwidth Part were pre-empted. The lower half of Figure 176 illustrates example sets of pre-emption indications for *timeFrequencySet* = 'set1' when the Search Space period is 1 and 2 slots. These examples are also based upon the pre-emption illustrated in Figure 175

★ The pre-emption indications have limited resolution so in general, they indicate a higher level of pre-emption than the level that has actually occurred. The first pre-emption in Figure 175 does not impact the mobile broadband resource allocation and so the Base Station may decide to exclude this pre-emption from the set of pre-emption indications. This avoids the UE discarding data unnecessarily. If the set of pre-emption indications are used by multiple UE then it may be necessary to include the pre-emption because it may have had an impact upon at least one of the UE. The pre-emption indications will not impact a UE if the relevant downlink data has been decoded successfully

3.6.7 RESERVED RESOURCES

- Reserved Resources are used to indicate that specific Resource Elements are not available for reception of the PDSCH
- Reserved Resources help to 'future proof' the 3GPP specifications, i.e. provide forwards compatibility. For example, if a new Reference Signal is introduced within the release 17 version of the specifications then a release 15 UE will not have any knowledge of that Reference Signal. The new Reference Signal will generate bit errors if it is transmitted across the Resource Elements where a release 15 UE expects to receive the PDSCH. Reserved Resources can be used to inform the release 15 UE that it should not attempt reception of the PDSCH within the Resource Elements used by the new Reference Signal
- Reserved Resources can also be used in the context of LTE / New Radio (NR) spectrum sharing. In this case, the LTE and NR carriers occupy the same spectrum. The packet schedulers belonging to the LTE and NR technologies can co-ordinate to avoid collisions between the LTE and NR PDSCH transmissions. However, LTE cells will transmit the Cell specific Reference Signal (CRS) across the channel bandwidth. The NR cells will have to avoid transmission on the Resource Elements allocated to the LTE CRS otherwise there will be interference towards the LTE cell. The Resource Elements allocated to the LTE CRS can be configured as Reserved Resources for UE receiving data on the NR cell. This avoids those UE from attempting to decode the PDSCH from Resource Elements that include the LTE CRS. Similarly, the LTE cells will broadcast the LTE Synchronisation Signals and PBCH so additional Reserved Resources can be configured to avoid NR UE from attempting to decode the PDSCH from those Resource Elements
- The following sections describe the solutions for configuring Reserved Resources

3.6.7.1 LTE SPECIFIC PATTERNS

- The *RateMatchPatternLTE-CRS* parameter structure shown in Table 106 can be used to configure Reserved Resources based upon the pattern generated by the LTE Cell specific Reference Signal (CRS). This parameter structure can be included within either *ServingCellConfigCommon* or *ServingCellConfig*
- The 'Rate Matching' term is used because Reserved Resources puncture the normal PDSCH resources. Physical layer Rate Matching has to adjust the number of bits after channel coding to account for the reduced number of Resource Elements available to the PDSCH

RateMatchPatternLTE-CRS	
carrierFreqDL	0 to 16383
carrierBandwidthDL	n6, n15, n25, n50, n75, n100
mbsfn-SubframeConfigList	1 to 8 instances of *EUTRA-MBSFN-SubframeConfig*
nrofCRS-Ports	n1, n2, n4
v-Shift	n0, n1, n2, n3, n4, n5

Table 106 – *RateMatchPatternLTE-CRS* parameter structure

- *carrierFreqDL* defines a subcarrier offset between NR Reference Point 'A' (Figure 108 in section 2.3.1) and the center of the LTE channel bandwidth. The range from 0 to 16 383 is obtained by allocating 14 bits. The minimum range for this information element is required to be $4 \times 12 \times 275 = 13\ 200$, where 4 corresponds to the maximum ratio between LTE and NR subcarrier spacings, 12 corresponds to the number of subcarriers per Resource Block and 275 corresponds to the maximum number of NR Resource Blocks
- *carrierFreqDL* provides flexibility in terms of the LTE and NR center frequencies, i.e. the two technologies do not need to have the same center frequency (nor the same channel bandwidth) when sharing spectrum
- *carrierBandwidthDL* defines the LTE channel bandwidth in terms of Resource Blocks, i.e. 6 PRB $\Rightarrow$ 1.4 MHz, 15 PRB $\Rightarrow$ 3 MHz, 25 PRB $\Rightarrow$ 5 MHz, 50 PRB $\Rightarrow$ 10 MHz, 75 PRB $\Rightarrow$ 15 MHz, 100 PRB $\Rightarrow$ 20 MHz
- *mbsfn-SubframeConfigList* allows the specification of LTE subframes configured for Multimedia Broadcast Multicast Services (MBMS) Single Frequency Network (MBSFN). These subframes transmit the LTE CRS using a different pattern, i.e. the LTE CRS is restricted to the first one or two symbols within these subframes (the non-MBSFN region)
- *nrofCRS-Ports* specifies the number of logical antenna ports used by the CRS within the LTE cell (antenna ports 0 to 3 belonging LTE). The number of Resource Elements occupied by the CRS increases as the number of antenna ports increases
- *v-Shift* defines the frequency domain position of the CRS within an LTE Resource Block. This is a cell specific parameter because the frequency domain position of the CRS depends upon the LTE PCI
- The *RateMatchPatternLTE-CRS* parameter structure does not define Reserved Resources for the LTE Synchronisation Signals nor the LTE PBCH. Additional Reserved Resources can be configured for these transmissions using the Resource Block Bitmap approach described in the next section
- 3GPP References: TS 38.214, TS 38.331

3.6.7.2 RESOURCE BLOCK PATTERNS

★ The *RateMatchPattern* parameter structure shown in Table 107 can be used to configure Reserved Resources which occupy specific combinations of Resource Blocks and symbols. This parameter structure can be included within the *ServingCellConfigCommon* or *ServingCellConfig* when defining Reserved Resources within a cell. Alternatively, the parameter structure can be included within *PDSCH-Config* when defining Reserved Resources within a Bandwidth Part

<table>
<tr><td colspan="11">RateMatchPattern</td></tr>
<tr><td>rateMatchPatternId</td><td colspan="10">0 to 3</td></tr>
<tr><td rowspan="9">patternType</td><td colspan="10">CHOICE</td></tr>
<tr><td colspan="8">bitmaps</td><td colspan="2">controlResourceSet</td></tr>
<tr><td>resourceBlocks</td><td colspan="7">BIT STRING {SIZE 275}</td><td rowspan="7">controlResourceSetId</td><td rowspan="7">0 to 11</td></tr>
<tr><td rowspan="3">symbolsInResourceBlock</td><td colspan="7">CHOICE</td></tr>
<tr><td colspan="4">oneSlot</td><td colspan="3">twoSlots</td></tr>
<tr><td colspan="4">BIT STRING {SIZE 14}</td><td colspan="3">BIT STRING {SIZE 28}</td></tr>
<tr><td rowspan="3">periodicityAndPattern</td><td colspan="7">CHOICE</td></tr>
<tr><td>n2</td><td>n4</td><td>n5</td><td>n8</td><td>n10</td><td>n20</td><td>n40</td></tr>
<tr><td>2 bits</td><td>4 bits</td><td>5 bits</td><td>8 bits</td><td>10 bits</td><td>20 bits</td><td>40 bits</td></tr>
<tr><td>subcarrierSpacing</td><td colspan="10">15, 30, 60, 120 kHz</td></tr>
</table>

Table 107 – *RateMatchPattern* parameter structure

★ *rateMatchPatternId* specifies the identity of the Rate Matching Pattern. Up to 4 Rate Matching Patterns can be configured within a cell, i.e. using *ServingCellConfigCommon* or *ServingCellConfig*. An additional 4 Rate Matching Patterns can be configured within a Bandwidth Part, i.e. using *PDSCH-Config*

★ If *patternType* is set to 'bitmaps' then it is necessary to configure a series of bitmaps which identify the combinations of Resource Blocks and symbols which are not available to the PDSCH. Figure 177 illustrates examples of these bitmaps when resources are reserved for the LTE Synchronisation Signals (SS) and PBCH. This example assumes that a 3 MHz LTE channel is positioned within a larger NR channel. A first Rate Matching Pattern is configured for the Synchronisation Signals reservation and a second Rate Matching Pattern is configured for the PBCH reservation. This example assumes that both LTE and NR use the 15 kHz subcarrier spacing

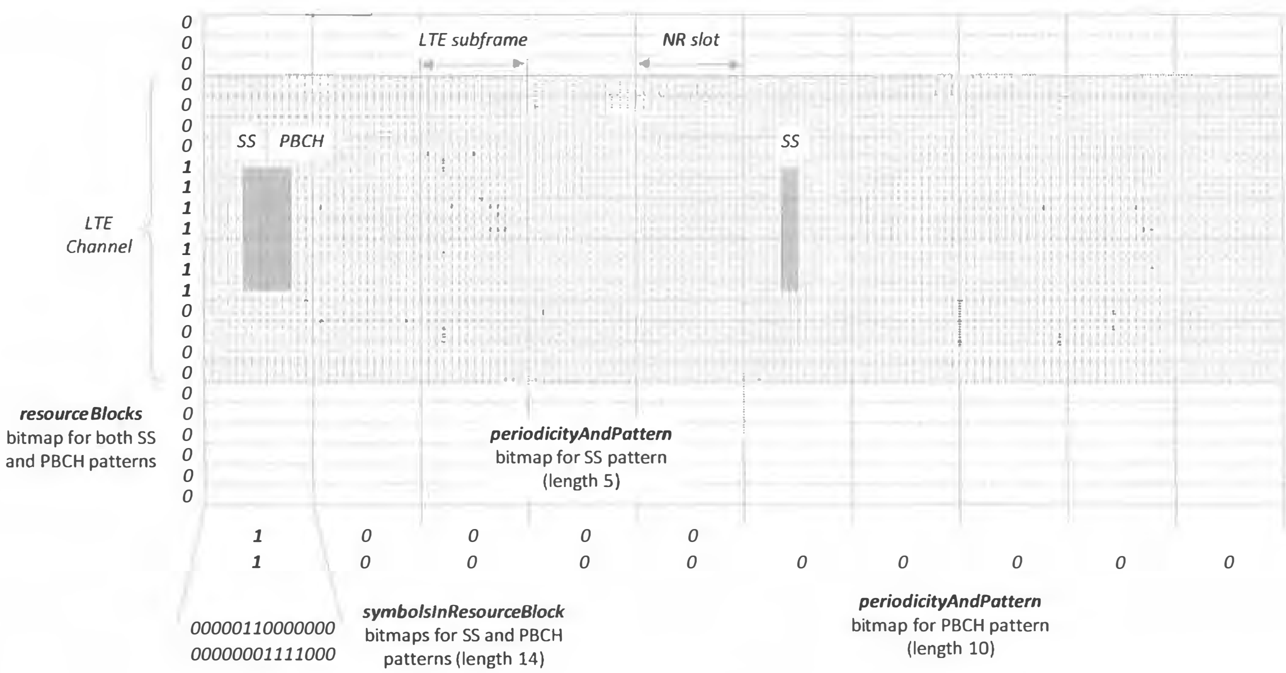


Figure 177 – Bitmap patterns used to Reserve Resources for LTE SS and PBCH (15 kHz subcarrier spacing for both LTE and NR)

★ The *resourceBlocks* bitmap identifies the set of Resource Blocks which are not available to the PDSCH. If the Rate Matching Pattern is configured using *ServingCellConfigCommon* or *ServingCellConfig* then each bit belonging to the *resourceBlocks* bitmap corresponds to a Common Resource Block within the channel bandwidth. If the Rate Matching Pattern is configured using *PDSCH-Config* then each bit belonging to the *resourceBlocks* bitmap corresponds to a Physical Resource Block within the Bandwidth Part

★ The *symbolsInResourceBlock* bitmap identifies the symbols during which the *resourceBlocks* bitmap should be applied. This bitmap can have a length of 14 bits to span the duration of 1 slot, or a length of 28 bits to span the duration of 2 slots. The example illustrated in Figure 177 uses a bitmap which spans a single slot because the LTE Synchronisation Signals and PBCH have durations of less than 1 slot. If NR was using a 30 kHz subcarrier spacing then it would still be possible to use a bitmap length of 14 bits because the LTE Synchronisation Signals are fully contained within the first half of a subframe while the PBCH is fully contained within the second half of a subframe

★ The *periodicityAndPattern* bitmap expands upon the time domain pattern provided by the *symbolsInResourceBlock* bitmap. Each bit belonging to the *periodicityAndPattern* bitmap corresponds to 1 cycle of the *symbolsInResourceBlock* bitmap. The examples illustrated in Figure 177 use a bitmap length of 5 for the LTE Synchronisation Signals because they repeat every 5 slots, and a bitmap length of 10 for the LTE PBCH because it repeats every 10 slots. If the *periodicityAndPattern* bitmap is excluded from the parameter structure then it is assumed that the pattern repeats with a period equal to the duration of the *symbolsInResourceBlock* bitmap, i.e. with a period of either 1 or 2 slots

★ 3GPP specifies that the total duration defined by the combination of the *symbolsInResourceBlock* and *periodicityAndPattern* bitmaps should not exceed 40 ms

★ *subcarrierSpacing* is included when the Rate Matching Pattern is configured using either *ServingCellConfigCommon* or *ServingCellConfig*. It is not included when the Rate Matching Pattern is configured using *PDSCH-Config*. In that case, the subcarrier spacing is assumed to equal the subcarrier spacing configured for the Bandwidth Part

★ If *patternType* is set to 'controlResourceSet' then the Rate Matching Pattern is based upon the Resource Blocks and symbols which have been configured for a specific PDCCH Control Resource Set (CORESET). The CORESET itself only specifies the Resource Blocks and a number of symbols. It does not specify the timing of those symbols. The Search Space Sets associated with the CORESET must be used to identify the timing of the symbols. All Search Space Sets linked to the CORESET are used for this purpose

★ The resources allocated to a CORSET can be reserved when the CORSET is used by the PDCCH. The reservation can be cleared when the CORESET is not being used by the PDCCH. This allows the CORESET resources to be used by the PDSCH

★ The Rate Matching Patterns configured using either the bitmap approach or the CORESET approach can be dynamically activated/deactivated using the 'Rate Matching Indicator' field within DCI Format 1_1. Rate Matching Patterns are categorised as 'dynamic' if they are linked to a Rate Matching Pattern Group within *PDSCH-Config*

★ Table 108 illustrates the configuration of Rate Matching Pattern Groups within *PDSCH-Config*. The first row within this table corresponds to the configuration of Rate Matching Patterns using the parameter structure presented in Table 107

★ Either 1 or 2 Rate Matching Pattern Groups can be configured. If a single group is configured then the 'Rate Matching Indicator' field within DCI Format 1_1 requires only a single bit to activate/deactivate that group. If two groups are configured then the 'Rate Matching Indicator' field requires two bits to activate/deactivate those groups

★ Each Rate Matching Pattern Group can contain up to 8 Rate Matching Patterns (up to 4 cell level patterns and up to 4 Bandwidth Part patterns). The union of all patterns within a group is used to define the set of dynamically Reserved Resources

rateMatchPatternToAddModList	SEQUENCE {1 to 4 instances of RateMatchPattern}	
rateMatchPatternToReleaseList	SEQUENCE {1 to 4 instances of RateMatchPatternId}	
rateMatchPatternGroup1	1 to 8 instances of CHOICE	
	cellLevel	bwpLevel
	RateMatchPatternId (0 to 3)	RateMatchPatternId (0 to 3)
rateMatchPatternGroup2	1 to 8 instances of CHOICE	
	cellLevel	bwpLevel
	RateMatchPatternId (0 to 3)	RateMatchPatternId (0 to 3)

Table 108 – Section from *PDSCH-Config* which allows the configuration of Rate Matching Pattern Groups

★ Rate Matching Patterns which are not linked to a Rate Matching Pattern Group are categorised as 'semi-static' and do not require activation by DCI Format 1_1

★ 3GPP References: TS 38.214, TS 38.331, TS 38.212

3.6.7.3 RESOURCE ELEMENT PATTERNS

★ The LTE Specific Patterns described in section 3.6.7.1 represent a solution for configuring Reserved Resources with a resolution of individual Resource Elements. Alternatively, Zero Power (ZP) CSI Reference Signals can be configured to define Reserved Resources with a resolution of individual Resource Elements. ZP CSI Reference Signals are described in section 3.7.4.2

★ A ZP CSI Reference Signal defines a set of Resource Elements which do not contain any transmission for the UE, i.e. they can be used to define Reserved Resources. The set of Resource Elements may contain other transmissions so they are not necessarily 'zero power'

★ The configuration of ZP CSI Reference Signals is shown within the *PDSCH-Config* presented in Table 88. They can be configured with aperiodic, semi-persistent or periodic triggering. Aperiodic triggering relies upon the 'Zero Power CSI Reference Signal Trigger' field within DCI Format 1_1. Semi-Persistent triggering relies upon the 'SP ZP CSI-RS Resource Set Activation/Deactivation' MAC Control Element. Periodic triggering does not require a lower layer activation command

★ 3GPP References: TS 38.214, TS 38.331, TS 38.212, TS 38.211

3.6.8 REPETITION

★ A UE can be configured to receive the PDSCH with repetition. In this case, the UE receives repetitions of the downlink Transport Block across consecutive slots. There is one repetition within each slot and each repetition uses the same allocation of symbols

★ Repetitions help to improve reliability and reduce latency, i.e. they are suitable for the Ultra Reliable Low Latency Communications (URLLC) use case. Reliability is improved because each repetition increases the probability of successful reception. Latency is reduced relative to dynamic HARQ re-transmissions which require the Base Station to wait for a HARQ acknowledgement from the UE before scheduling a re-transmission. Repetitions can also help to reduce the PDCCH load because the PDCCH is not required to provide a resource allocation for each individual transmission. Repetitions decrease system capacity by consuming resources across multiple slots. Repetitions are autonomous so resources are consumed across multiple slots even if the UE achieves successful reception from the first transmission

★ The PDSCH is limited to a single transmission layer when repetition is used, i.e. repetition is intended to improve reliability rather than increase end-user throughputs. A Base Station may configure repetition when a UE moves into an area of weak coverage, and subsequently release the repetition when the UE returns to good coverage. This approach allows the UE to benefit from multiple layers when experiencing good coverage

★ The '*pdsch-AggregationFactor*' within *PDSCH-Config* (Table 88) indicates the level of repetition. This information element can be configured with a value of 2, 4 or 8. Support for repetition is likely to increase when 3GPP addresses the requirements of the Internet of Things (IoT) and the Massive Machine Type Communications (mMTC) use case

★ Each repetition uses a different Redundancy Version (RV) to provide an Incremental Redundancy (IR) gain during the soft combining procedure at the UE receiver. The use of different Redundancy Versions means that different sets of bits are selected for transmission after channel coding. Bit selection is part of the Rate Matching procedure described in section 3.6.3. 3GPP has standardised the Redundancy Version patterns shown in Table 109. For example, if a UE is configured with 8 repetitions and the DCI providing the resource allocation specifies Redundancy Version 0, then the series of 8 repetitions will uses Redundancy Versions {0,2,3,1,0,2,3,1}

Redundancy Version indicated by DCI	Redundancy Version applicable to the n^{th} transmission			
	n mod 4 = 0	n mod 4 = 1	n mod 4 = 2	n mod 4 = 3
0	0	2	3	1
2	2	3	1	0
3	3	1	0	2
1	1	0	2	3

Table 109 – Redundancy Versions to be applied when PDSCH repetition is configured

★ A repetition is omitted if it coincides with symbols which have been configured for uplink transmission

★ 3GPP References: TS 38.214

3.7 REFERENCE SIGNALS

3.7.1 DEMODULATION REFERENCE SIGNAL FOR PBCH

★ The UE uses this Demodulation Reference Signal (DMRS) to estimate the propagation channel experienced by the PBCH. The resultant information is used to help demodulate the PBCH and subsequently decode the Master Information Block (MIB)

★ The DMRS for the PBCH is transmitted by the Base Station using antenna port 4000, i.e. the same antenna port as used by the Synchronisation Signals and the PBCH

★ The DMRS occupies 144 Resource Elements. These Resource Elements are interleaved with those allocated to the PBCH. The combination of the Synchronisation Signals, PBCH and DMRS for the PBCH forms an SS/PBCH Block. An SS/PBCH Block occupies 4 symbols in the time domain and 240 subcarriers in the frequency domain (see section 3.4)

★ The Resource Elements allocated to the DMRS within an SS/PBCH Block are presented in Table 110. There are no Resource Elements for the DMRS within the first symbol (this symbol is not used by the PBCH). The remaining symbols include Resource Elements for the DMRS within the sections used by the PBCH. The DMRS is allocated every 4th Resource Element within those sections

	Number of Resource Elements	Subcarrier allocated to the DMRS for PBCH	
Symbol 0	0	None	
Symbol 1	60	0+v, 4+v, 8+v, 12+v, ..., 236+v	v = PCI mod 4
Symbol 2	24	0+v, 4+v, 8+v, ..., 44+v 192+v, 196+v, 200+v, ..., 236+v	
Symbol 3	60	0+v, 4+v, 8+v, 12+v, ..., 236+v	

Table 110 – Resource Elements within an SS/PBCH Block allocated to the DMRS for PBCH

★ The specific Resource Elements used by the DMRS are dependent upon the Physical layer Cell Identity (PCI). A 'PCI mod 4' rule is used to identify the set of Resource Elements. This means that cells with PCI {0,4,8,12,...} will use the same Resource Element allocation. Similarly, cells with PCI {1,5,9,13,...} will use the same Resource Element allocation, as will cells using PCI {2,6,10,14,...} and cells using PCI {3,7,11,15,...}. The dependence upon PCI is illustrated in Figure 178

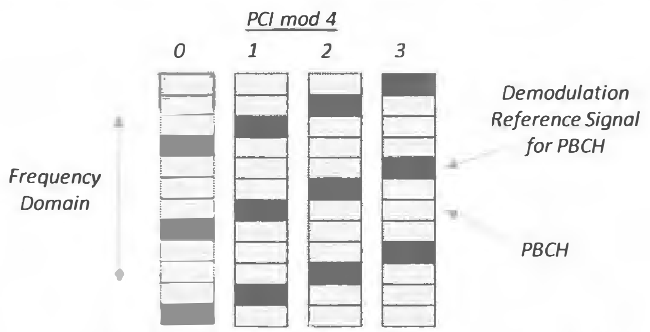


Figure 178 – Resource Elements allocated to the DMRS for PBCH

★ The DMRS itself is a pseudo random sequence of length 144. The variables used to initialise this pseudo random sequence depend upon the operating band. For operating bands below 3 GHz, the pseudo random sequence is initialised using a combination of the:

- PCI (0 to 1007)
- Half Frame (0 or 1) – indicates if the SS/PBCH Block is within the 1st or 2nd half of the radio frame
- 2 Least Significant Bits (LSB) of the SS/PBCH Index (0 to 3)

★ For operating bands above 3 GHz, the pseudo random sequence is initialised using a combination of the:

- PCI (0 to 1007)
- 3 Least Significant Bits (LSB) of the SS/PBCH Index (0 to 8)

★ The UE knows the PCI at the time of decoding the PBCH but does not always know the other variables, e.g. when completing initial cell selection. The UE has to complete blind decoding attempts to deduce these variables. All operating bands require the UE to complete up to 8 blind decoding attempts. Blind decoding increases the UE processing requirement so the number of attempts is kept to a minimum. The benefit of blind decoding attempts is that they allow the UE to deduce the relevant variables and so avoid the requirement to signal them to the UE elsewhere. However, the Half Frame Index is also provided within the Physical layer payload of the Master Information Block (MIB)

★ 3GPP References: TS 38.211

3.7.2 DEMODULATION REFERENCE SIGNAL FOR PDCCH

★ The UE uses this Demodulation Reference Signal (DMRS) to estimate the propagation channel experienced by the PDCCH. The resultant information is used to help demodulate the PDCCH and subsequently decode the Downlink Control Information (DCI)

★ The DMRS for the PDCCH is transmitted by the Base Station using antenna port 2000, i.e. the same antenna port as used by the PDCCH

★ The DMRS occupies 25 % of the Resource Elements within the Resource Blocks used by the PDCCH. These Resource Elements are in fixed positions which do not depend upon the PCI nor any other planning parameter (subcarriers 1, 5, 9, 13, 17, ...). The Resource Elements used by the DMRS are illustrated in Figure 179

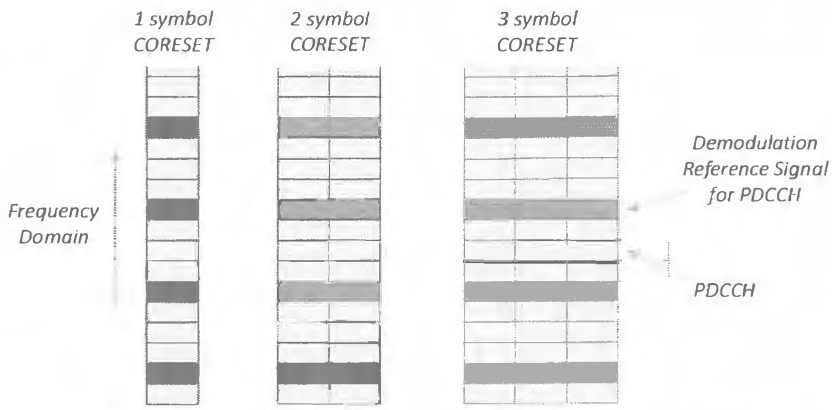


Figure 179 – Resource Elements allocated to the DMRS for the PDCCH

★ By default, a UE assumes that the DMRS for the PDCCH is quasi co-located with the SS/PBCH Block in terms of Doppler shift, Doppler spread, average delay, delay spread and spatial receive parameters. This indicates that the PDCCH and its DMRS are beamformed in the same way as the selected SS/PBCH Block. The Base Station can provide CSI Reference Signal information which supersedes this default assumption. This allows the DMRS to be quasi co-located with a CSI Reference Signal which uses a more directional beam towards the UE

★ The DMRS itself is a pseudo random sequence which can be initialised using either the PCI or *pdcch-DMRS-ScramblingId* which can be provided within the *ControlResourceSet* parameter structure shown in Table 62 (section 3.5.1). In the case of decoding the PDCCH within the Type 0 Common Search Space, the pseudo random sequence is always initialised by the PCI. The Type 0 Common Search Space is used to receive the resource allocation for SIB1. A UE must be capable of receiving SIB1 using only the information provided by the MIB (which does not specify a cell specific scrambling identity for the DMRS)

★ 3GPP References: TS 38.211, TS 38.213, TS 38.331

3.7.3 DEMODULATION REFERENCE SIGNAL FOR PDSCH

★ The PDSCH is always transmitted in combination with a Demodulation Reference Signal (DMRS). The DMRS and PDSCH are transmitted using the same precoding and the same antenna ports, i.e. they both experience the same composite propagation channel. The UE has knowledge of the sequence transmitted by the DMRS so can deduce the composite propagation channel by comparing the received DMRS with the transmitted DMRS

★ The DMRS is transmitted within the set of Resource Blocks allocated to the PDSCH. For example, if a UE is allocated 10 Resource Blocks for the PDSCH then both the DMRS and the PDSCH will be transmitted across those 10 Resource Blocks

★ The DMRS is transmitted on the same antenna ports as the PDSCH, i.e. antenna ports within the range 1000 to 1011

★ The DMRS for the PDSCH has been specified to be flexible and to support a wide range of configurations. These configurations account for the requirements associated with both Single User and Multi-User MIMO. DMRS configurations depend upon the following variables:

- PDSCH DMRS Configuration Type 1 or Type 2
- PDSCH Mapping Type A or Type B
- DMRS Starting Symbol for Mapping Type A
- Single or Double Symbol DMRS
- PDSCH DMRS Additional Positions
- PDSCH Duration

PDSCH DMRS Configuration Types 1 and 2

- ★ The Configuration Type impacts the frequency domain resources used by the DMRS. Configuration Type 1 uses 50 % of the Resource Elements within the symbols allocated to the DMRS, whereas Configuration Type 2 uses 33 %
- ★ The higher density of Resource Elements used by Configuration Type 1 helps the UE to generate a more accurate channel estimate. This makes Configuration Type 1 suitable for transmissions which require high reliability, or for UE which are experiencing poor coverage. The higher density generates an increased overhead and in the case of Multi-User MIMO, it reduces the scope for frequency multiplexing with the DMRS belonging to other UE
- ★ Figure 180 illustrates Configuration Type 1 which allocates every second Resource Element to the DMRS. This creates a transmission comb and allows antenna ports to be frequency multiplexed. For example antenna ports 1000 and 1001 can be frequency multiplexed with antenna ports 1002 and 1003. Antenna ports sharing the same Resource Elements are differentiated using an Orthogonal Cover Code (OCC) which allows Code Division Multiplexing (CDM)

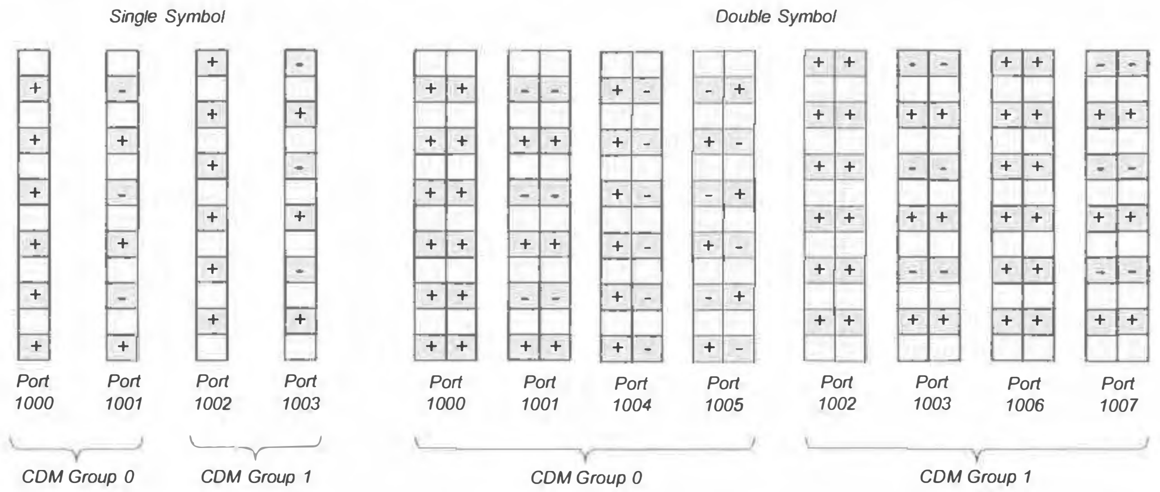


Figure 180 – PDSCH DMRS Configuration Type 1

- ★ Figure 180 illustrates that Single Symbol transmission with Configuration Type 1 supports 4 antenna ports so is able to support up to 4×4 MIMO, whereas Double Symbol transmission supports 8 antenna ports so is able to support up to 8×8 MIMO
- ★ First consider the single symbol configurations. A UE receiving 4 layers of data (rank 4) with Single User MIMO can be allocated antenna ports 1000 to 1003. These 4 antenna ports fully occupy the DMRS symbol and there are no Resource Elements available for the PDSCH. A UE receiving a single layer of data (rank 1) with Single User MIMO can be allocated antenna port 1000. This antenna port occupies only half of the Resource Elements within the DMRS symbol. A UE receiving 2 layers of data (rank 2) with Single User MIMO can be allocated antenna ports 1000 and 1001, i.e. Code Division Multiplexing is prioritised over Frequency Division Multiplexing. This pair of antenna ports occupies only half of the Resource Elements within the DMRS symbol. In both of these cases, the remaining Resource Elements can be used by the PDSCH
- ★ In the case of Multi-User MIMO, a first UE could be allocated single layer transmission with port 1000, while a second UE is allocated single layer transmission with port 1001 and a third UE is allocated single layer transmission with port 1002. From the perspective of each UE, only a single port is utilised and each UE may think that it is possible to frequency multiplex the PDSCH within the DMRS symbol. However, this would create PDSCH to DMRS interference. For example, if the UE using antenna port 1000 frequency multiplexed the PDSCH with the DMRS then the PDSCH would create interference towards the DMRS belonging to the UE using antenna port 1002
- ★ 3GPP TS 38.212 specifies the 'Antenna Ports' field belonging to Downlink Control Information (DCI) Format 1_1 such that the Base Station can indicate whether or not the PDSCH is frequency multiplexed with the DMRS. Table 111 presents an example look-up table which is applicable to Configuration Type 1 with Single Symbol DMRS transmission

Signalled Value	Allocated DMRS Port	Number of DMRS CDM Groups without Data	Signalled Value	Allocated DMRS Port	Number of DMRS CDM Groups without Data
0	0	1	6	3	2
1	1		7	0, 1	
2	0, 1		8	2, 3	
3	0	2	9	0, 1, 2	
4	1		10	0, 1, 2, 3	
5	2		11	0, 2	

Table 111 – Example look-up table for Antenna Port allocation within DCI Format 1_1 (DMRS Configuration Type 1, Single Symbol)

★ In the case of Single User MIMO, the Base Station can signal a value of 0 or 1 to allocate 1 port for MIMO with single layer transmission (rank 1). Alternatively, the Base Station can signal a value of 2 to allocate 2 ports for MIMO with dual layer transmission (rank 2). In both cases, the look-up table indicates that only 1 CDM Group is transmitted without data. This indicates that the Resource Elements belonging to the second CDM Group can be used by the PDSCH

★ In the case of Single User MIMO, the Base Station can signal a value of 9 to allocate 3 ports for MIMO with 3 layer transmission (rank 3). Alternatively, the Base Station can signal a value of 10 to allocate 4 ports for MIMO with 4 layer transmission (rank 4). In both cases, the look-up table indicates that 2 CDM Groups are transmitted without data. This results from the allocated DMRS ports occupying both CDM Groups. In this case, the PDSCH cannot be frequency multiplexed with the DMRS

★ In the case of Multi-User MIMO, the Base Station can signal a value of 3, 4, 5 or 6 to allocate 1 port for MIMO with single layer transmission (rank 1) and indicate that the second CDM Group is being used for transmissions towards other UE, i.e. the PDSCH cannot be frequency multiplexed with the DMRS

★ Similarly, in the case of Multi-User MIMO, the Base Station can signal a value of 7 or 8 to allocate 2 ports for MIMO with dual layer transmission (rank 2) and indicate that the second CDM Group is being used for transmissions towards other UE

★ Figure 181 illustrates Configuration Type 2 which allocates every third pair of Resource Elements to the DMRS. This reduces the number of subcarriers used by the DMRS relative to Configuration Type 1 and increases the scope for frequency multiplexing. In this case, up to 6 antenna ports can be multiplexed using Single Symbol transmission, and up to 12 antenna ports can be multiplexed using Double Symbol transmission

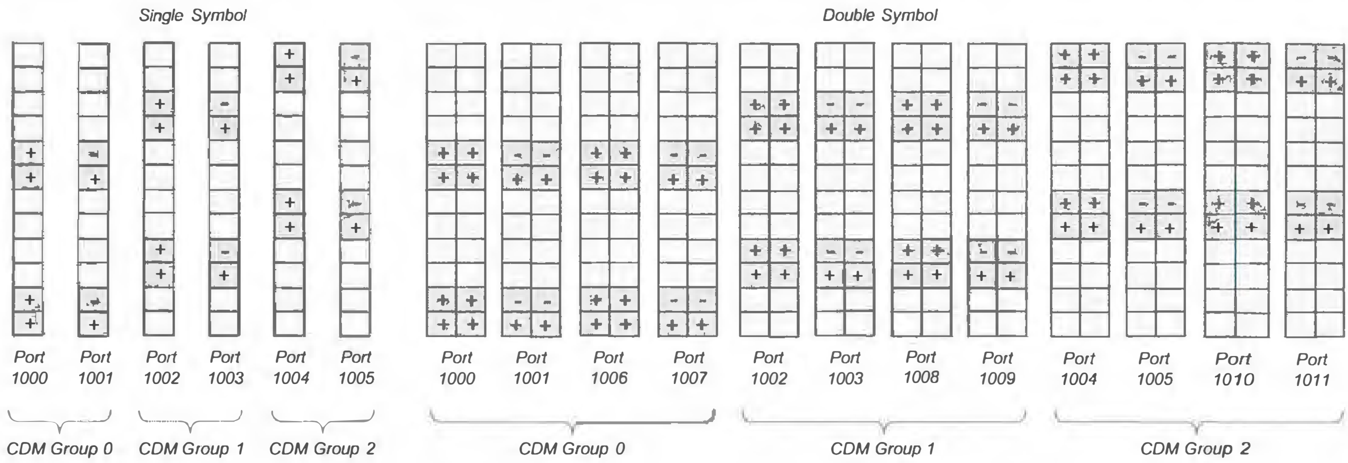


Figure 181 – PDSCH DMRS Configuration Type 2

★ Configuration Type 1 with a Single Symbol is always applicable when the PDSCH resource allocation has been received using DCI Format 1_0. This means that Configuration Type 1 is always applicable to random access MSG2 and MSG4, Paging messages and System Information. Configuration Type 1 with a Single Symbol is also applicable to other PDSCH transmissions which occur before the Base Station has provided the UE with the *PDSCH-Config* parameter structure presented in Table 88 (section 3.6). Each of these cases support frequency multiplexing of the DMRS with the PDSCH

★ The *PDSCH-Config* parameter structure can be used to provide the set of parameters shown in Table 112. Inclusion of the '*dmrs-Type*' information element indicates that Configuration Type 2 will be used for the DMRS. Exclusion of this information element indicates that Configuration Type 1 will be used

DMRS-DownlinkConfig		
dmrs-Type	type2	
dmrs-AdditionalPosition	pos0, pos1, pos3	
maxLength	len2	
scramblingID0	0 to 65535	
scramblingID1	0 to 65535	
phaseTrackingRS	SetupRelease {PTRS-DownlinkConfig }	
	frequencyDensity	SEQUENCE {2 instances within range 1 to 276}
	timeDensity	SEQUENCE {3 instances within range 0 to 29}
	epre-Ratio	0 to 3
	resourceElementOffset	offset01, offset10, offset11

Table 112 – *DMRS-DownlinkConfig* parameter structure

PDSCH Mapping Types A and B

★ The PDSCH Mapping Type has an impact upon the time domain symbols allocated to the PDSCH. This impacts the symbols allocated to the DMRS because the DMRS can only use a subset of the resources allocated to the PDSCH. Mapping Type A is sometimes referred to as providing 'Slot' based scheduling', whereas Mapping Type B is sometimes referred to as providing 'Non-Slot' based Scheduling or 'Mini Slot' based scheduling' (Mapping Type B is restricted to allocating up to 7 symbols)

★ Table 113 presents the PDSCH starting symbols and lengths which are allowed for each Mapping Type. The length is defined as a duration in terms of symbols. A single resource allocation is always contained within a single slot so the sum of the Starting Symbol and Length does not exceed 14 when using the normal cyclic prefix, and 12 when using the extended cyclic prefix

PDSCH Mapping Type	Normal Cyclic Prefix (14 symbols per slot)			Extended Cyclic Prefix (12 symbols per slot)		
	S	L	S + L	S	L	S + L
Type A	0 to 3	3 to 14	3 to 14	0 to 3	3 to 12	3 to 12
Type B	0 to 12	2, 4, 7	2 to 14	0 to 10	2, 4, 6	2 to 12

Table 113 – Allowed combinations of Starting Symbol (S) and Length (L)

★ Selection between Mapping Types A and B is part of the PDSCH time domain resource allocation. Time domain resource allocation is based upon providing a pointer to a row within a look-up table. The look-up table can be a 3GPP standardised table or a configured table. In both cases, the tables include a column for the PDSCH Mapping Type. Examples are shown in Table 95 for a 3GPP standardised look-up table and in Table 97 for a configured look-up table (both in section 3.6.4.1)

★ When using Mapping Type A, the DMRS can be configured to be located within either symbol 2 or symbol 3. The Master Information Block (MIB) provides this information for the reception of the PDSCH for SIB1. The *ServingCellConfigCommon* parameter structure within SIB1, or within dedicated signalling provides the configuration for other PDSCH transmissions. Both the MIB and the *ServingCellConfigCommon* parameter structure use the *dmrs-TypeA-Position* information element to indicate the first symbol occupied by the DMRS. Numbering is relative to the start of the slot rather than the start of the PDSCH resource allocation. This means that *dmrs-TypeA-Position* cannot be set to 2 if the PDSCH resource allocation starts in symbol 3

★ Figure 182 illustrates examples of the Resource Elements allocated to the DMRS for PDSCH Mapping Type A. These examples assume PDSCH DMRS Configuration Type 1 (every second Resource Element is allocated to the DMRS). The second example is known as a 'front loaded' configuration because the DMRS occupies the first symbol allocated to the DMRS

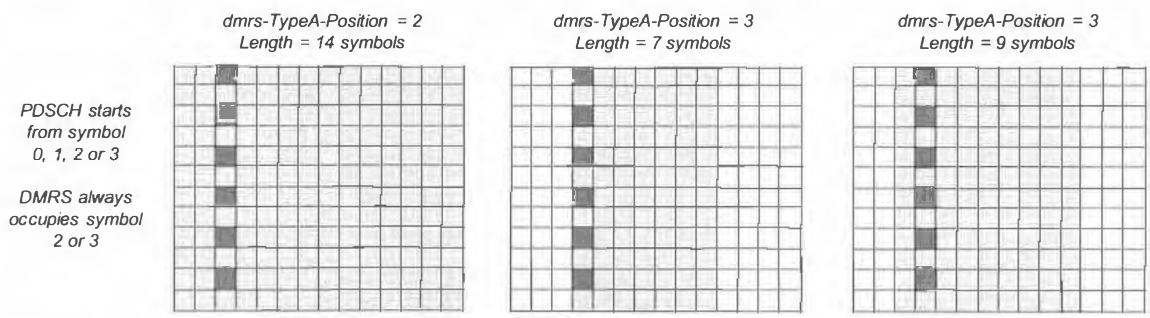


Figure 182 – Example resource allocations using PDSCH Mapping Type A

★ Figure 183 illustrates examples of the Resource Elements allocated to the DMRS for PDSCH Mapping Type B. Resource allocations based upon Mapping Type B can start from symbols 0 to 12. In this case, the first symbol used by the DMRS is always the first symbol of the resource allocation. This is known as a 'Front Loaded' scheme because the DMRS is at the front of the PDSCH transmission. A 'Front Loaded' scheme can reduce latency because the UE can start estimating the propagation channel from the DMRS as soon as the first symbol has been received. PDSCH Mapping Type B allows resource allocations as short as 2 symbols

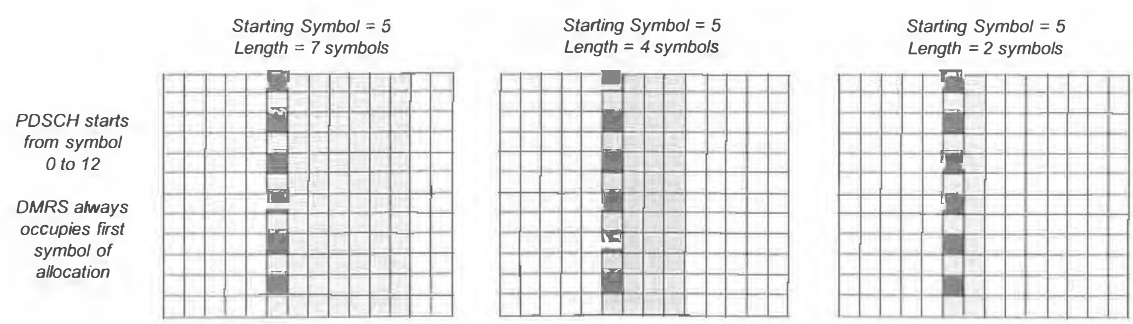


Figure 183 – Example resource allocations using PDSCH Mapping Type B

Additional DMRS Positions

★ Mapping Types A and B both allow the DMRS to use additional symbols. Additional DMRS symbols can help to improve the UE channel estimation performance. If a PDSCH transmission includes 2 DMRS symbols then the propagation channel can be measured at 2 time instants and then interpolated between those time instants. Increasing the number of DMRS symbols, reduces the gap between channel estimates and reduces the requirement for long interpolations. This is particularly important for high speed scenarios where the propagation channel can change rapidly and there are large frequency offsets to track. The drawback of additional DMRS symbols is an increased overhead

★ The requirement for additional DMRS symbols can depend upon the subcarrier spacing because higher subcarrier spacings have shorter symbols which allow less time for the propagation channel to change, i.e. higher subcarrier spacings require fewer additional DMRS symbols. For example, 4 DMRS symbols may be required to achieve good performance for very high speed scenarios when using a 30 kHz subcarrier spacing, while 3 DMRS symbols may be sufficient for the same scenario when using the 60 kHz subcarrier spacing

★ The number of additional symbols and their positions are determined using a combination of the *dmrs-AdditionalPosition* parameter presented in Table 112, and the duration of the PDSCH resource allocation. 3GPP TS 38.211 specifies the look-up table presented as Table 114. The DMRS can use up to 3 additional symbols when the PDSCH resource allocation is relatively long, i.e. a total of 4 symbols. In the case of Mapping Type A, the first symbol allocated to the DMRS is referenced as l_0 which corresponds to the value of *dmrs-TypeA-Position*, and symbol positions are defined relative to the start of the slot. In the case of Mapping Type B, the first symbol allocated to the DMRS is always symbol '0', and symbol positions are defined relative to the start of the PDSCH resource allocation

<table>
<tr><th rowspan="3">Duration (symbols)</th><th colspan="4">PDSCH Mapping Type A</th><th colspan="4">PDSCH Mapping Type B</th></tr>
<tr><th colspan="4">dmrs-AdditionalPosition</th><th colspan="4">dmrs-AdditionalPosition</th></tr>
<tr><th>0</th><th>1</th><th>2</th><th>3</th><th>0</th><th>1</th><th>2</th><th>3</th></tr>
<tr><td>2</td><td colspan="4">Not Applicable</td><td>0</td><td>0</td><td colspan="2" rowspan="6">Not Applicable</td></tr>
<tr><td>3</td><td rowspan="12">l_0</td><td colspan="3" rowspan="5">l_0</td><td colspan="2">Not Applicable</td></tr>
<tr><td>4</td><td>0</td><td>0</td></tr>
<tr><td>5</td><td colspan="2">Not Applicable</td></tr>
<tr><td>6</td><td>0</td><td>0, 4</td></tr>
<tr><td>7</td><td>0</td><td>0, 4</td></tr>
<tr><td>8</td><td colspan="3" rowspan="2">l_0, 7</td><td colspan="4" rowspan="7">Not Applicable</td></tr>
<tr><td>9</td></tr>
<tr><td>10</td><td rowspan="3">l_0, 9</td><td rowspan="3">l_0, 6, 9</td><td rowspan="2">l_0, 6, 9</td></tr>
<tr><td>11</td></tr>
<tr><td>12</td><td rowspan="3">l_0, 5, 8, 11</td></tr>
<tr><td>13</td><td rowspan="2">l_0, 11 or 12</td><td rowspan="2">l_0, 7, 11</td></tr>
<tr><td>14</td></tr>
</table>

Table 114 – Additional DMRS Symbols for PDSCH Mapping Type A/B (Single Symbol DMRS)

★ A special case exists for PDSCH Mapping Type A with a duration of 13 or 14 symbols and *dmrs-AdditionalPosition* = 1. In this case, symbol 11 is used by default, but symbol 12 is used if spectrum sharing with LTE is configured and the allocation of DMRS symbols coincide with the resources reserved for the LTE Cell specific Reference signal

★ Figure 184 illustrates some example PDSCH resource allocations which are configured with additional DMRS symbols. The first two examples are based upon PDSCH Mapping Type A, whereas the third example is based upon PDSCH Mapping Type B

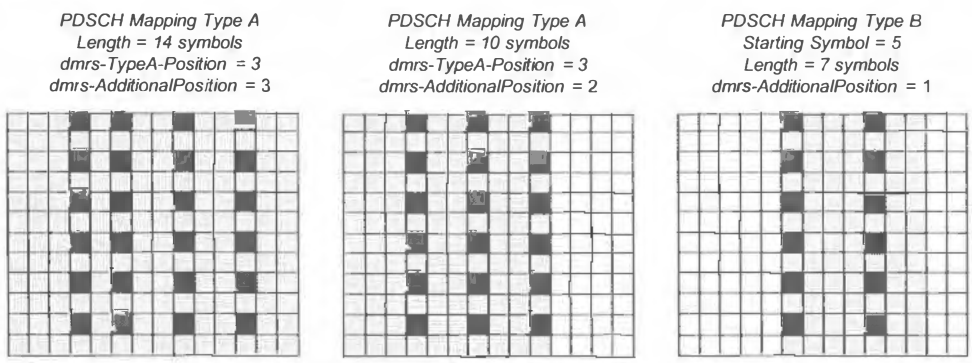


Figure 184 – Example resource allocations with additional DMRS symbols

Double Symbol DMRS

★ The concept of 'Double Symbol' DMRS has already been introduced within the section describing Configuration Types 1 and 2. It was illustrated in that section that using a pair of symbols increases the code multiplexing capability of the DMRS, i.e. there are 4 antenna ports per CDM group rather than 2 antenna ports per CDM group. This increases the total number of antenna ports and so increases the scope for Multi-User MIMO

★ When allocating Double Symbol DMRS, a different look-up table is applied when configuring additional DMRS positions, i.e. Table 114 is replaced by Table 115. In this case, only values of 0 and 1 are used by the *dmrs-AdditionalPosition* parameter. The maximum number of symbols allocated to the DMRS remains equal to 4

★ The use of Double Symbol DMRS can be restricted using the *maxLength* parameter presented in Table 112. If this parameter is excluded from *DMRS-DownlinkConfig* then only single symbol transmission is permitted. If *maxLength* is included within *DMRS-DownlinkConfig* then both single and double symbol transmission is permitted. In this case, selection between single and double symbol DMRS is controlled by the 'Antenna Ports' field within DCI Format 1_1

<table>
<tr><th rowspan="3">Duration (symbols)</th><th colspan="4">PDSCH Mapping Type A</th><th colspan="4">PDSCH Mapping Type B</th></tr>
<tr><th colspan="4">dmrs-AdditionalPosition</th><th colspan="4">dmrs-AdditionalPosition</th></tr>
<tr><th>0</th><th>1</th><th>2</th><th>3</th><th>0</th><th>1</th><th>2</th><th>3</th></tr>
<tr><td>< 4</td><td colspan="2">Not Applicable</td><td colspan="2" rowspan="11">Not Applicable</td><td colspan="2" rowspan="3">Not Applicable</td><td colspan="2" rowspan="5">Not Applicable</td></tr>
<tr><td>4</td><td rowspan="10">l_0, $l_0 + 1$</td><td rowspan="6">l_0, $l_0 + 1$</td></tr>
<tr><td>5</td></tr>
<tr><td>6</td><td colspan="2" rowspan="2">0, 1</td></tr>
<tr><td>7</td></tr>
<tr><td>8</td><td colspan="4" rowspan="7">Not Applicable</td></tr>
<tr><td>9</td></tr>
<tr><td>10</td><td rowspan="3">l_0, $l_0 + 1$, 8, 9</td></tr>
<tr><td>11</td></tr>
<tr><td>12</td></tr>
<tr><td>13</td><td rowspan="2">l_0, $l_0 + 1$, 10, 11</td></tr>
<tr><td>14</td></tr>
</table>

Table 115 – Additional DMRS Symbols for PDSCH Mapping Type A/B (Double Symbol DMRS)

★ Figure 185 illustrates some example PDSCH resource allocations which are configured with additional DMRS symbols. The first two examples are based upon PDSCH Mapping Type A, whereas the third example is based upon PDSCH Mapping Type B. In the case of Mapping Type B with Double Symbol transmission, configuring an additional DMRS symbol does not actually increase the number of DMRS symbols

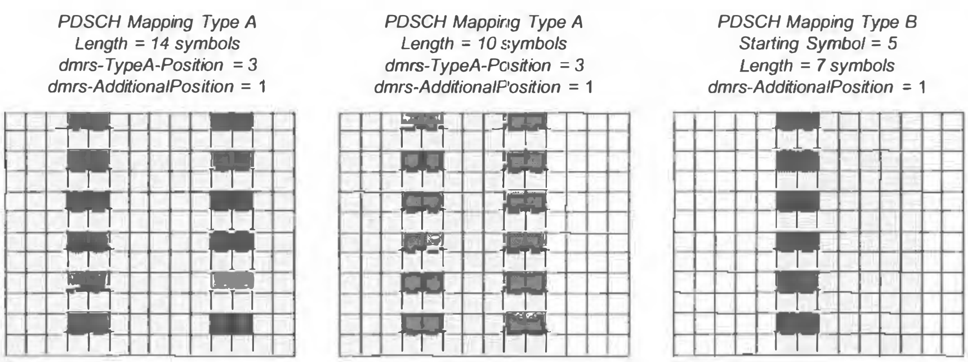


Figure 185 – Example resource allocations with Double Symbol DMRS

★ The Resource Elements allocated to the PDSCH DMRS are populated using a pseudo-random sequence. This sequence is initialised using a combination of the slot number, the symbol number and a scrambling identity. Use of the slot and symbol numbers helps to randomise the downlink interference as a function of time. Table 112 shows that the *DMRS-DownlinkConfig* parameter structure can be used to configure up to 2 scrambling identities. DCI Format 1_1 uses the 'DMRS Sequence Initialisation' field to indicate which scrambling identity will be applied to the DMRS (assuming 2 have been configured). In the case of DCI Format 1_0, the first scrambling identity is always used (assuming it has been configured). The PCI is used as the scrambling identity when specific values have not been configured

★ 3GPP References: TS 38.211, TS 38.212, TS 38.213, TS 38.214, TS 38.331

3.7.4 CHANNEL STATE INFORMATION REFERENCE SIGNAL

★ The Channel State Information (CSI) Reference Signal is a multi-purpose downlink transmission. The Base Station can configure the UE to use the CSI Reference Signal for one or more of the following:

- Channel State Information (CSI) Reporting: the UE provides CSI reports to the Base Station based upon measurements from the CSI Reference Signal. For example, the UE derives Channel Quality Indicators (CQI), Rank Indicators (RI) and Precoding Matrix Indicators (PMI) from CSI Reference Signal measurements (Channel State Information is described in section 13.6)
- Beam Management: initial beam selection based upon the set of SS/PBCH Blocks can be refined using the CSI Reference Signal. A specific network implementation may use a set of relatively broad beams to transmit the SS/PBCH Blocks. A set of more directional beams could be used to transmit the CSI Reference Signal. A UE could then measure each of the CSI Reference Signal transmissions to identify the best of the more directional beams. A UE can be configured to measure and report Layer 1 (L1) RSRP for each of the CSI Reference Signals (Beam Management is described in section 9)
- Connected Mode Mobility: Connected Mode mobility uses Measurement Reporting Events, e.g. Event A3 can be used to indicate that a neighbouring cell has become better than a serving cell. These Measurement Reporting Events can be triggered using measurements from the CSI Reference Signal, i.e. handovers can be triggered using RSRP, RSRQ or SINR measured from the CSI Reference Signal (Measurement Reporting Events are described in section 11)
- Radio Link Failure Detection: the Physical layer of the UE can use the CSI Reference Signal to generate 'in-sync' and 'out-of-sync' indications. These indications are provided to the RRC layer which uses them to monitor the radio link and detect Radio Link Failure when conditions become poor. A UE can use RRC Re-establishment to recover from Radio Link Failure (Radio Link Failure Detection is described in section 13.9.2)
- Beam Failure Detection and Recovery: the Physical layer of the UE can use the CSI Reference Signal to generate 'Beam Failure Instance' indications. These indications are provided to the MAC layer which uses them to monitor the beam and detect beam failure when conditions become poor. A UE can also use the CSI Reference Signal to recover from Beam Failure. The UE attempts the random access procedure if the RSRP measured from a candidate CSI Reference Signal is greater than a configured threshold (Beam Failure Detection and Recovery is described in section 13.9.1)
- Fine Tuning of Time and Frequency Synchronisation: 3GPP has adopted the CSI Reference Signal as a solution for the Tracking Reference Signal (TRS), i.e. the Tracking Reference Signal is a CSI Reference Signal Resource Set with a specific configuration. The TRS can be viewed as a replacement for the LTE Cell specific Reference Signal (the TRS is described in section 3.7.5)

★ Some of the procedures listed above can also be completed using measurements from SS/PBCH Blocks. For example, Connected Mode mobility can be based upon RSRP, RSRQ or SINR measurements from an SS/PBCH Block. Similarly, Radio Link Failure detection and Beam Failure detection and recovery can be based upon measurements from an SS/PBCH Block

★ The procedures listed above use **'Non-Zero Power' (NZP) CSI Reference Signals** configured for ***'Channel Measurement'*** (CM). Dedicated signalling is used to configure the UE to receive these Reference Signals

★ **NZP CSI Reference Signals** can also be configured for ***'Interference Measurement'*** (IM). A UE is required to complete interference measurements when generating Channel State Information (CSI). For example, CQI reports are generated based upon a Signal to Interference plus Noise Ratio (SINR). The appropriate interference measurement to apply when generating CQI reports depends upon the transmission mode. If a UE is scheduled downlink resources using Multi-User MIMO then interference levels will include the interference generated by transmissions towards co-scheduled UE, i.e. the spatial separation between transmissions towards each UE within the Multi-User MIMO group is not ideal and there will be some level of interference. In this case, it is more meaningful to generate CQI reports after accounting for the interference generated by the non-ideal separation of Multi-User MIMO transmissions

★ Figure 186 illustrates an example Multi-User MIMO scenario which involves 3 UE being allocated a common set of Resource Blocks and symbols. Each UE is configured with 2 NZP CSI Reference Signal resources for 'Interference Measurement' and 1 NZP CSI Reference Signal resource for 'Channel Measurement'. The resources are configured such that 2 UE complete interference measurements while the 3rd UE receives its NZP CSI Reference Signal for channel measurement, i.e. 2 UE measure the interference levels generated when transmissions are scheduled towards the 3rd UE. This allows each UE to generate CQI reports which reflect the multi-user MIMO radio conditions

★ This type of solution requires consideration of the overhead generated by the NZP CSI Reference Signal. The overhead increases as the number of co-scheduled UE within the multi-user MIMO group increases. Figure 186 illustrates an example with 3 UE which requires the allocation of 3 NZP CSI Reference Signal resources. The addition of a 4th UE would require the allocation of a 4th NZP CSI Reference Signal resource, and so forth

★ If a UE is scheduled downlink resources using single user MIMO then interference levels are likely to be dominated by intercell interference (or thermal noise) and so UE measurements should target those sources of interference. 3GPP has specified a third category of CSI Reference Signal resources which can be used for this purpose. These resources are known as **CSI Interference Measurement (IM) Resources.** The Resource Elements configured for this purpose may be used to measure background interference levels, i.e. the serving cell does not transmit anything within these Resource Elements so the UE can measure background interference originating from neighbouring cells

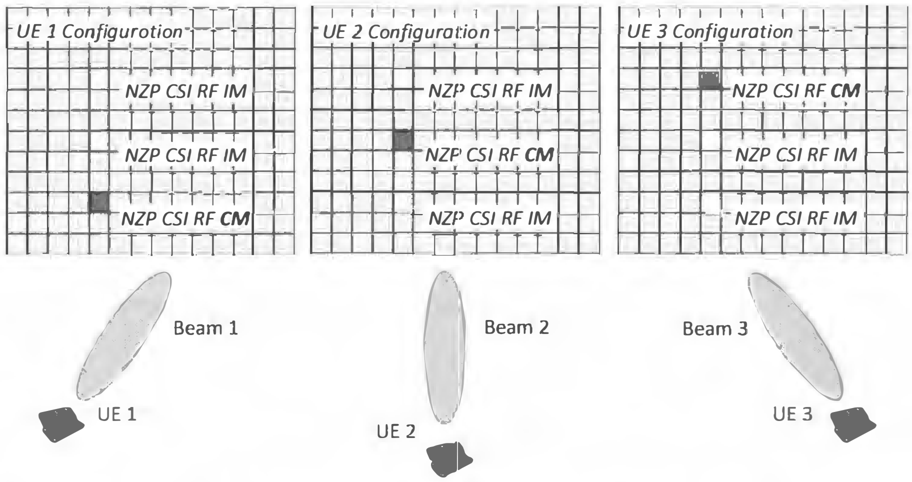


Figure 186 – NZP CSI Reference Signals for 'Channel Measurement' and 'Interference Measurement' with Multi-User MIMO

★ There is a fourth category of CSI Reference Signal known as a **'Zero Power' (ZP) CSI Reference Signal**. ZP CSI Reference Signals are used within the context of 'Reserved Resources' described in section 3.6.7. A ZP CSI Reference Signal defines a set of Resource Elements which do not contain any transmission for the UE, i.e. those Resource Elements are reserved so they can be used for something else. They puncture the PDSCH transmission so the Physical layer Rate Matching procedure after channel coding has to account for a reduced number of Resource Elements. The name 'Zero Power' can be somewhat misleading because the Resource Elements allocated to the ZP CSI Reference Signal may contain other transmissions

★ Figure 187 summarises the four categories of CSI Reference Signal resource. These categories are described in greater detail within the following sections. Note that three of the categories are configured within the *CSI-ReportConfig* parameter structure because these categories are associated with UE measurements and reporting. The fourth category is configured within *PDSCH-Config* because this category is used to define Reserved Resources which are not available to the PDSCH

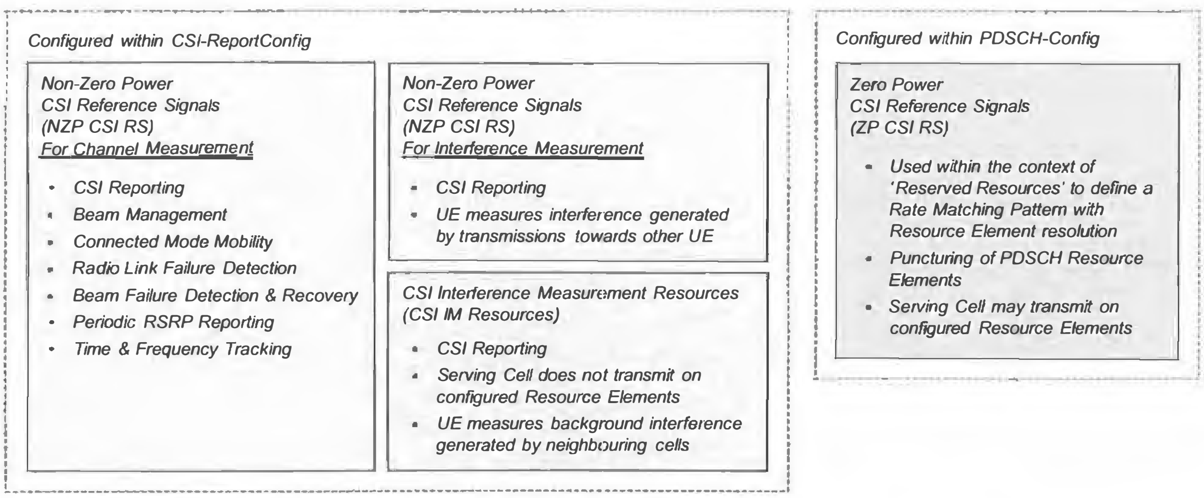


Figure 187 – Categories of CSI Reference Signal

★ The *CSI-ReportConfig* parameter structure is used to configure NZP CSI Reference Signal Resources for both Channel Measurement and Interference Measurement. It is also used to configure CSI Interference Measurement (IM) Resources. The hierarchy of parameters associated with the configuration of these resources is illustrated in Figure 188. A set of three information elements corresponding to the three types of resource point towards appropriate instances of *CSI-ResourceConfig*. Instances of *CSI-ResourceConfig* are configured within the *CSI-MeasConfig* parameter structure

★ Figure 188 indicates that *CSI-ResourceConfig* can list up to 16 NZP CSI Reference Signal Resource Sets when configuring the UE for Channel Measurement. This is applicable when the Resource Set triggering mechanism is aperiodic. Only a single Resource Set is listed when the triggering mechanism is either periodic or semi-persistent. Table 116 presents the structure of *CSI-ResourceConfig* and shows that the triggering mechanism is defined by the *resourceType*. Table 116 also illustrates that an SSB Resource Set can be configured in addition to, or as an alternative to the NZP CSI Reference Signal Resource Set. The option to specify an SSB Resource Set highlights the possibility of using the Synchronisation Signals as an alternative to the NZP CSI Reference Signal

★ Each NZP CSI Reference Signal Resource Set includes up to 64 NZP CSI Reference Signal Resources. The Resource defines the set of Resource Elements allocated to the NZP CSI Reference Signal. It also defines power offsets between the Reference Signal, the PDSCH and the Synchronisation Signals. In addition, information regarding Quasi Co-Location (QCL) can be included. The definition of an NZP CSI Reference Signal Resource is presented in section 3.7.4.1

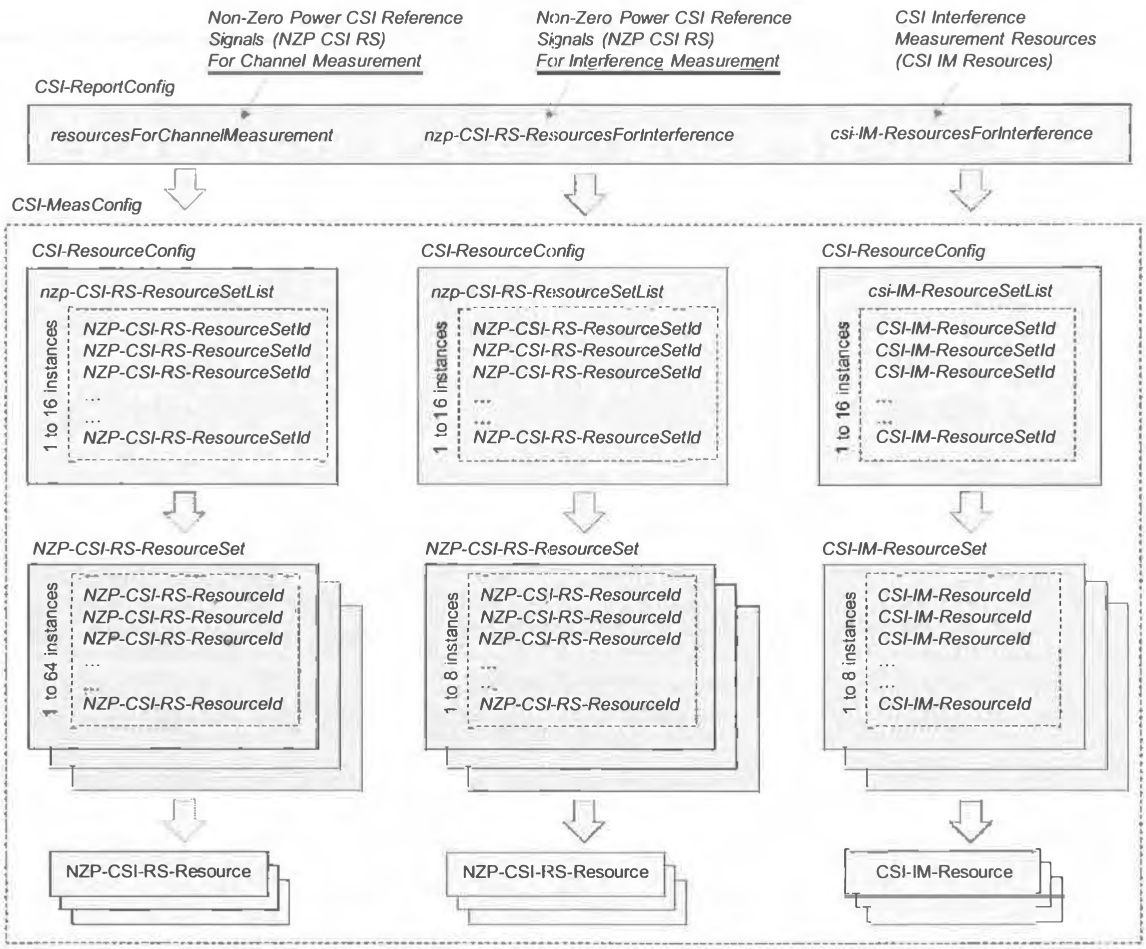


Figure 188 – Hierarchy of parameters used to configure NZP CSI Reference Signal Resources and CSI IM Resources

	CSI-ResourceConfig			
csi-ResourceConfigId	0 to 111			
csi-RS-ResourceSetList	CHOICE			
	nzp-CSI-RS-SSB		csi-IM-Resource	
	nzp-CSI-RS-ResourceSetList	SEQUENCE {1 to 16 instances of *NZP-CSI-RS-ResourceSetId*}	csi-IM-ResourceSetList	SEQUENCE {1 to 16 instances of *CSI-IM-ResourceSetId*}
	csi-SSB-ResourceSetList	SEQUENCE {1 instance of *CSI-SSB-ResourceSetId*}		
bwp-Id	0 to 4			
resourceType	aperiodic, semiPersistent, periodic			

Table 116 – Parameter structure used to configure NZP CSI Reference Signal Resources and CSI IM Resources

★ If *CSI-ResourceConfig* is used to configure NZP CSI Reference Signal Resource Sets for Interference Measurement then the pattern is the same as that used for Channel Measurement

★ If *CSI-ResourceConfig* is used to configure CSI IM Resources then it can list up to 16 CSI IM Resource Sets. Each CSI IM Resource Set includes up to 8 CSI IM Resources. The Resource defines the set of Resource Elements allocated to the CSI IM Resource. In this case, there is no power offset information, nor any Quasi Co-Location (QCL) information because the Base Station does not transmit anything within the allocated Resource Elements. The definition of a CSI IM Resource is presented in section 3.7.4.3

★ CSI Interference Measurement Resources should be planned to occupy different Resource Elements in neighbouring cells. The objective of these resources is to allow UE to measure levels of intercell interference. This measurement will be compromised if neighbouring cells have the same configuration and thus do not transmit when the UE is attempting to measure interference levels

★ The CSI Reference Signal uses the subcarrier spacing belonging to the parent Bandwidth Part. The identity of the parent Bandwidth Part is specified within the *CSI-ResourceConfig* parameter structure (*bwp-Id*)

★ A Base Station can transmit the CSI Reference Signal from 1, 2, 4, 8, 12, 16, 24 or 32 antenna ports. Port numbering ranges from 3000 to 3031

★ The Resource Elements allocated to the CSI Reference Signal are populated using a pseudo random sequence. Initialisation of this sequence depends upon the slot number, the symbol number and either the *scramblingID* or *sequenceGenerationConfig*. The former is configured as part of the *NZP-CSI-RS-Resource* parameter structure, whereas the latter is configured as part of the *CSI-RS-Resource-Mobility* parameter structure

★ The Base Station uses dedicated signalling to configure the CSI Reference Signal for each UE. In some cases, multiple UE can be provided with the same configuration information so the CSI Reference Signal becomes shared between a group of UE. This helps to reduce the overhead generated by the CSI Reference Signal. Alternatively, if different UE have different antenna port capabilities then one UE can be configured with a subset of the antenna ports used by another UE

★ As indicated by Table 116, NZP CSI Reference Signal Resources and CSI Interference Measurement Resources can be configured as 'aperiodic', 'semi-persistent' or 'periodic'. The triggering mechanisms applicable to these resource types are summarised in Table 117. This table also shows the triggering mechanisms for ZP CSI Reference Signal Resources

	NZP CSI RS (Channel Measurement) NZP CSI RS (Interference Measurement) CSI Interference Measurement Resources	ZP CSI RS
Aperiodic	'CSI Request' within DCI Format 0_1	'ZP CSI RS Trigger' within DCI Format 1_1
Semi-Persistent	'SP CSI-RS / CSI-IM Resource Set Act./Deact.' MAC CE	'SP ZP CSI-RS Resource Set Act./Deact.' MAC CE
Periodic	semi-static configuration (RRC signalling)	

Table 117 – Triggering mechanisms for CSI Reference Signals

★ Aperiodic CSI Reference Signal Resources are triggered using Downlink Control Information (DCI) on the PDCCH. Each trigger leads to a single transmission of the appropriate CSI Reference Signal Resource Set

  o Aperiodic NZP CSI Reference Signals and CSI Interference Measurement Resources are triggered using a DCI Format which allocates uplink resources for the PUSCH, i.e. DCI Format 0_1. This approach allows the UE to include measurement results within the allocated resources for the uplink transmission. DCI Format 0_1 is presented in section 3.5.5

  o Aperiodic ZP CSI Reference Signals are triggering using a DCI Format which allocates downlink resources for the PDSCH, i.e. DCI Format 1_1. This approach has been adopted because ZP CSI Reference Signals define Reserved Resources which puncture the PDSCH. DCI Format 1_1 is presented in section 3.5.7

★ Semi-Persistent CSI Reference Signal Resources are triggered using MAC Control Elements (MAC CE). These MAC Control Elements are used to provide activation and deactivation commands. Semi-Persistent CSI Reference Signals are initially deactivated after configuration and after a handover procedure. A MAC Control Element is required to inform the UE that the CSI Reference Signal has become active. The CSI Reference Signal remains active until a deactivation command is sent. The MAC Control Element used to activate/deactivate NZP CSI Reference Signals and CSI Interference Measurement Resources is presented in Figure 189

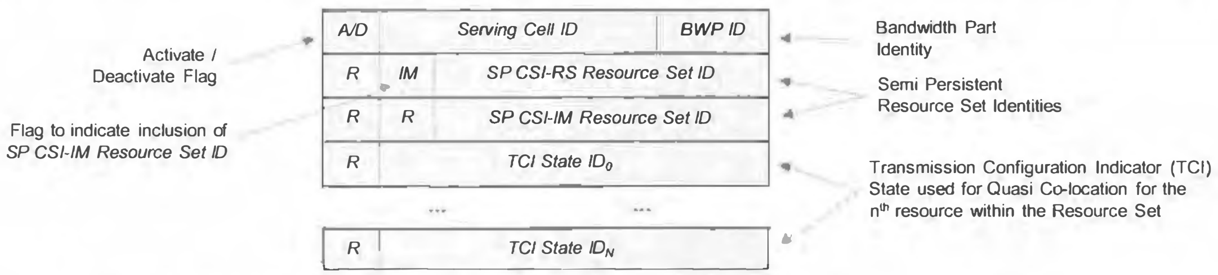


Figure 189 – 'Semi Persistent CSI RS / CSI IM Resource Set Activation / Deactivation' MAC Control Element

★ This MAC Control Element includes a flag to differentiate between activation and deactivation. It also specifies the identities of the serving cell and Bandwidth Part. A Resource Set Identity can be included for an NZP CSI Reference Signal Resource Set and for a CSI Interference Measurement Resource Set. A list of Transmission Configuration Indicators (TCI) can be included for the NZP CSI Reference Signal Resource Set. There is a one-to-one mapping between each resource belonging to the Resource Set and each TCI State. Each TCI State identifies a Quasi Co-location (QCL) relationship for the corresponding NZP CSI Reference Signal Resource (TCI States and QCL are described in section 2.6)

★ The MAC Control Element used to activate/deactivate ZP CSI Reference Signal Resources is presented in section 3.7.4.2

★ Periodic CSI Reference Signal Resources are active as soon as they have been configured. They remain active unless the UE is reconfigured to release the resources

★ 3GPP References: TS 38.331, TS 38.214, TS 38.321, TS 38.212, TS 38.211

3.7.4.1 NZP CSI REFERENCE SIGNAL RESOURCE

★ The Base Station can configure a UE with one or more Non Zero Power (NZP) CSI Reference Signal 'Resource Sets'. Each Resource Set includes one or more CSI Reference Signal Resources. A single Resource Set is configured when periodic or semi persistent triggering is used. Multiple Resource Sets can be configured when aperiodic triggering is used. The triggering mechanism is configured within the parent parameter structure (*CSI-ResourceConfig* presented in Table 116, section 3.7.4)

★ The parameter structure used to configure an NZP CSI Reference Signal Resource Set is presented in Table 118. This parameter structure includes a Resource Set identity and a sequence of up to 64 CSI Reference Signal Resource identities. These identities point towards instances of the *NZP-CSI-RS-Resource* parameter structure presented in Table 119

NZP-CSI-RS-ResourceSet	
nzp-CSI-ResourceSetId	0 to 63
nzp-CSI-RS-Resources	SEQUENCE { 1 to 64 instances of *NZP-CSI-RS-ResourceId* }
repetition	on, off
aperiodicTriggeringOffset	0 to 4
trs-Info	true

Table 118 – Parameter structure used to configure an NZP CSI Reference Signal Resource Set

★ The Resource Set parameter structure includes a flag to indicate whether or not 'repetition' is enabled. If the Base Station sets the repetition flag to 'ON' then all CSI Reference Signals belonging to the Resource Set are transmitted using the same beam, i.e. they are transmitted using the same spatial domain filter. The repetition flag can only be set 'ON' when all of the CSI Reports linked to the Resource Set have *reportQuantity* set to either 'cri-RSRP' or 'none'. The 'cri-RSRP' value indicates that the UE reports the CSI Reference Signal Resource Indicator (CRI) and the RSRP measured from the CSI Reference Signal

★ Figure 190 illustrates the use of the repetition flag during Beam Management procedures P-2 and P-3 (these procedures are described in section 9). Procedure P-2 is used to refine the original downlink beam selection completed during P-1. The beam selected during P-1 may not be very directional, while the beam selected during P-2 is likely to be more directional. Figure 190 indicates that the UE has been configured with 4 CSI Reference Signal Resources belonging to Resource Set 1. The repetition flag has been set to 'OFF' so the Base Station can apply different beamforming to each CSI Reference Signal. The UE is able to measure each CSI Reference Signal and identify the best beam for downlink data transfer. The Resource Set is linked to a *reportQuantity* set to 'cri-RSRP' so the UE provides the Base Station with the identity of the CSI Reference Signal transmitted by the best beam and the associated RSRP measurement

★ Procedure P-3 is used to select the best beam at the UE. The Base Station transmits repetitions of the CSI Reference Signal using the beam selected during P-2. This provides the UE with sufficient time to switch between its own beam positions and identify the best beam for pairing with the already selected Base Station beam. Figure 190 indicates that the UE has been configured with 4 CSI Reference Signal Resources belonging to Resource Set 2. The repetition flag has been set to 'ON' so the Base Station applies the same beamforming to each CSI Reference Signal. In this case, the Resource Set is linked to a *reportQuantity* set to 'none' so the UE does not provide the Base Station with any information regarding the selected beam

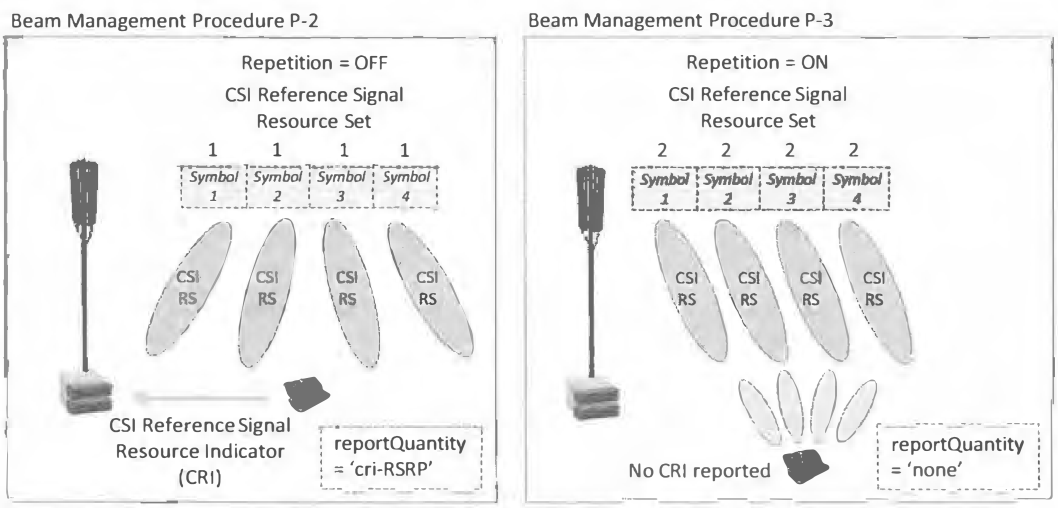


Figure 190 – Use of the 'Repetition' flag during Beam Management procedures

★ The parameter structure presented in Table 118 also includes an '*aperiodicTriggeringOffset*'. This information element is applicable when aperiodic triggering has been configured. It defines a time offset between the slot during which the UE receives the trigger and the slot during which the Resource Set is transmitted

★ The final information element within Table 118 is the '*trs-Info*' flag. This is used to indicate that the CSI Reference Signal Resource Set is to be used as a Tracking Reference Signal (TRS), i.e. it is to be used for fine tuning of time and frequency synchronisation. The use of a CSI Reference Signal Resource Set as a TRS is described in section 3.7.5

★ The parameter structure used to configure an NZP CSI Reference Signal Resource is shown in Table 119. Each resource is allocated an identity within the range 0 to 63. The *resourceMapping* section is the key to understanding the set of Resource Elements allocated to the CSI Reference Signal. The information within this section can be used to identify a row within Table 120. The row number itself is only explicitly signalled when using row 1, 2 or 4. In other cases, the UE has to deduce the row number using a combination of information elements. For example, row 3 can be deduced if *nrofPorts* = 2, whereas row 5 can be deduced if the *nrofPorts* = 4 and *frequencyDomainAllocation* = 'other'

★ The *frequencyDomainAllocation* bit strings provided by the *row1*, *row2*, *row4* and *other* information elements specify the starting subcarrier allocation for the CSI Reference Signal:

- *row1*: a single bit should be set to '1' and k_0 within Table 120 is set equal to the position of that bit. For example, if *row1* = 0010 then k_0 = 2, and row 1 within Table 120 indicates that subcarriers 2, 6 and 10 are allocated to the CSI Reference Signal
- *row2*: a single bit should be set to '1' and k_0 within Table 120 is set equal to the position of that bit. For example, if *row2* = 0000 0100 0000 then k_0 = 5, and row 2 within Table 120 indicates that subcarrier 5 is allocated to the CSI Reference Signal
- *row4*: a single bit should be set to '1' and k_0 within Table 120 is based upon the position of that bit. For example, if *row4* = 010 then k_0 = 4 (k_0 is set equal to the bit position × 4). For this example, row 4 within Table 120 indicates that subcarriers 4, 5, 6 and 7 are allocated to the CSI Reference Signal. These values are calculated from $k_0 + k'$ and $k_0 + 2 + k'$, where k' = 0 and 1
- *other*: more than a single bit can be set to '1' depending upon the existence of k_0, k_1, k_2, k_3, k_4 and k_5 within the relevant row of Table 120. In this case, k_{n-1} is set equal to 2 × the bit position of the n[th] bit set to '1'. For example, row 15 uses k_0, k_1 and k_2 so 3 bits should be set to '1', e.g. 010110
    - k_0 = is set equal to 2 × the 1[st] bit position set to '1' ($k_0 = 2$ in this example)
    - k_1 = is set equal to 2 × the 2[nd] bit position set to '1' ($k_1 = 6$ in this example)
    - k_2 = is set equal to 2 × the 3[rd] bit position set to '1' ($k_2 = 8$ in this example)

  For this example, row 15 within Table 120 indicates that subcarriers 2, 3, 6, 7, 8 and 9 are allocated to the CSI Reference Signal. These values are calculated from $k_0 + k'$, $k_1 + k'$ and $k_2 + k'$, where k' = 0 and 1

NZP-CSI-RS-Resource						
nzp-CSI-RS-ResourceId	0 to 63					
resourceMapping	frequencyDomainAllocation CHOICE					
	row1	row2	row4	other		
	BIT STRING {4 bits}	BIT STRING {12 bits}	BIT STRING {3 bits}	BIT STRING {6 bits}		
	nrofPorts	1, 2, 4, 8, 12, 16, 24, 32				
	firstOFDMSymbolInTimeDomain	0 to 13				
	firstOFDMSymbolInTimeDomain2	2 to 12				
	cdm-Type	noCDM, fd-CDM2, cdm4-FD2-TD2, cdm8-FD2-TD4				
	density	CHOICE				
		0.5	1	3	spare	
		evenPRBs, oddPRBs				
	freqBand	startingRB	0 to 274, step 4			
		nrofRBs	24 to 276, step 4			
powerControlOffset	-8 to 15					
powerControlOffsetSS	-3, 0, 3, 6 dB					
scramblingID	0 to 1023					
periodicityAndOffset	CHOICE					
	4 slots	0 to 3	20 slots	0 to 19	160 slots	0 to 159
	5 slots	0 to 4	32 slots	0 to 31	320 slots	0 to 319
	8 slots	0 to 7	40 slots	0 to 39	640 slots	0 to 639
	10 slots	0 to 9	64 slots	0 to 63		
	16 slots	0 to 15	80 slots	0 to 79		
qcl-InfoPeriodicCSI-RS	TCI-StateId	0 to 127				

Table 119 – Parameter structure used to configure an NZP CSI Reference Signal Resource

★ *firstOFDMSymbolInTimeDomain* provides the value of l_0, whereas *firstOFDMSymbolInTimeDomain2* provides the value of l_1. The l_0 and l_1 variables are symbol indices appearing in Table 120

★ *cdm-Type* is applicable when multiple ports share the same Resource Element allocation. In this case, code division multiplexing is used to differentiate the transmissions from each port, i.e. orthogonal codes are superimposed upon the transmissions from each port. The value 'fd-CDM2' means that code division multiplexing is used to differentiate 2 Resource Elements which occupy different subcarriers. The value 'cdm4-FD2-TD2' means that code division multiplexing is used to differentiate 4 Resource Elements which occupy a grid of 2 subcarriers × 2 symbols. The value 'cdm8-FD2-TD4' means that code division multiplexing is used to differentiate 8 Resource Elements which occupy a grid of 2 subcarriers × 4 symbols

★ *density* quantifies the number of Resource Elements allocated to the CSI Reference Signal per Resource Block per Port. A density of 0.5 means that every second Resource Block includes 1 Resource Element allocated to the CSI Reference Signal per Port

★ *freqBand* specifies the set of Resource Blocks allocated to the CSI Reference Signal. Both *startingRB* and *nrofRBs* are configured as integer multiples of 4 Resource Blocks. Numbering is based upon the Common Resource Block grid. If the values of *startingRB* and *nrofRBs* lead to a resource allocation which extends outside the relevant Bandwidth Part then the resource allocation is truncated such that it remains inside the Bandwidth Path. The bandwidth allocated to the CSI Reference Signal is always ≥ 24 Resource Blocks, unless the Bandwidth Part occupies less than 24 Resource Blocks in which case the bandwidth is set equal to the number of Resource Blocks within the Bandwidth Part

Row	Ports	Density	CDM Type	$(\bar{k}, \bar{l})$	CDM Group Index	k'	l'
1	1	3	No CDM	$(k_0, l_0), (k_0+4, l_0), (k_0+8, l_0)$	0, 0, 0	0	0
2	1	1, 0.5	No CDM	(k_0, l_0)	0	0	0
3	2	1, 0.5	FD-CDM2	(k_0, l_0)	0	0, 1	0
4	4	1	FD-CDM2	$(k_0, l_0), (k_0+2, l_0)$	0, 1	0, 1	0
5	4	1	FD-CDM2	$(k_0, l_0), (k_0, l_0+1)$	0, 1	0, 1	0
6	8	1	FD-CDM2	$(k_0, l_0), (k_1, l_0), (k_2, l_0), (k_3, l_0)$	0, 1, 2, 3	0, 1	0
7	8	1	FD-CDM2	$(k_0, l_0), (k_1, l_0), (k_0, l_0+1), (k_1, l_0+1)$	0, 1, 2, 3	0, 1	0
8	8	1	CDM4 (FD2, TD2)	$(k_0, l_0), (k_1, l_0)$	0, 1	0, 1	0, 1
9	12	1	FD-CDM2	$(k_0, l_0), (k_1, l_0), (k_2, l_0), (k_3, l_0), (k_4, l_0), (k_5, l_0)$	0, 1, 2, 3, 4, 5	0, 1	0
10	12	1	CDM4 (FD2, TD2)	$(k_0, l_0), (k_1, l_0), (k_2, l_0)$	0, 1, 2	0, 1	0, 1
11	16	1, 0.5	FD-CDM2	$(k_0, l_0), (k_1, l_0), (k_2, l_0), (k_3, l_0), (k_0, l_0+1), (k_1, l_0+1), (k_2, l_0+1), (k_3, l_0+1)$	0, 1, 2, 3, 4, 5, 6, 7	0, 1	0
12	16	1, 0.5	CDM4 (FD2, TD2)	$(k_0, l_0), (k_1, l_0), (k_2, l_0), (k_3, l_0)$	0, 1, 2, 3	0, 1	0, 1
13	24	1, 0.5	FD-CDM2	$(k_0, l_0), (k_1, l_0), (k_2, l_0), (k_0, l_0+1), (k_1, l_0+1), (k_2, l_0+1), (k_0, l_1), (k_1, l_1), (k_2, l_1), (k_0, l_1+1), (k_1, l_1+1), (k_2, l_1+1)$	0, 1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11	0, 1	0
14	24	1, 0.5	CDM4 (FD2, TD2)	$(k_0, l_0), (k_1, l_0), (k_2, l_0), (k_0, l_1), (k_1, l_1), (k_2, l_1)$	0, 1, 2, 3, 4, 5	0, 1	0, 1
15	24	1, 0.5	CDM8 (FD2, TD4)	$(k_0, l_0), (k_1, l_0), (k_2, l_0)$	0, 1, 2	0, 1	0, 1, 2, 3
16	32	1, 0.5	FD-CDM2	$(k_0, l_0), (k_1, l_0), (k_2, l_0), (k_3, l_0), (k_0, l_0+1), (k_1, l_0+1), (k_2, l_0+1), (k_3, l_0+1), (k_0, l_1), (k_1, l_1), (k_2, l_1), (k_3, l_1), (k_0, l_1+1), (k_1, l_1+1), (k_2, l_1+1), (k_3, l_1+1)$	0, 1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 13, 14, 15	0, 1	0
17	32	1, 0.5	CDM4 (FD2, TD2)	$(k_0, l_0), (k_1, l_0), (k_2, l_0), (k_3, l_0), (k_0, l_1), (k_1, l_1), (k_2, l_1), (k_3, l_1)$	0, 1, 2, 3, 4, 5, 6, 7	0, 1	0, 1
18	32	1, 0.5	CDM8 (FD2, TD4)	$(k_0, l_0), (k_1, l_0), (k_2, l_0), (k_3, l_0)$	0, 1, 2, 3	0, 1	0, 1, 2, 3

Table 120 – CSI Reference Signal mappings to Resource Elements

★ Figure 191 illustrates examples of the CSI Reference Signal for rows 1 and 2. Row 1 is a special case because it has a high density when compared to all other rows. This configuration is used by the Tracking Reference Signal (TRS) described in section 3.7.5. It is also intended for Beam Management procedures. The high density of Resource Elements helps to improve measurement accuracy. Row 1 uses single port transmission so code division multiplexing is not necessary. The example in Figure 191 assumes *firstOFDMSymbolInTimeDomain* $= l_0 = \bar{l} = 5$. The figure illustrates a single NZP CSI Reference Signal Resource. Multiple resources can be configured within a Resource Set to increase the number of Resource Elements allocated to the CSI Reference Signal

★ Row 2 allows a single Resource Element to be allocated to the CSI Reference Signal anywhere within the Resource Element grid. In practice, there will be some restriction upon the location of the CSI Reference Signal because it must avoid any Resource Elements which have already been allocated for other purposes, e.g. the Demodulation Reference Signal (DMRS). Row 2 is the second configuration which supports single port transmission so does not require code division multiplexing. The example in Figure 191 assumes $k_0 = \bar{k} = 2$ and *firstOFDMSymbolInTimeDomain* $= l_0 = \bar{l} = 5$

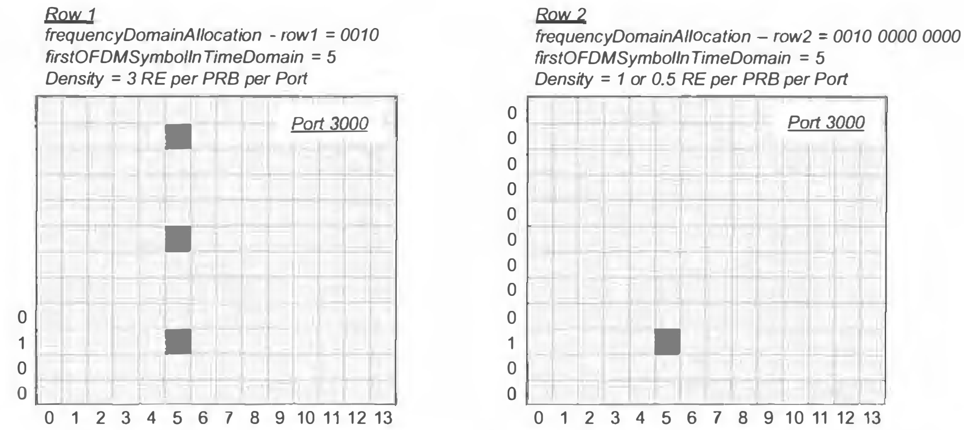


Figure 191 – CSI Reference Signals based upon 'Row 1' and 'Row 2'

★ Figure 192 illustrates an example of the CSI Reference Signal for row 3. This is the only row which provides support for transmission across 2 ports. Row 3 allocates 2 Resource Elements across 2 ports so the density is equal to 1 Resource Element per Resource Block per Port. A density of 0.5 can be achieved if the allocated Resource Elements are restricted to every second Resource Block. Row 3 uses code division multiplexing to differentiate between the transmissions on each port. The CSI Reference Signal on port 3000 is multiplied by {+1,+1}, while the CSI Reference Signal on port 3001 is multiplied by {+1,-1}. The example in Figure 192 assumes $k_0 = \bar{k} = 4$ and *firstOFDMSymbolInTimeDomain* $= l_0 = \bar{l} = 5$. In this case, $k' = \{0,1\}$ so the allocated subcarriers are $k = \bar{k} + 0$ and $k = \bar{k} + 1$

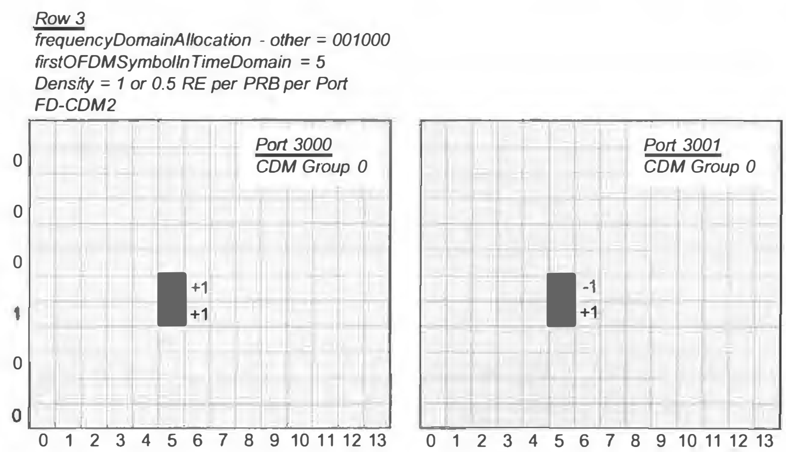


Figure 192 – CSI Reference Signals based upon 'Row 3'

★ Figure 193 illustrates examples of the CSI Reference Signal for rows 4 and 5. These rows support transmission across 4 ports. In these cases, the allocated Resource Elements are assigned to Code Division Multiplexing (CDM) groups. Ports 3000 and 3001 share the same Resource Element allocation and belong to the same CDM group. Similarly, ports 3002 and 3003 share the same Resource Element allocation and belong to the same CDM group. The ports belonging to Row 4 use a combination of frequency division multiplexing and code division multiplexing, whereas the ports belonging to Row 5 use a combination of time division multiplexing and code division multiplexing

★ The numbering of ports has been specified to ensure that transmissions belonging to the same CDM group have consecutive port numbers. This approach helps to allow CSI Reference Signals to be re-used by UE with different antenna port configurations. For example, a UE which supports 4 antenna port transmission could be configured with the 'row 4' example illustrated in Figure 193, while a UE which only supports 2 antenna port transmission could be configured using the 'row 3' example illustrated in Figure 192. Both figures use the same Resource Elements and CDM sequences for ports 3000 and 3001. This makes it possible for both UE to share the same transmission from the Base Station

★ Row 4 uses k_0 and $k_0 + 2$ combined with $k' = \{0,1\}$ to generate the column of 4 Resource Elements, i.e. k_0+0, k_0+1, k_0+2+0, k_0+2+1. In contrast, row 5 uses k_0 with $k' = \{0,1\}$ in combination with l_0 and $l_0 + 1$ to generate the 2×2 grid of Resource Elements. Both rows retain a density of 1 Resource Element per Resource Block per port because 4 Resource Elements are allocated across 4 ports

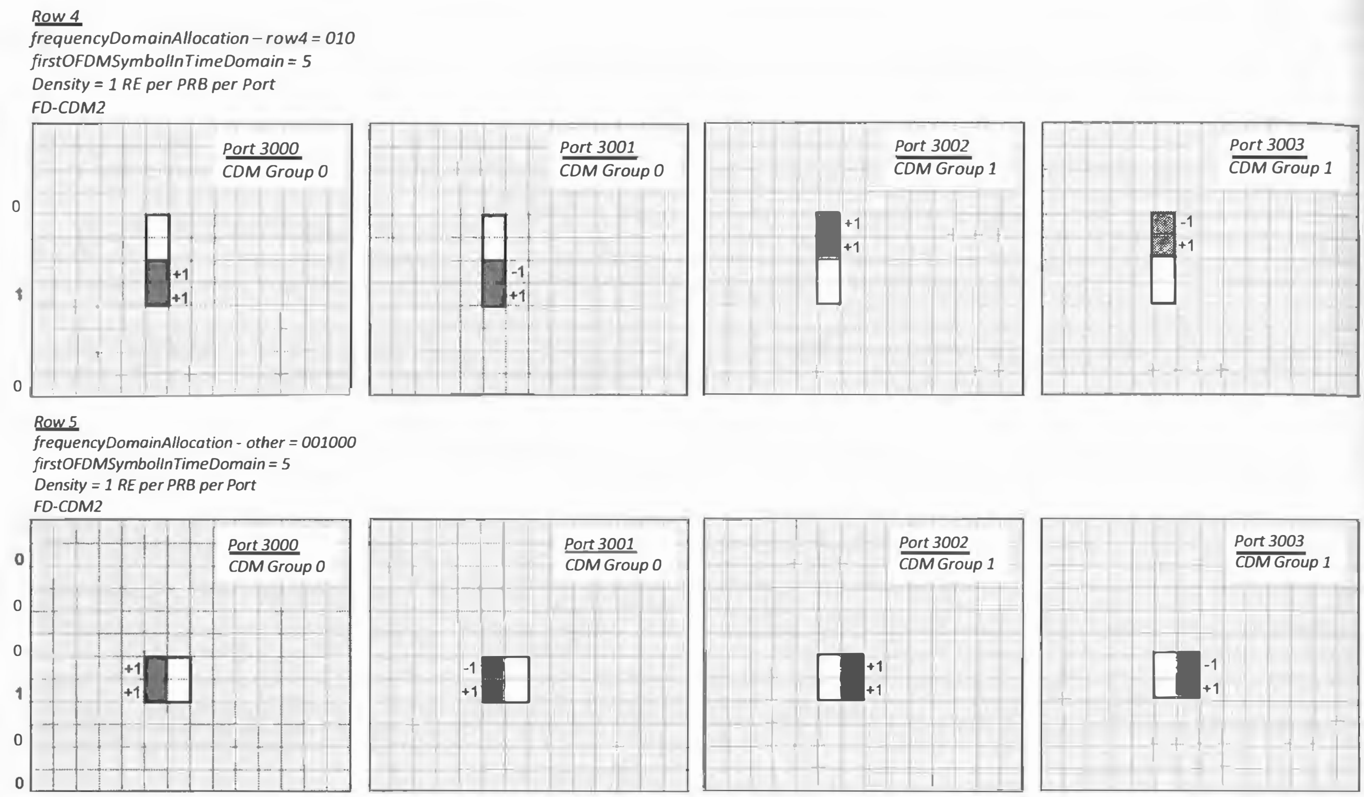


Figure 193 – CSI Reference Signals based upon 'Row 4' and 'Row 5'

★ Figure 194 illustrates an example of the CSI Reference Signal for row 6 which supports transmission across 8 ports. In this case, frequency multiplexing is used to isolate a set of 4 CDM groups. Similar to the previous example, ports belonging to the same CDM group have consecutive numbering. Row 6 uses k_0, k_1, k_2 and k_3 so 4 bits are set to '1' within the *frequencyDomainAllocation*. The example in Figure 194 assumes that bits 0, 2, 4 and 5 have been set to '1', which leads to k_0=0, k_1=4, k_2=8 and k_3=10. The total set of allocated subcarriers is {0, 1, 4, 5, 8, 9, 10, 11} because $k' = \{0,1\}$, i.e. each value of k' is added to each value of k_n. The density of 1 Resource Element per Resource Block per port is retained because there are 8 Resource Elements allocated across 8 ports

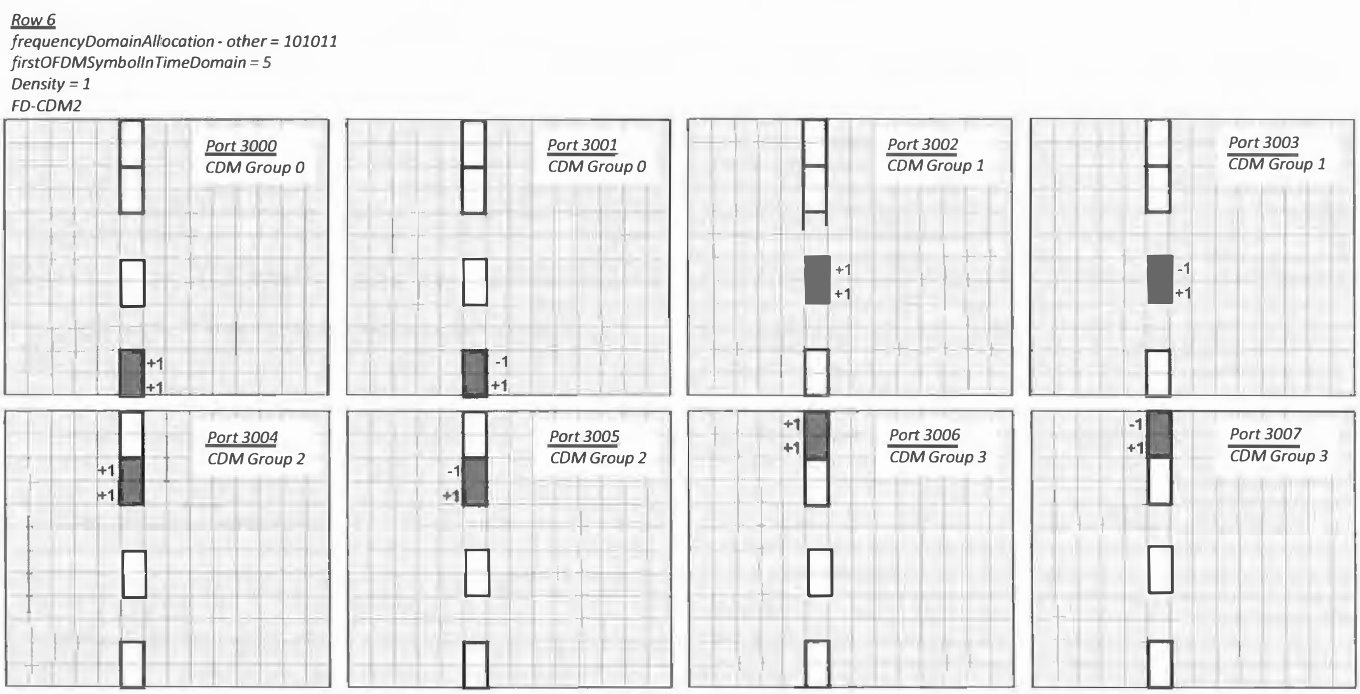


Figure 194 – CSI Reference Signals based upon 'Row 6'

★ Figure 195 illustrates examples of the CSI Reference Signal for rows 7 to 12. These examples are presented using a single Resource Element grid for all ports (to keep the figure relatively compact). In reality, each port will have its own Resource Element grid as shown for previous examples. Rows 7 and 8 transmit the CSI Reference Signal across 8 ports, while rows 9 and 10 transmit across 12 ports, and rows 11 and 12 transmit across 16 ports. The maximum density remains as 1 Resource Element per Resource Block per Port

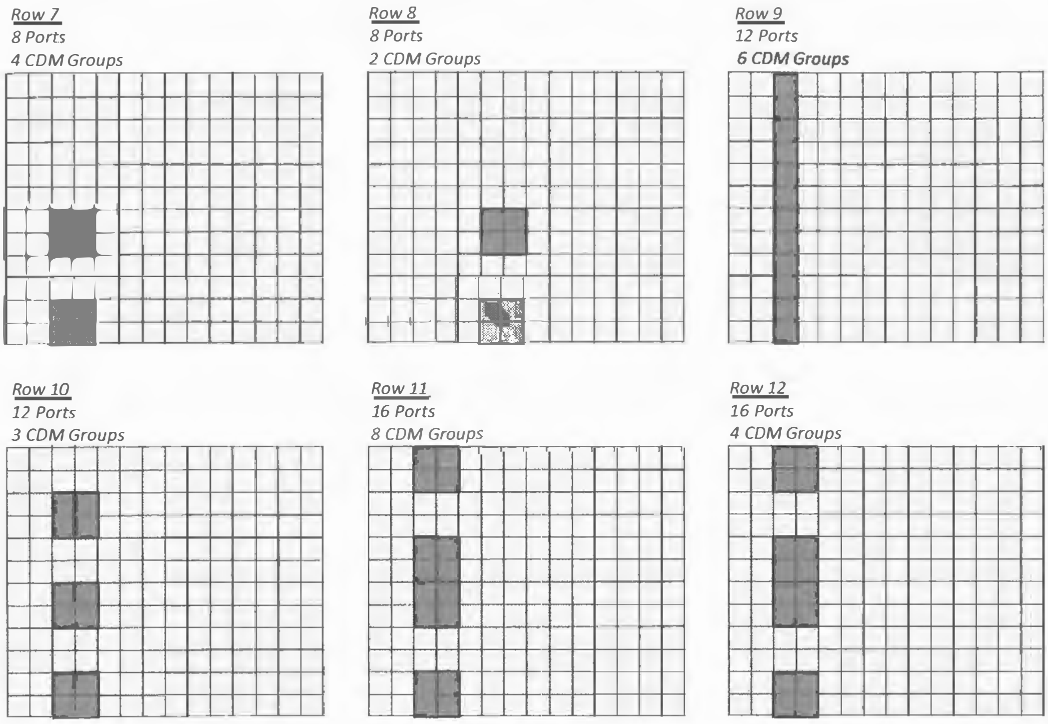


Figure 195 – CSI Reference Signals based upon 'Rows 7 to 12' (antenna ports superimposed upon each other)

★ Figure 196 illustrates examples of the CSI Reference Signal for rows 13 to 18. Rows 13, 14 and 15 transmit the CSI Reference Signal across 24 ports, while rows 16, 17 and 18 transmit across the maximum of 32 ports. The overhead generated by the CSI Reference Signal increases as the number of ports increases. In the case of 32 ports, the CSI Reference Signal occupies 32 / 168 = 19 % of Resource Elements

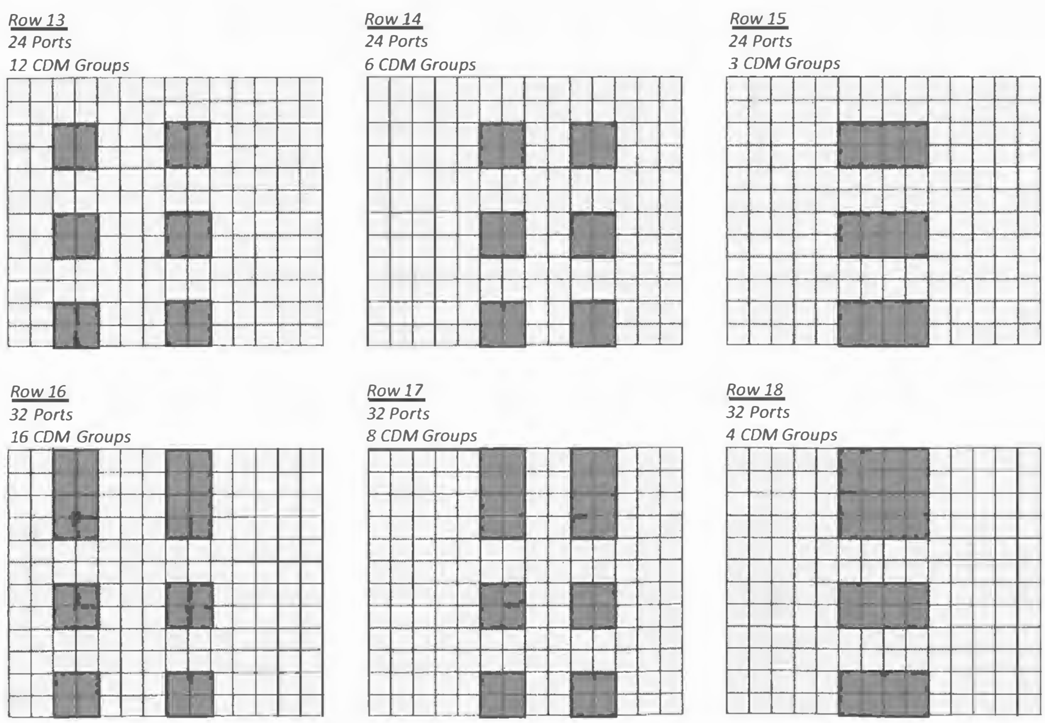


Figure 196 – CSI Reference Signals based upon 'Rows 13 to 18' (antenna ports superimposed upon each other)

- ★ Returning to the *NZP-CSI-RS-Resource* parameter structure shown in Table 119, the *powerControlOffset* information element specifies the transmit power difference between the CSI Reference Signal and the PDSCH. Knowledge of this power difference is important when generating Channel State Information (CSI). For example, a UE will report lower CQI values if the PDSCH transmit power is reduced. The *powerControlOffsetSS* information element specifies the power difference between the CSI Reference Signal and the Secondary Synchronisation Signal

- ★ The *scramblingID* is used as an input when generating the pseudo random sequence which populates the Resource Elements allocated to the CSI Reference Signal

- ★ The *periodicityAndOffset* is applicable to periodic and semi-persistent CSI Reference Signal Resources. It is used to define the slot timing of the CSI Reference Signal transmissions. The period can range from 4 to 640 slots, e.g. 4 to 640 ms when using the 15 kHz subcarrier spacing, and 0.5 to 80 ms when using the 120 kHz subcarrier spacing. All CSI Reference Signal Resources within a set are configured with the same periodicity but may be configured with different offsets. This principle is used by the Tracking Reference Signal (TRS) when it is configured to occupy 2 consecutive slots

- ★ *qcl-InfoPeriodicCSI-RS* is used to link the CSI Reference Signal to a Transmission Configuration Indicator (TCI) State. This is done to provide the UE with information regarding Quasi Co-Location (QCL). QCL means that transmissions from different antenna ports have some common 'large scale' radio channel characteristics, e.g. Doppler Shift; Doppler Spread; Average Delay; Delay Spread; Spatial Receiver Parameters. 3GPP has defined QCL Types A, B, C and D to specify different combinations of these radio channel characteristics. For example, QCL Type B means that Doppler Shift and Doppler Spread are expected to be the same for the antenna ports which are Quasi Co-Located. Providing the UE with knowledge of QCL helps the UE with its channel estimation, frequency offset estimation and synchronisation procedures. A TCI State indicates that the CSI Reference Signal is Quasi Co-Located with either a specific SS/PBCH Block or another CSI Reference Signal. The TCI State also indicates the appropriate QCL Type (A, B, C or D). Section 2.6 describes the concepts of QCL and TCI States in greater detail

3.7.4.2 ZP CSI INTERFERENCE MEASUREMENT RESOURCE

- ★ Zero Power (ZP) CSI Reference Signals are configured within the *PDSCH-Config* parameter structure. The relevant sections of this parameter structure are shown in Table 121. The first entry is used to configure up to 32 ZP CSI Reference Signal Resources. Each Resource is configured using an instance of the *ZP-CSI-RS-Resource* parameter structure (Table 122). The second entry can be used to release up to 32 ZP CSI Reference Signal Resources

PDSCH-Config	
zp-CSI-RS-ResourceToAddModList	SEQUENCE { 1 to 32 instances of *ZP-CSI-RS-Resource* }
zp-CSI-RS-ResourceToReleaseList	SEQUENCE { 1 to 32 instances of *ZP-CSI-RS-ResourceId* }
aperiodic-ZP-CSI-RS-ResourceSetsToAddModList	SEQUENCE { 1 to 3 instances of *ZP-CSI-RS-ResourceSet* }
aperiodic-ZP-CSI-RS-ResourceSetsToReleaseList	SEQUENCE { 1 to 3 instances of *ZP-CSI-RS-ResourceSetId* }
sp-ZP-CSI-RS-ResourceSetsToAddModList	SEQUENCE { 1 to 16 instances of *ZP-CSI-RS-ResourceSet* }
sp-ZP-CSI-RS-ResourceSetsToReleaseList	SEQUENCE { 1 to 16 instances of *ZP-CSI-RS-ResourceSetId* }
p-ZP-CSI-RS-ResourceSet	SetupRelease { *ZP-CSI-RS-ResourceSet* }

Table 121 – Sections of *PDSCH-Config* used to configure ZP CSI Reference Signals

- ★ The Base Station can then configure up to 3 aperiodic ZP CSI Reference Signal Resource Sets. Each Resource Set is configured using the *ZP-CSI-RS-ResourceSet* parameter structure (Table 123). This parameter structure simply assigns an identity and groups up to 16 ZP CSI Reference Signal Resources into a set. Resource Set identities 1 to 3 are used for aperiodic triggering. DCI Format 1_1 includes a 'ZP CSI-RS Trigger' field which can be used to trigger an aperiodic Resource Set. This field occupies up to 2 bits to allow the 3 Resource Sets to be addressed

- ★ The Base Station can configure up to 16 semi persistent ZP CSI Reference Signal Resource Sets. Each Resource Set is configured using the *ZP-CSI-RS-ResourceSet* parameter structure. Semi persistent Resource Sets are triggered using the downlink MAC Control Element shown in Figure 197. This MAC Control Element is used for both activation and deactivation purposes so it includes a 1 bit flag to differentiate between commands. The MAC Control Element includes a 4 bit field to address a specific Resource Set

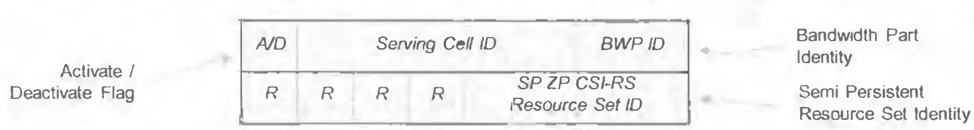


Figure 197 – MAC Control Element used to trigger Semi Persistent Zero Power CSI Reference Signal Resource Sets

★ Aperiodic and semi-persistent ZP CSI Reference Signal Resources can be released by specifying their Resource Set identities

★ The Base Station can configure a single ZP CSI Reference Signal Resource Set for periodic reception. This Resource Set is always allocated identity 0

★ The *ZP-CSI-RS-Resource* parameter structure used to configure an individual Resource is presented in Table 122. This parameter structure re-uses fields from the *NZP-CSI-RS-Resource* parameter structure, i.e. the *resourceMapping* and *periodicityAndOffset* fields. These fields are used in the same way as for NZP CSI Reference Signal Resources. This means that ZP Resources can use the same Resource Element patterns as NZP Resources (illustrated in Figure 191 to Figure 196)

ZP-CSI-RS-Resource						
zp-CSI-RS-ResourceId	0 to 31					
resourceMapping	frequencyDomainAllocation CHOICE					
	row1	row2	row4	other		
	BIT STRING {4 bits}	BIT STRING {12 bits}	BIT STRING {3 bits}	BIT STRING {6 bits}		
	nrofPorts	1, 2, 4, 8, 12, 16, 24, 32				
	firstOFDMSymbolInTimeDomain	0 to 13				
	firstOFDMSymbolInTimeDomain2	2 to 12				
	cdm-Type	noCDM, fd-CDM2, cdm4-FD2-TD2, cdm8-FD2-TD4				
	density	CHOICE				
		0.5	1	3	spare	
		evenPRBs, oddPRBs				
	freqBand	startingRB	0 to 274, step 4			
		nrofRBs	24 to 276, step 4			
periodicityAndOffset	CHOICE					
	4 slots	0 to 3	20 slots	0 to 19	160 slots	0 to 159
	5 slots	0 to 4	32 slots	0 to 31	320 slots	0 to 319
	8 slots	0 to 7	40 slots	0 to 39	640 slots	0 to 639
	10 slots	0 to 9	64 slots	0 to 63		
	16 slots	0 to 15	80 slots	0 to 79		

Table 122 – Parameter structure used to configure a ZP CSI Reference Signal Resource

★ The *ZP-CSI-RS-ResourceSet* parameter structure used to configure a Resource Set is presented in Table 123. This parameter structure simply assigns an identity and lists the set of Resources which belong to the Resource Set

ZP-CSI-RS-ResourceSet	
zp-CSI-RS-ResourceSetId	0 to 15
zp-CSI-RS-ResourceIdList	SEQUENCE { 1 to 16 instances of *ZP-CSI-RS-ResourceId* }

Table 123 – Parameter structure used to configure a ZP CSI Reference Signal Resource Set

3.7.4.3 CSI INTERFERENCE MEASUREMENT RESOURCES

★ CSI Interference Measurement (IM) Resources allow a UE to measure downlink interference levels in the absence of transmissions from the serving cell. The serving cell does not transmit anything within the Resource Elements allocated to the CSI IM Resources. This allows the UE to measure background interference levels without the complication of having to subtract a signal from the serving cell

★ CSI IM Resources are configured within the *CSI-ResourceConfig* parameter structure. This parameter structure can include up to 16 CSI IM Resource Set identities. Each identity points towards a CSI IM Resource Set which includes up to 8 CSI IM Resource identities. Each of these identities points towards a specific CSI IM Resource. This hierarchy of parameter structures is presented in Figure 198

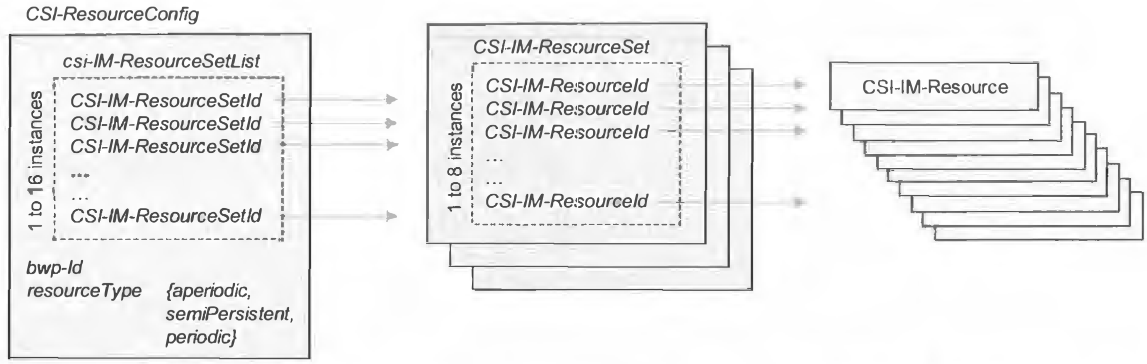


Figure 198 – Parameter structures used to configure CSI Interference Measurement (IM) Resources

★ The parameter structure used to configure a CSI IM Resource Set is presented in Table 124. This parameter structure includes a Resource Set identity and a sequence of up to 8 CSI IM Resource identities

CSI-IM-ResourceSet	
csi-IM-ResourceSetId	0 to 63
csi-IM-Resources	SEQUENCE { 1 to 8 instances of *csi-IM-ResourceId* }

Table 124 – Parameter structure used to configure a CSI IM Resource Set

★ The parameter structure used to configure a CSI IM Resource is presented in Table 125. This parameter structure includes a CSI IM Resource identity and a specification of the resources which are allocated to the CSI IM Resource. There is a choice of configuring either pattern 0 or pattern 1:

- o Pattern 0 corresponds to a 2×2 grid of Resource Elements. *subcarrierLocation-p0* and *symbolLocation-p0* specify the first subcarrier and first symbol belonging to the 2×2 grid
- o Pattern 1 corresponds to a 4×1 grid of Resource Elements (4 subcarriers × 1 symbol). *subcarrierLocation-p1* and *symbolLocation-p1* specify the first subcarrier and the only symbol belonging to the 4×1 grid

Examples of patterns 0 and 1 are illustrated in Figure 199

CSI-IM-Resource						
csi-IM-ResourceId	0 to 31					
csi-IM-ResourceElementPattern	CHOICE					
	pattern0			pattern1		
	subcarrierLocation-p0	0, 2, 4, 6, 8 10		subcarrierLocation-p1	0, 4, 8	
	symbolLocation-p0	0 to 12		symbolLocation-p1	0 to 13	
freqBand	startingRB	0 to 274, step 4				
	nrofRBs	24 to 276, step 4				
periodicityAndOffset	CHOICE					
	4 slots	0 to 3	20 slots	0 to 19	160 slots	0 to 159
	5 slots	0 to 4	32 slots	0 to 31	320 slots	0 to 319
	8 slots	0 to 7	40 slots	0 to 39	640 slots	0 to 639
	10 slots	0 to 9	64 slots	0 to 63		
	16 slots	0 to 15	80 slots	0 to 79		

Table 125 – Parameter structure used to configure a CSI IM Resource

★ The *freqBand* section of the parameter structure specifies the set of contiguous Resource Blocks across which the CSI IM Resource is configured. The *startingRB* is relative to Common Resource Block 0, i.e. the lower edge of the channel bandwidth, rather than the lower edge of the Bandwidth Part. The *nrofRBs* information element has a minimum value of 24 but if the Bandwidth Part occupies less than 24 Resource Blocks then the CSI IM Resource occupies only the Resource Blocks within the Bandwidth Part

★ The *periodicityAndOffset* section of the parameter structure is applicable when the *resourceType* within the *CSI-ResourceConfig* is set to either periodic or semi-persistent (shown in Figure 198). In these cases, the period defines the time interval between successive resource allocations, while the offset defines a time shift which is applied to the periodic transmission pattern

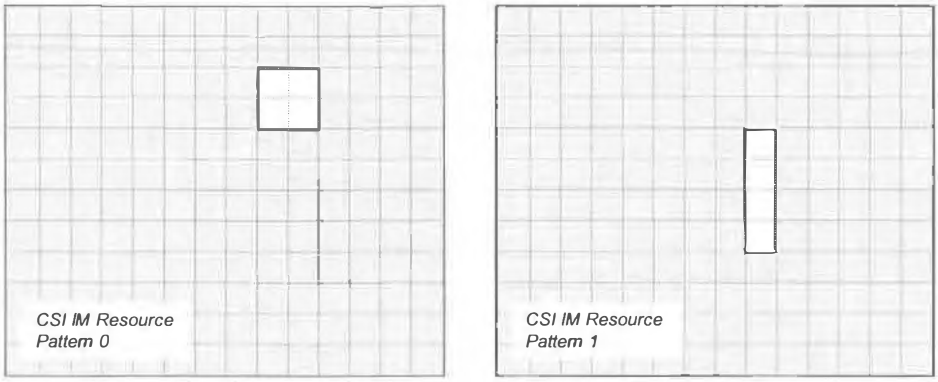


Figure 199 – Examples of CSI IM Resource Patterns 0 and 1

3.7.5 TRACKING REFERENCE SIGNAL

★ The Tracking Reference Signal (TRS) is a downlink transmission which allows the UE to track time and frequency variations with a high resolution. The Synchronisation Signals allow a relatively coarse synchronisation while the TRS allows fine tuning. Improved synchronisation can benefit the performance of data transfer in both the uplink and downlink directions. The TRS can be viewed as being similar to the Cell specific Reference Signal (CRS) used by LTE. However, the TRS generates a lower overhead by occupying a reduced percentage of Resource Elements and using only a single antenna port

★ 3GPP has adopted the CSI Reference Signal as a solution for the TRS. This means that the TRS is a CSI Reference Signal Resource Set with a specific configuration. The configuration has been selected to maximise tracking performance while maintaining a reasonable overhead. The *trs-Info* flag within the *NZP-CSI-RS-ResourceSet* parameter structure (Table 118 in section 3.7.4.1) indicates that the CSI Reference Signal Resource Set is to be used as a TRS

★ Both Frequency Ranges 1 and 2, support the TRS configured as a Non-Zero Power (NZP) CSI Reference Signal Resource Set which includes 4 CSI Reference Signal Resources across 2 consecutive slots, with 2 Resources within each slot

★ In addition, Frequency Range 2 supports the TRS configured as an NZP CSI Reference Signal Resource Set which includes 2 CSI Reference Signal Resources within a single slot

★ The CSI Reference Signal Resources within a specific slot are always separated by 4 symbols. Both Frequency Ranges can use the following symbol pairs: {4, 8}, {5, 9} or {6, 10}, while Frequency Range 2 can also use the symbol pairs {0, 4}, {1, 5}, {2, 6}, {3, 7}, {7, 11}, {8, 12} or {9, 13}

★ Each CSI Reference Signal Resource within the Resource Set always uses a single port with a density of 3 Resource Elements per Resource Block, i.e. based upon row 1 within Table 120 (section 3.7.4.1). The relatively high density helps to improve the UE's ability to track time and frequency offsets

★ Figure 200 illustrates an example of the TRS across 2 slots. The spacing of the Resource Elements allocated to the TRS provides the UE with visibility of variations in both the time and frequency domains

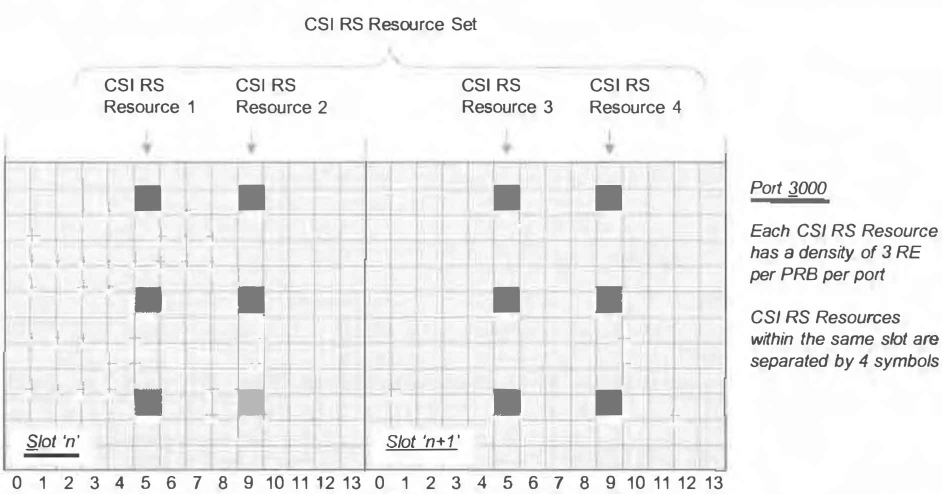


Figure 200 – CSI Reference Signal Resource Set across 2 slots for Tracking Reference Signal (TRS)

★ The TRS is intended to be a relatively wideband transmission so the UE can track variations across the downlink Bandwidth Part. The TRS occupies the whole Bandwidth Part if the Bandwidth Part spans less than 52 Resource Blocks. Otherwise, the TRS is configured with a bandwidth of either 52 Resource Blocks or the bandwidth of the Bandwidth Part

★ A UE is always configured with a periodic TRS. The period between transmissions can be configured to be either 10, 20, 40 or 80 ms. The 10 ms period is not used if the TRS is allocated more than 52 Resource Blocks

★ In addition, a UE can be configured with an aperiodic TRS. An aperiodic transmission can be used to provide a time and frequency reference at the start of a data transfer. This is particularly useful when the periodic TRS has a relatively long period and the data transfer occurs towards the end of the period, i.e. the UE has not updated its time and frequency offset information for a relatively long time. This combination of periodic and aperiodic TRS transmissions is shown in Figure 201

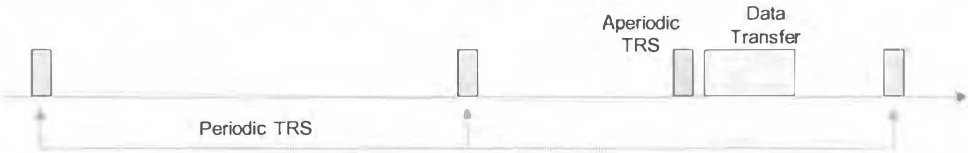


Figure 201 – Combination of periodic and aperiodic TRS

★ Aperiodic TRS can also be useful immediately after specific events. For example, transmission of an aperiodic TRS on a Secondary Cell immediately after Secondary Cell activation allows the UE to fine tune its time and frequency synchronisation with minimal delay. Consequently, data transfer can then start with minimal delay. Similarly, aperiodic TRS transmissions can be useful immediately after a change of the active Bandwidth Part, or immediately after a change of beam

★ 3GPP References: TS 38.214

3.7.6 PHASE TRACKING REFERENCE SIGNAL

★ The downlink Phase Tracking Reference Signal (PTRS) allows the UE to estimate and subsequently compensate for both phase noise and frequency offsets:

o phase noise is generated by using non-ideal oscillators at both the transmitter and receiver. These oscillators do not generate completely perfect sine waves. Instead they generate sine waves which have relatively small random phase variations, i.e. phase noise is superimposed upon the sine wave. It is more difficult to manufacture oscillators with good phase noise properties at high frequencies. Phase noise does not have a significant impact when using frequencies below 6 GHz (Frequency Range 1) but has an increased impact when using frequencies above 6 GHz (Frequency Range 2). The use of larger subcarrier spacings in Frequency Range 2 helps to increase resilience against phase noise. Nevertheless, the PTRS is required for phase noise estimation and compensation when using Frequency Range 2

o frequency offsets are generated by using non-ideal oscillators at both the transmitter and receiver. They are also generated by mobility, i.e. Doppler frequency offsets. Frequency offsets are relatively small shifts away from the ideal center frequency. They cause a continuous phase increase (or decrease) rather than a random phase noise. A non-ideal oscillator may generate a center frequency of '$X + \Delta$' instead of 'X'. 3GPP TS 38.104 specifies that wide area Base Stations must be accurate to within 0.05 parts per million (ppm), while local area Base Stations must be accurate to within 0.1 ppm. 3GPP TS 38.101-1 specifies that UE must be accurate to within 0.1 ppm. Doppler frequency offsets increase with mobility and operating frequency. Frequency offsets can be significant within both Frequency Range 1 and Frequency Range 2. Thus, the PTRS can be used for frequency offset estimation and compensation within both frequency ranges

★ Phase noise tends to change as a function of time but remains relatively constant as a function of frequency. This characteristic has led to the PTRS being designed to have a relatively high density in the time domain but a low density in the frequency domain, i.e. the PTRS can occupy a high percentage of symbols but a low percentage of subcarriers

★ Frequency offsets cause the modulation constellation to rotate. The rate of rotation increases as the frequency offset increases. A frequency offset can be measured by identifying the phase of the modulation constellation at two points in time and then calculating the rate of rotation between those two points. This process can be completed using 2 DMRS symbols, as illustrated in the left half of Figure 202. Alternatively, the process can be completed using a single DMRS symbol in combination with a PTRS transmission. This is illustrated in the right half of Figure 202. The latter generates a lower overhead so there is increased potential to achieve higher PDSCH throughputs

★ A Base Station with multiple antenna panels may be designed to use a single local oscillator which is shared across antenna panels. In this case, there is a single source of phase noise and frequency offset so it is sufficient to transmit the PTRS using a single antenna port. A different Base Station with multiple antenna panels may be designed to use a separate local oscillator for each antenna panel. In this case, there are multiple sources of phase noise and frequency offset so it is necessary to transmit the PTRS using multiple antenna ports. The release 15 version of the specifications focuses upon single antenna panel transmission and the PTRS is limited to single port transmission in the downlink direction

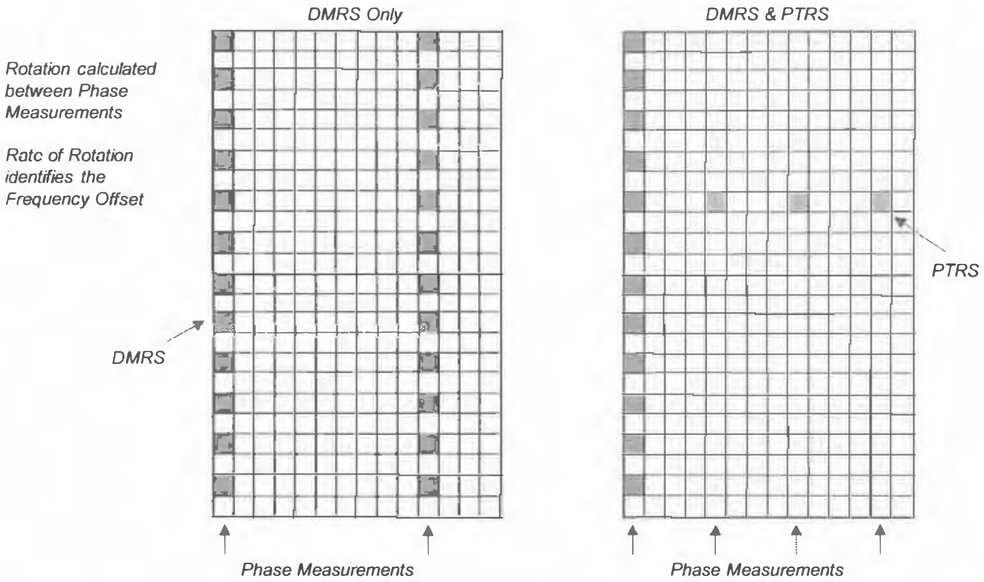


Figure 202 – Frequency Offset estimation using only DMRS and using DMRS with PTRS

★ The *PTRS-DownlinkConfig* parameter structure is visible within the *DMRS-DownlinkConfig* parameter structure presented in Table 112 (section 3.7.3), i.e. the PTRS is configured within the PDSCH DMRS parameter structure. The PTRS-*DownlinkConfig* parameter structure is presented in Table 126

PTRS-DownlinkConfig	
frequencyDensity	SEQUENCE {2 instances within range 1 to 276}
timeDensity	SEQUENCE {3 instances within range 0 to 29}
epre-Ratio	0 to 3
resourceElementOffset	offset01, offset10, offset11

Table 126 – Parameter structure used to configure the Downlink Phase Tracking Reference Signal

★ The first two parameters define the density of PTRS Resource Elements. The density in the frequency domain depends upon the number of allocated Resource Blocks, while the density in the time domain depends upon the allocated MCS

★ The *frequencyDensity* information element provides a set of two Resource Block thresholds (N_{RB0} and N_{RB1}). These two thresholds are presented in Table 127. They are used to create 3 operating regions. If the number of allocated Resource Blocks is less than the first threshold then the PTRS is not transmitted. If the number of allocated Resources Blocks is between the two thresholds then the frequency density is 2. Otherwise, the frequency density is 4

Scheduled Bandwidth	Frequency Density (K_{PTRS})
$N_{RB} < N_{RB0}$	PTRS is not used
$N_{RB0} \leq N_{RB} < N_{RB1}$	2
$N_{RB1} \leq N_{RB}$	4

Table 127 – Frequency density of the Phase Tracking Reference Signal as a function of allocated Resource Blocks

★ The PTRS overhead becomes larger for small Resource Block allocations so there is a point at which the benefit of including the PTRS is outweighed by the cost of the overhead. This provides the reasoning for disabling the PTRS for small Resource Block allocations

★ The *frequencyDensity* represents the frequency domain spacing between Resource Blocks allocated to the PTRS. The value of 2 means that every 2nd Resource Block includes a single PTRS subcarrier, whereas the value of 4 means that every 4th Resource Block includes a single PTRS subcarrier, i.e. the value of 2 corresponds to a higher density than the value of 4 so the density figures can be viewed as being 1/2 and 1/4. The general strategy is to use a higher density for medium sized Resource Block allocations to achieve a more accurate channel estimate, and to use a lower density for larger Resource Block allocations to minimise the overhead (for larger Resource Block allocations, there are more Resource Blocks to accommodate the PTRS so the absolute number of Resource Blocks which include the PTRS can still be relatively high)

★ If the *frequencyDensity* information element is excluded from the parameter structure, the value of K_{PTRS} is set to 2

★ The equation used to calculate the set of subcarriers allocated to the PTRS is shown below. The value of 'i' is incremented until the subcarrier number 'k' falls outside the PDSCH resource allocation. The step size between PTRS subcarriers is given by $K_{PTRS} \times 12$

Subcarrier Offset
0 to 11

0, 1, 2, ...

$$k = k_{ref}^{RE} + \left(i \times K_{PTRS} + k_{ref}^{RB}\right) \times 12$$

Resource Block Offset, 0 to 3

2 or 4 based upon number
of allocated Resource Blocks

$$k_{ref}^{RB} = \begin{cases} n_{RNTI} \bmod K_{PTRS} & \text{if } N_{RB} \bmod K_{PTRS} = 0 \\ n_{RNTI} \bmod (N_{RB} \bmod K_{PTRS}) & \text{otherwise} \end{cases}$$

★ The equation includes a subcarrier offset (k_{ref}^{RE}) and a Resource Block offset (k_{ref}^{RB}). The Resource Block offset is calculated from the RNTI which has been allocated to the UE. This effectively randomises the Resource Blocks used for the PTRS by different UE. There are two alternative calculations for k_{ref}^{RB}. These calculations ensure that the number of Resource Blocks used by the PTRS is maximised

★ The subcarrier offset (k_{ref}^{RE}) depends upon the DMRS antenna port, the DMRS Configuration Type, and the *resourceElementOffset* presented in Table 126. The dependency upon these variables is presented in Table 128. The values have been selected to ensure that the PTRS uses the same subcarriers as the DMRS. For example, antenna ports 1000 and 1001, with DMRS Configuration Type 1 use even numbered subcarriers for the DMRS, whereas antenna ports 1002 and 1003 use odd numbered subcarriers. The PTRS has not been specified to be used with the DMRS 'Double Symbol' configuration. This means that antenna ports 1004 to 1007 are not applicable when using Configuration Type 1, and antenna ports 1006 to 1011 are not applicable when using Configuration Type 2

★ The performance of the PTRS is maximised if neighbouring cells transmit the PTRS using different subcarriers, i.e. PDSCH to PTRS interference is preferred relative to PTRS to PTRS interference. This translates into a requirement to configure neighbouring cells with different values of *resourceElementOffset*

DMRS Antenna Port	k_{ref}^{RE}							
	DMRS Configuration Type 1 *resourceElementOffset*				DMRS Configuration Type 2 *resourceElementOffset*			
	00	01	10	11	00	01	10	11
1000	0	2	6	8	0	1	6	7
1001	2	4	8	10	1	6	7	0
1002	1	3	7	9	2	3	8	9
1003	3	5	9	11	3	8	9	2
1004	-	-	-	-	4	5	10	11
1005	-	-	-	-	5	10	11	4

Table 128 – PTRS Subcarrier Offset as a function of the DMRS antenna port, DMRS Configuration Type and *resourceElementOffset*

★ The *timeDensity* information element provides a set of three MCS Index thresholds (*ptrs-MCS1*, *ptrs-MCS2* and *ptrs-MCS3*). These thresholds are presented in Table 129 which also includes a fourth threshold, *ptrs-MCS4*. This fourth threshold has a value which depends upon the MCS table being used. The value of *ptrs-MCS4* is set to 29 if MCS Index 28 is the highest index which has a Target Code Rate specified. The value of *ptrs-MCS4* is set to 28 if MCS Index 27 is the highest index which has a Target Code Rate specified

Scheduled MCS Index	Time Density (L_{PTRS})
I_{MCS} < *ptrs-MCS1*	PTRS is not used
ptrs-MCS1 ≤ I_{MCS} < *ptrs-MCS2*	4
ptrs-MCS2 ≤ I_{MCS} < *ptrs-MCS3*	2
ptrs-MCS3 ≤ I_{MCS} < *ptrs-MCS4*	1

Table 129 – Time density of the Phase Tracking Reference Signal as a function of MCS

★ The 4 MCS thresholds are used to create 4 operating regions. If the allocated MCS Index is less than the first threshold then the PTRS is not transmitted. Otherwise, the time density (L_{PTRS}) can have values of 4, 2 or 1 based upon the allocated MCS. The impact of phase noise becomes negligible for low MCS because the low coding rate is sufficient to protect the data (low coding rate indicates high channel coding redundancy). This provides the reasoning for allowing the PTRS to be disabled when low MCS values are allocated

★ The *timeDensity* represents the time domain spacing between symbols allocated to the PTRS. The value of 4 means that every 4th symbol can include the PTRS, while the value of 2 means that every 2nd symbol can include the PTRS, and the value of 1 means that every symbol can include the PTRS. The symbols allocated to the PTRS account for the symbols allocated to the DMRS. 3GPP TS 38.211 specifies an algorithm which avoids the PTRS being allocated the same symbols as the DMRS and also avoids the PTRS being allocated symbols immediately after the DMRS (unless the time density is 1). Figure 203 illustrates some example PTRS allocations

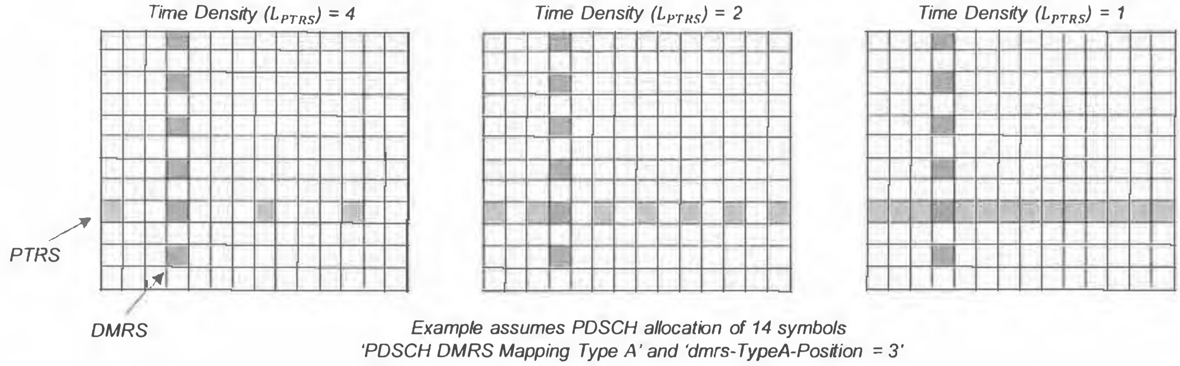


Figure 203 – Example PTRS symbols for each *timeDensity*

- ★ If the *timeDensity* information element is excluded from the parameter structure, the value of L_{PTRS} is set to 1
- ★ If neither *frequencyDensity* nor *timeDensity* are included then the UE assumes that the PTRS is not transmitted when the number of allocated Resource Blocks is less than 3, or the allocated MCS is less than 10 when using the 64QAM MCS table, or the allocated MCS is less than 5 when using the 256QAM MCS table, or the allocated MCS is less than 15 when using the Low Spectral Efficiency MCS table
- ★ The PTRS is not transmitted when the PDSCH resources are allocated using an SI-RNTI, RA-RNTI nor P-RNTI
- ★ The *epre-Ratio* information element shown in Table 126 can be used to indicate that the transmit power of the PTRS is boosted relative to the PDSCH. Table 130 presents the Energy Per Resource Element (EPRE) ratio as a function of the *epre-Ratio* and the number of PDSCH layers. A value of '1' means that boosting is not applied, whereas a value of '0' means that boosting is applied when the number of PDSCH layers is greater than 1

	Number of PDSCH Layers					
epre-Ratio	1	2	3	4	5	6
0	0	3	4.77	6	7	7.78
1	0	0	0	0	0	0

Table 130 – Power Boosting of the PTRS relative to the PDSCH

- ★ The PTRS is transmitted using a single logical antenna port. The Base Station applies DTX to the PTRS Resource Elements on all other antenna ports. Figure 204 illustrates an example for a PDSCH transmission using 2 ports (2×2 MIMO). The DTX Resource Elements allow the power of the PTRS to be boosted without impacting the power allocated to other Physical Channels and Signals. The PTRS power can be doubled when 2 ports are used for the PDSCH (3 dB increase). Similarly, the PTRS power can be tripled when 3 ports are used for the PDSCH (4.77 dB increase)

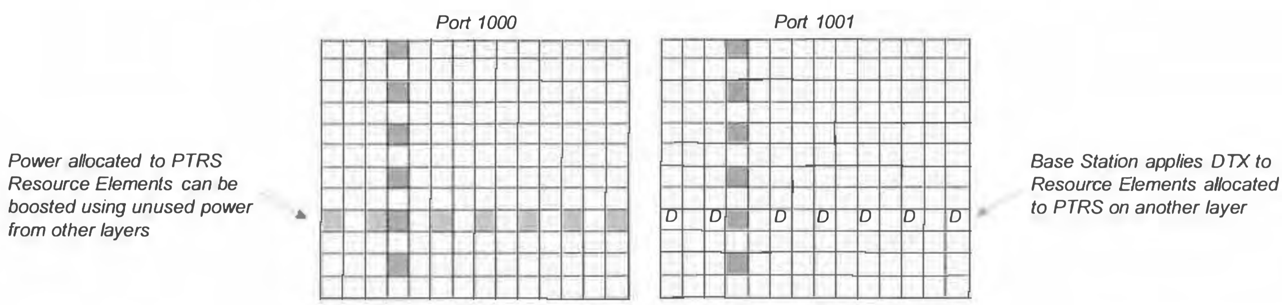


Figure 204 – Unused Resource Elements allow PTRS Power Boosting

- ★ Sharing downlink transmit power across antenna ports is only possible when the set of antenna ports share the same power amplifier. It is not possible to share downlink transmit power when antenna ports use different power amplifiers. This means that the rows within Table 130 correspond to different Base Station architectures. The *epre-Ratio* value of '1' corresponds to a Base Station architecture which uses different power amplifiers for each antenna port. This could correspond to analogue beamforming which uses a separate power amplifier for each beam. The *epre-Ratio* value of '0' corresponds to a Base Station architecture which allows antenna ports to share power amplifiers. This could correspond to digital beamforming which uses a set of shared power amplifiers to generate multiple beams
- ★ Table 130 includes columns for up to 6 layers rather than the maximum of 8 layers supported by the PDSCH. This results from the restriction that limits the PTRS to transmissions which are configured to use the Single Symbol DMRS. The Single Symbol DMRS supports a maximum of 6 layers and so the PDSCH also supports a maximum of 6 layers when using the PTRS. This is consistent with

Table 128 which shows the set of 6 antenna ports which are supported when using the Single Symbol DMRS. The transmission of 8 PDSCH layers requires the Double Symbol DMRS

- 3GPP TS 38.214 specifies the rules for identifying which antenna port is used by the PTRS. When a single Transport Block is scheduled, the lowest indexed port is selected. When two Transport Blocks are scheduled, the lowest indexed port belonging to the Transport Block with the highest MCS is selected. If both Transport Blocks have equal MCS then the lowest indexed port belonging to Transport Block 0 is selected

- The Base Station can take advantage of the 'Layer Indicator' (LI) reported by the UE within its Channel State Information (CSI). The LI identifies the layer with the best channel conditions. The performance of the PTRS is maximised if it is transmitted using the layer with the best channel conditions. If the PTRS is transmitted using port 1000, while the UE reports that layer 3 has the best channel conditions, then the Base Station can use the precoding associated with layer 3 when transmitting the PTRS from port 1000

- The DMRS and PTRS are assumed to be Quasi-Co-located (QCL) in terms of QCL-TypeA {Doppler Shift, Doppler Spread, Average Delay, Delay Spread} and QCL-TypeD {Spatial Rx Parameter}

- As part of the UE capability signalling, a UE is able to provide recommendations regarding the Resource Block and MCS thresholds presented in Table 127 and Table 129. These recommendations allow the Base Station to configure UE specific thresholds rather than applying a common set of general thresholds across all UE. The recommendations provided by the UE are presented in Table 131. These recommendations are provided for each subcarrier spacing, i.e. the UE provides 4 instances of these recommendations to cater for the 15, 30, 60 and 120 kHz subcarrier spacings

PTRS-DensityRecommendationDL	
frequencyDensity1	1 to 276
frequencyDensity2	1 to 276
timeDensity1	0 to 29
timeDensity2	0 to 29
timeDensity3	0 to 29

Table 131 – Content of *PTRS-DensityRecommendationDL* parameter structure

- The sequence used to populate the set of PTRS Resource Elements is the same as that used for the DMRS, i.e. a pseudo random sequence based upon a length-31 Gold sequence

- 3GPP References: TS 38.211, TS 38.214, TS 38.331

4 DOWNLINK TRANSMISSION SCHEMES

4.1 PBCH

★ The PBCH uses a single antenna port for transmission (antenna port 4000). In contrast, the 4G PBCH can use either 1 or 2 antenna ports for transmission. The drawback associated with allowing either 1 or 2 antenna ports is the requirement for the UE to use blind detection to determine the number of antenna ports. Specifying a single antenna port for the 5G PBCH helps to reduce both the UE processing requirement and the PBCH acquisition time

★ Specifying single antenna port transmission for the PBCH allows network vendors to implement their own precoding solutions which are transparent to the UE, i.e. the Base Station applies precoding to improve the performance of the PBCH but the UE has no explicit knowledge of this precoding. The PBCH uses a Demodulation Reference Signal (DMRS) which is transmitted using the same antenna port as the PBCH itself. This means that the same precoding is applied to both the PBCH and the PBCH DMRS. The UE can use the DMRS to estimate the composite impact of the precoding and the propagation channel. In addition, the Synchronisation Signals (SS) are also transmitted using the same antenna port (based upon the concept of the SS/PBCH Block). This means that the Synchronisation Signals are also precoded in the same way as the PBCH. The UE can use the Secondary Synchronisation Signal as an additional Demodulation Reference Signal for the PBCH

★ Using a common antenna port for both the PBCH and the Synchronisation Signals means that additional care is required when implementing transparent precoding for the PBCH. This is because the same precoding will be applied to the Synchronisation Signals and it is necessary to ensure that the Synchronisation Signal detection performance is not degraded

★ The precoding applied by the Base Station can include a set of beamforming coefficients to generate an SS/PBCH Block beam. A burst of SS/PBCH Blocks can be used to provide coverage across the target coverage area. Each SS/PBCH Block within the burst has a different set of beamforming coefficients applied to generate a set of beams with different combinations of azimuth and elevation. The beamforming coefficients are applied to both the PBCH and its DMRS (and the Synchronisation Signals)

4.2 PDCCH

★ The PDCCH and its DMRS use a single antenna port for transmission (antenna port 2000). 3GPP has not specified the precoding for PDCCH transmit diversity but network vendors can implement solutions which are transparent to the UE. The same precoding is applied to both the PDCCH and its DMRS so the UE can use the DMRS to estimate the composite impact of both the precoding and the propagation channel

★ 3GPP has specified an RRC information element which provides the UE with information regarding the 'precoder granularity' (shown in Table 132). This information element is provided when configuring the Control Resource Set (CORESET) for PDCCH transmission. The complete *ControlResourceSet* parameter structure is presented in Table 62, section 3.5.1

extract from *ControlResourceSet*	
precoderGranularity	sameAsREG-bundle, allContiguousRBs

Table 132 – Extract from *ControlResourceSet* parameter structure

★ The precoder granularity describes the frequency domain resolution of the precoding applied by the Base Station. For example, if the precoder granularity was 10 Resource Blocks, then the Base Station would apply a first set of precoding coefficients to the first 10 Resource Blocks, a second set of precoding coefficients to the second 10 Resource Blocks, etc. Having knowledge of the precoder granularity helps the UE to generate estimates of the composite propagation channel. For the previous example, the UE would know that it needs to generate an estimate for each set of 10 Resource Blocks. A large granularity helps to improve the quality of the channel estimate because the UE has an increased number of Resource Blocks from which to calculate the result. However, a large granularity can also have a negative impact upon performance because it reduces the flexibility of the Base Station to apply frequency selective precoding

★ Figure 205 illustrates example transmission patterns for both values of *precoderGranularity*. These examples assume that the Resource Blocks allocated to the CORESET are distributed across three non-consecutive sections of the channel bandwidth (recall that Resource Blocks are allocated to a CORESET using a bitmap where each bit represents a set of 6 Resource Blocks). These examples also assume that there are 2 Resource Elements Groups (REG) within each REG Bundle, and that the REG Bundles allocated to each Control Channel Element (CCE) are interleaved across the CORESET (also recall that 1 CCE = 6 REG, so in this example there are 3 REG Bundles per CCE. Figure 205 illustrates the transmission of 12 REG Bundles so the PDCCH is transmitting 4 CCE, i.e. a PDCCH aggregation level of 4)

★ When *precoderGranularity* is set to '*sameAsREG-bundle*', the UE assumes that the Base Station applies the same precoding coefficients to all Resource Blocks within a Resource Element Group (REG) Bundle. In this case, the DMRS is only transmitted within the Resource Blocks being used to transfer the PDCCH. The UE processing requirement is relatively high because the UE has to generate a separate channel estimate for each REG Bundle

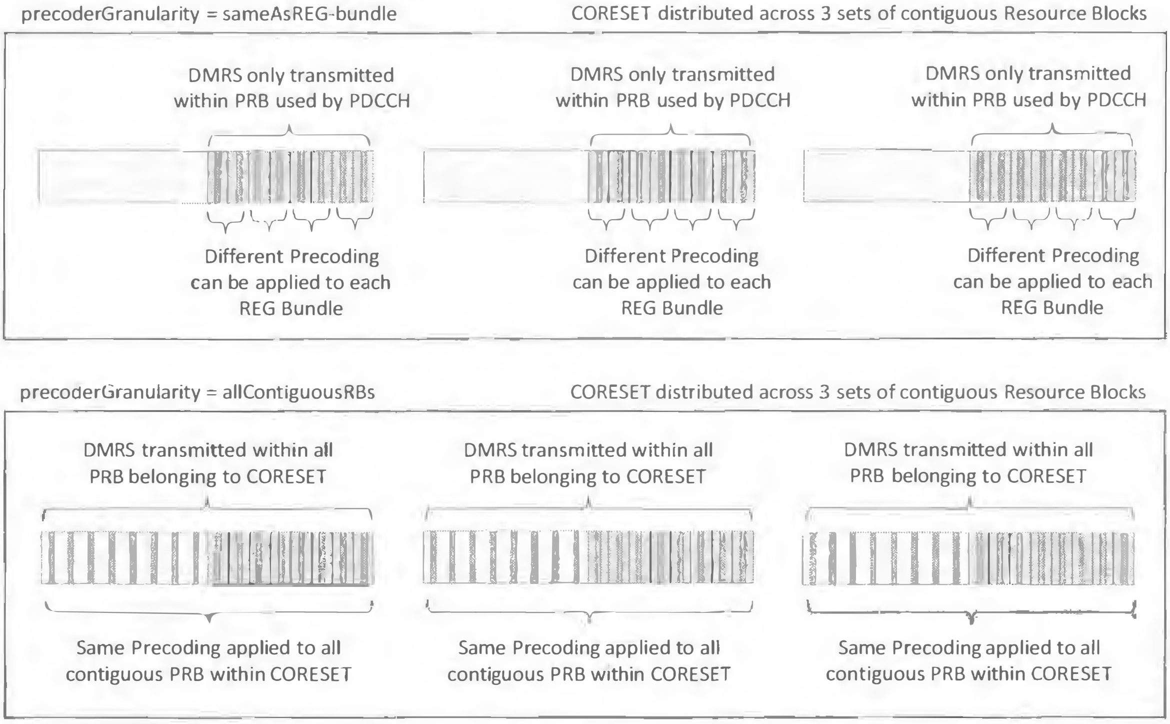


Figure 205 – Precoder Granularity for the PDCCH

- When *precoderGranularity* is set to '*allContiguousRBs*' then the UE assumes that the Base Station applies the same precoding coefficients to all REG within a specific set of contiguous Resource Blocks belonging to the CORESET. In this case, the DMRS is transmitted within all Resource Blocks belonging to the CORESET, i.e. some Resource Blocks include the DMRS but do not include the PDCCH. This solution increases the number of DMRS transmissions which can be used to generate each channel estimate. The example illustrated in Figure 205 requires the UE to generate 3 channel estimates
- The precoding adopted by the Base Station also has a dependence upon the UE capability. The UE uses the *precoderGranularityCORESET* information element shown in Table 133 to indicate whether or not it supports a precoder granularity equal to the size of the CORESET, i.e. a scenario which requires the UE to generate a single channel estimate from all Resource Blocks within the CORESET (requires all Resource Blocks within the CORESET to be contiguous, and *precoderGranularity* to be set to '*allContiguousRBs*'). This configuration can be used as a solution to improve PDCCH coverage, although PDCCH coverage can also be improved by using the higher aggregation levels of 8 and 16

extract from *Phy-ParametersCommon*	
precoderGranularityCORESET	supported

Table 133 – Extract from *Phy-ParametersCommon* parameter structure

- The Base Station link adaptation algorithm is responsible for selecting a PDCCH aggregation level which matches the current radio conditions. In the case of UE specific transmissions, the aggregation level can be optimised for each UE. In the case of common transmissions, e.g. resource allocations for Paging messages on the PDSCH, then it is necessary to use a relatively high aggregation level to cater for UE which may be at cell edge
- The type of PDCCH payload also impacts the beamforming applied by the Base Station. If the PDCCH is being used to allocate PDSCH resources for the transmission of a Paging message or System Information, then the PDCCH is likely to use the same beamforming as the set of SS/PBCH Blocks, i.e. relatively wide beams. PDCCH transmissions will be required across all SS/PBCH beam positions to ensure that messages are broadcast across the entire cell area
- If the PDCCH is being used to allocate PDSCH resources for the transmission of application data, then the PDCCH can use more directional beamforming. The Beam Refinement procedure (described in section 9.2) allows the UE to identify and report a specific directional beam based upon the CSI Reference Signal. The Base Station can then use this directional beam when transmitting the PDCCH towards the UE. Figure 206 illustrates examples of the PDCCH using SS/PBCH beams when allocating PDSCH resources for paging, and using a more directional CSI Reference Signal beam when allocating PDSCH resources for application data
- Directional beams are more likely to require frequent beam switching and may be more susceptible to beam failure. Thus, it may be decided that the Base Station should use a wider SS/PBCH beam for the PDCCH, while using a more directional beam for the PDSCH

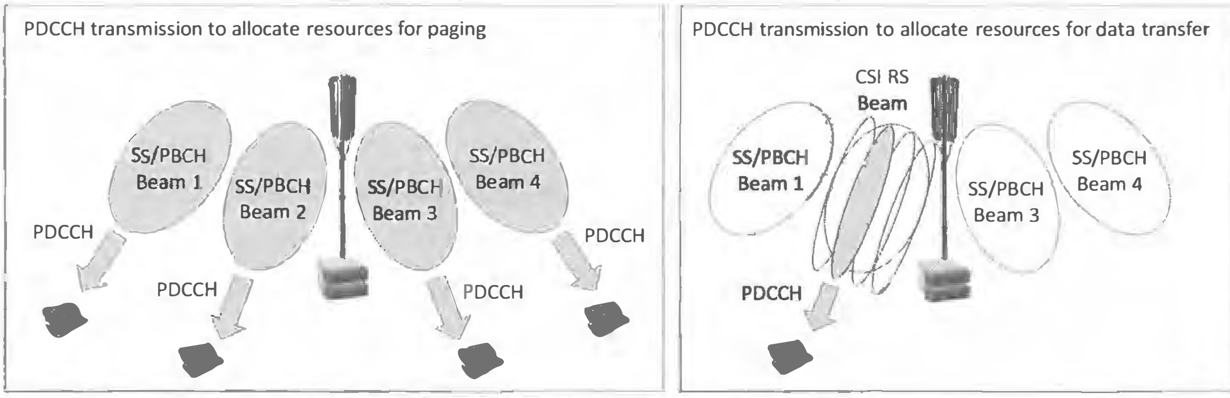


Figure 206 – Example beamforming applied to the PDCCH

4.3 PDSCH

★ 3GPP TS 38.214 specifies a single transmission scheme for the PDSCH – Transmission Scheme 1. This transmission scheme allows the Base Station to transfer PDSCH data with up to 8 layers, and using antenna ports within the range 1000 to 1011. The PDSCH is transmitted in combination with its Demodulation Reference Signal (DMRS) to allow coherent reception at the UE

★ Open Loop, Semi-Open Loop and Closed Loop transmission schemes are not explicitly defined. However, 3GPP has standardised the UE feedback mechanisms to support these transmission schemes. For example, a UE can be instructed to report CQI and Rank Indicator (RI) for an Open Loop scheme, or CQI, RI and Precoding Matrix Indicator (PMI) for a Closed Loop scheme. This allows network vendors to implement their own variants of the single transmission scheme

★ Semi-Open Loop MIMO relies upon the UE reporting CQI, RI and a partial PMI. The partial PMI provides only coarse precoding information. The Base Station refines the coarse PMI using open loop techniques, e.g. randomly cycling through a set of refined precoder values linked to the coarse precoder value

★ PMI reporting is based upon a set of 4 codebook categories specified by 3GPP - Type 1 Single Panel and Multi-Panel codebooks for a maximum rank of 8; Type 2 Single Panel and Port Selection codebooks which are optimised for multi-user MIMO but are restricted to a maximum rank of 2. Type 1 codebooks provide relatively coarse information, whereas Type 2 codebooks provide more detailed information at the cost of an increased signalling overhead. Section 13.6.3 describes the set of 4 codebook categories

★ The UE does not require explicit knowledge of the precoding applied by the Base Station because the same precoding is applied to both the PDSCH and the DMRS. The UE can use the DMRS to estimate the composite propagation channel which includes the impact of the Base Station precoding and the radio propagation channel. The DMRS is typically accommodated within a single symbol but additional DMRS symbols can be configured for rapidly changing radio environments

★ Base Station precoding is likely to include both precoding for MIMO and precoding for beamforming. Precoding for MIMO is typically short term and frequency selective, whereas precoding for beamforming is typically longer term and less frequency selective. The two stages of precoding are illustrated in Figure 169 within section 3.6.3.

★ The concept of Resource Block Bundling helps the UE to generate channel estimates from the DMRS. Resource Block Bundles correspond to Precoding Resource Block Groups (PRG). The Resource Blocks belonging to a PRG are assumed to experience similar channel conditions and have the same precoding applied by the Base Station, i.e. a UE can generate a single channel estimate from a PRG. Large PRG allow the UE to calculate each channel estimate across a larger set of Resource Blocks. This helps to improve the accuracy of the channel estimate, especially when coverage conditions are poor. Small PRG provide the Base Station with increased flexibility to apply frequency selective precoding. Resource Block Bundling is described in greater detail within section 3.6.5

★ Multi-User MIMO (MU-MIMO) is an effective solution for increasing spectral efficiency and thus increasing system capacity. MU-MIMO allows multiple UE to share the same Resource Blocks when those UE have a high spatial separation. This means that UE are separated in the spatial domain rather than the time and frequency domains. The Base Station Packet Scheduler is responsible for identifying candidate UE which can be grouped for co-scheduling. Interference between the transmissions towards each UE is minimised by serving each UE with a separate directional beam. MU-MIMO is applicable to digital beamforming rather than analogue beamforming. In the case of analogue beamforming it is not possible to apply separate beamforming coefficients to the Resource Blocks allocated to individual UE. This is because the beamforming coefficients are applied to the RF signal so individual UE resource allocations are not visible

4.3.1 OPEN LOOP MIMO

★ Open Loop MIMO relies upon the UE providing feedback in terms of:

  o Rank Indicator (RI) – suggested number of transmission layers

  o Channel Quality Indicator (CQI) – suggested modulation scheme and coding rate

★ This approach is categorised as 'Open Loop' because the UE is not required to provide feedback in terms of a Precoding Matrix Indicator (PMI). The Base Station can use the *CSI-reportConfig* parameter structure presented in Table 293 (section 13.6) to set *reportQuantity* to '*cri-RI-CQI*'. This means that the UE reports RI and CQI for MIMO, in combination with the CSI Reference Signal Resource Indicator (CRI) for Beam Management

★ The precise Open Loop MIMO transmission scheme is dependent upon the Base Station implementation and is transparent to the UE, i.e. the UE does not require explicit knowledge of the precoding applied by the Base Station

★ Candidate Open Loop MIMO transmission schemes include Precoder Cycling, 'Small Delay' Cyclic Delay Diversity (CDD) and 'Large Delay' Cyclic Delay Diversity

★ In the case of LTE, Transmission Mode 3 provides an Open Loop MIMO solution based upon 'Large Delay' CDD. In the case of LTE, the precoding is standardised so the UE is aware of the precoding applied by the Base Station at any point in time. This allows the PDSCH to be transmitted without a DMRS

★ Precoding for Large Delay CDD is defined using the equation:

$$\begin{bmatrix} y^{(0)}(i) \\ \vdots \\ y^{(P-1)}(i) \end{bmatrix} = W(i) \times D(i) \times U \times \begin{bmatrix} x^{(0)}(i) \\ \vdots \\ x^{(v-1)}(i) \end{bmatrix}$$

where, P is the number of output antenna ports, i is the sample number and v is the number of input layers

★ The Cyclic Delay Diversity itself is generated using the *D(i)* component of this equation. In the case of 4 layers, *D(i)* can be defined as:

$$D(i) = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & e^{-j\left(\frac{\pi}{2}\right)i} & 0 & 0 \\ 0 & 0 & e^{-j\left(\frac{2\pi}{2}\right)i} & 0 \\ 0 & 0 & 0 & e^{-j\left(\frac{3\pi}{2}\right)i} \end{bmatrix}$$

This matrix is in the same format as the identity matrix (identity matrix has a leading diagonal of all '1's and does not change the input after multiplication). However, the 2nd, 3rd and 4th leading diagonal elements are phasors with unity amplitude and a phase which increases for every input sample. Thus, the 2nd, 3rd and 4th rows of the input are multiplied by rotating phasors

★ If a time domain signal is multiplied by a rotating phasor then that signal is shifted in the frequency domain. In the case of precoding for Open Loop MIMO, the rotating phasors are applied in the frequency domain (prior to the IFFT used to generate the time domain CP-OFDM signal). Applying the rotating phasors in the frequency domain causes the signal to be shifted in the time domain, i.e. delay is introduced. The 4 phasors associated with *D(i)* have different rates of rotation so each input signal experiences a different delay. The delay increases as the phasor's rate of rotation increases. Introducing these delays generates diversity across the transmitted signals

★ Precoding for open loop spatial multiplexing is referred to as 'Large Delay' CDD when the maximum possible delays are applied, e.g. when there are 2 input layers, the phasors rotate 0° and 180° between input samples; when there are 4 input layers, the phasors rotate 0°, 90°, 180° and 270° between input samples

★ The input samples belonging to each layer are multiplied by the '*U*' matrix prior to having the CDD applied. The '*U*' matrix ensures that each input provided to the CDD includes a combination of the original input layers. This means that each antenna port transmits a combination of all layers but with different time delays. A typical '*U*' matrix is defined as:

$$U = \frac{1}{2}\begin{bmatrix} 1 & 1 & 1 & 1 \\ 1 & e^{-j\left(\frac{\pi}{2}\right)} & e^{-j\left(\frac{2\pi}{2}\right)} & e^{-j\left(\frac{3\pi}{2}\right)} \\ 1 & e^{-j\left(\frac{2\pi}{2}\right)} & e^{-j\left(\frac{4\pi}{2}\right)} & e^{-j\left(\frac{6\pi}{2}\right)} \\ 1 & e^{-j\left(\frac{3\pi}{2}\right)} & e^{-j\left(\frac{6\pi}{2}\right)} & e^{-j\left(\frac{9\pi}{2}\right)} \end{bmatrix}$$

★ The elements within the '*U*' matrix are not a function of the sample number '*i*'. They apply a fixed rotation to each input layer and do not generate a time delay in the same way as the *D(i)* matrix

★ The *W(i)* matrix can be used to provide additional precoding. In the case of Large Delay CDD for LTE, *W(i)* is the identity matrix scaled by $1/\sqrt{2}$ when using 2 antenna ports. In the case of 4 antenna ports, *W(i)* has entries which repeatedly cycle through a fixed pattern of values

4.3.2 SEMI-OPEN LOOP MIMO

★ Semi-Open Loop MIMO relies upon the UE providing feedback in terms of:

  - Rank Indicator (RI) – suggested number of transmission layers
  - Channel Quality Indicator (CQI) – suggested modulation scheme and coding rate
  - 'Partial' Precoding Matrix Indicator (PMI) – suggested partial precoding

★ This approach is categorised as 'Semi-Open Loop' because the UE is required to provide partial PMI feedback. It can be configured when using more than 2 antenna ports with the Type 1 Single Panel Codebook described in section 13.6.3.1. When using Closed Loop MIMO with more than 2 antenna ports, PMI reporting is divided into 2 stages. The first stage provides wideband information which does not change rapidly over time. This can involve beam selection, or beam group selection. The second stage provides sub-band information which changes more rapidly over time. This can involve beam selection from within a group and phase shift selection for co-phasing. The first stage of PMI feedback is represented by 'i1', whereas the second stage is represented by 'i2'. In the case of Semi-Open Loop MIMO, the UE only reports 'i1'

★ The Base Station can use the *CSI-reportConfig* parameter structure presented in Table 293 (section 13.6) to set the *reportQuantity* to '*cri-RI-i1-CQI*'. This means that the UE reports RI, CQI and 'i1' for MIMO, in combination with the CSI Reference Signal Resource Indicator (CRI) for Beam Management

★ The precise Semi-Open Loop MIMO transmission scheme is dependent upon the Base Station implementation and is transparent to the UE, i.e. the UE does not require explicit knowledge of the precoding applied by the Base Station. Figure 207 illustrates an example of Semi-Open Loop MIMO based upon the transmission of 8 CSI Reference Signals from a grid of 2×2 cross polar antenna elements. This configuration allows the UE to select from a set of 64 beams when using the Type 1 Single Panel Codebook. If the UE is configured to use 'Codebook Mode 2' then the first stage of PMI reporting corresponds to selecting a group of 4 beams. This group is selected and reported to the Base Station as 'i1'

★ The Base Station can then apply precoding based upon 'i1'. The example illustrated in Figure 207 assumes that the Base Station applies precoding which cycles through each of the 'i2' values associated with the reported 'i1'. This corresponds to cycling through the set of 4 beams and also cycling through a set of 4 co-phasing phase shifts. Figure 207 illustrates 4 examples of the precoding but in reality there would be 16 combinations of beam and phase shift. The Base Station can cycle through the set of precoding options in the frequency domain by applying different precoding to each Precoding Resource Block Group (PRG) (PRG are described in section 3.6.5). This type of Semi-Open Loop precoder cycling can provide performance benefits when the radio environment is relatively dynamic, i.e. if the UE were to provide specific 'i2' feedback then it would become out-of-date relatively quickly. Cycling through the set of 'i2' values helps to ensure that the precoding remains valid on average

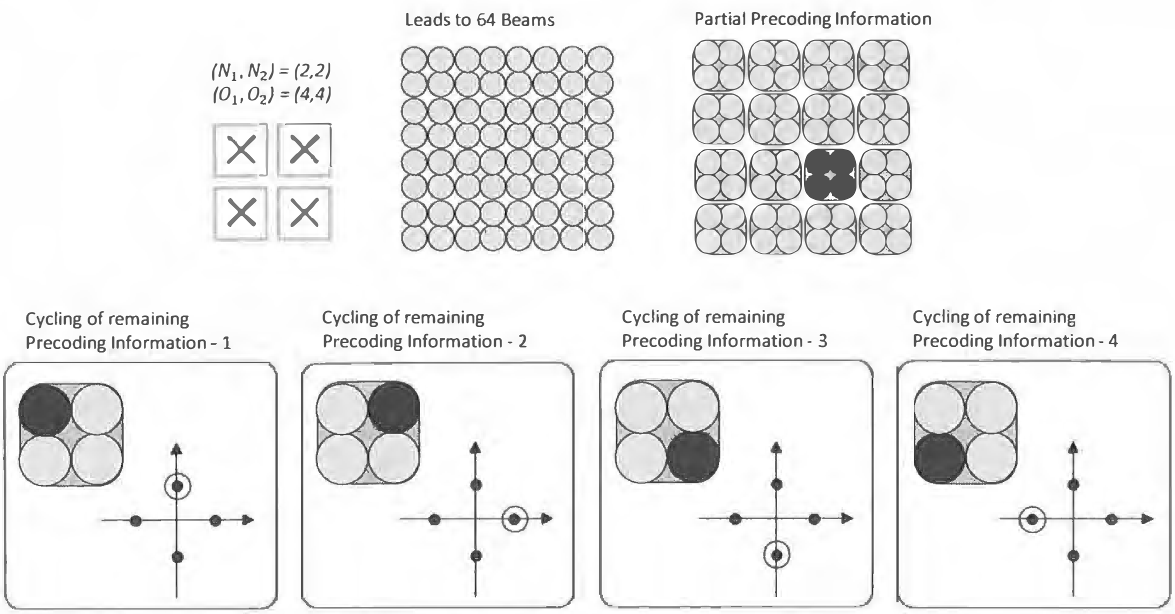


Figure 207 – Example solution for Semi-Open Loop MIMO

  - In general, reported CQI values are 'conditioned' upon the reported PMI values, i.e. the CQI value is valid when the Base Station transmits using the suggested precoding matrix. In the case of Semi-Open Loop MIMO, the UE is reporting only partial PMI so 3GPP has specified that the UE should assume a random selection of precoding matrix for the remaining PMI. 3GPP also specifies that the UE can assume that precoding is applied to Precoding Resource Block Groups (PRG) which have a size equal to *pdsch-BundleSizeForCSI* (shown in Table 293)

4.3.3 CLOSED LOOP MIMO

- Closed Loop MIMO relies upon the UE providing feedback in terms of:
  - Rank Indicator (RI) – suggested number of transmission layers
  - Channel Quality Indicator (CQI) – suggested modulation scheme and coding rate
  - Precoding Matrix Indicator (PMI) – suggested precoding
- This approach is categorised as 'Closed Loop' because the UE is required to provide feedback in terms of a Precoding Matrix Indicator (PMI). The Base Station can use the *CSI-reportConfig* parameter structure presented in Table 293 (section 13.6) to set *reportQuantity* to either '*cri-RI-PMI-CQI*' or '*cri-RI-LI-PMI-CQI*'. This means that the UE reports RI, CQI and PMI for MIMO, in combination with the CSI Reference Signal Resource Indicator (CRI) for Beam Management. The latter also instructs the UE to report the Layer Indicator (LI). The LI information can be used for mapping specific logical antenna ports onto the best transmission layer, e.g. the antenna port used by the Phase Tracking Reference Signal (PTRS)
- 3GPP has specified a set of 4 codebook categories for PMI reporting – Type 1 Single Panel and Multi-Panel codebooks for a maximum rank of 8; Type 2 Single Panel and Port Selection codebooks optimised for multi-user MIMO but which are restricted to a maximum of rank 2. Type 1 codebooks provide relatively coarse information, whereas Type 2 codebooks provide more detailed information at the cost of an increased signalling overhead. Section 13.6.3 describes the set of 4 codebook categories in greater detail
- 2×2 MIMO based upon the Type 1 Single Panel codebook is the simplest form of Closed Loop MIMO. In this case, PMI reporting involves the selection of 1 precoding matrix from a set of 4 precoding matrices when reporting rank 1, and the selection of 1 precoding matrix from a set of 2 precoding matrices when reporting rank 2. In this case, PMI reporting does not involve beam selection. The 2 sets of precoding matrices are presented in Table 299 (section 13.6.3.1), while Figure 392 and Figure 393 illustrate the precoding which is applied prior to any beamforming. Figure 169 (section 3.6.3) illustrates the application of the precoding for MIMO prior to the application of precoding for beamforming
- 2×2 MIMO is relatively straightforward because the 2 outputs from the precoding can be mapped onto the 2 antenna polarisations. This allows a polarisation beam to be generated for each output. When using higher order MIMO, it is not possible to map each precoding output onto a separate polarisation, e.g. there may be 4 outputs from the precoding but only 2 polarisations. Figure 208 illustrates two alternative solutions for transmitting the set of precoding outputs when the number of outputs is greater than 2
- The first solution is based upon the use of multiple beams with different combinations of azimuth and elevation. In this case, the UE is required to select multiple beam directions during PMI reporting rather than a single beam direction. Figure 208 assumes the use of 4×4 MIMO so it is necessary for the UE to report 2 beam directions (2 polarisation beams are associated with each beam direction so there is a total of 4 polarisation beams to transmit the set of 4 precoding outputs). The 4 transmissions are uncorrelated because they are transmitted using different combinations of polarisation, azimuth and elevation. The 2 beam directions selected by the UE will point in different directions so the connection relies upon scattering and reflections to allow the UE to receive transmissions from all beams
- The second solution is based upon the division of the antenna panel into multiple sections. Each section of the antenna panel is then able to generate its own pair of polarisation beams. Figure 208 assumes the use of 4×4 MIMO so it is necessary for the antenna panel to be divided into 2 sections (2 polarisation beams are generated by each section so there is a total of 4 polarisation beams to transmit the set of 4 precoded outputs). The 4 transmissions are uncorrelated because they are transmitted using different physical antenna elements. In the case of this second solution, each polarisation beam is generated using half the number of antenna elements. This means that the beams will be less directional and will have lower gain

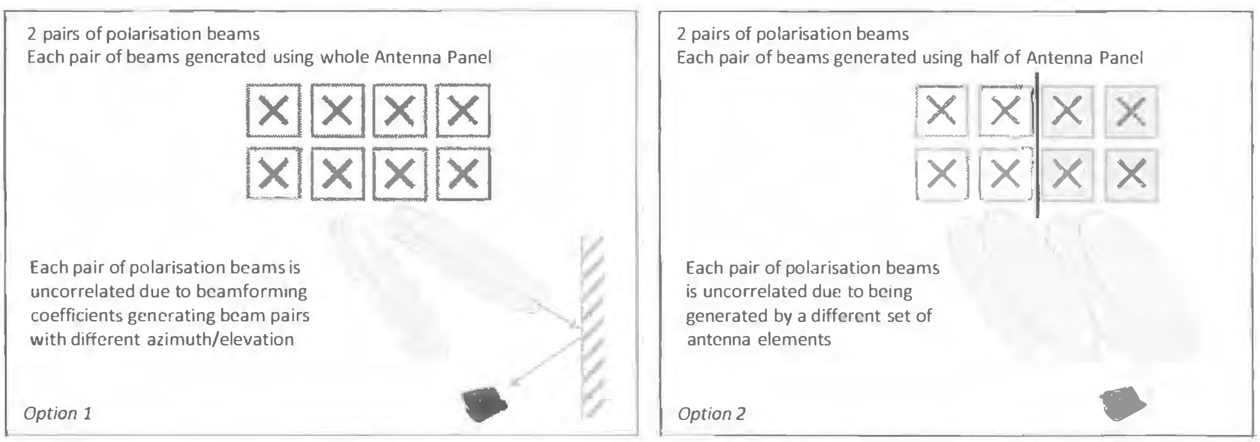


Figure 208 – Solutions for transmitting 4×4 MIMO precoder outputs

- The Type 1 Single Panel codebook supports the second solution for transmission ranks 3 and 4 when the number of CSI Reference Signals for MIMO measurements is ≥ 16. When using less than 16 CSI Reference Signals, it is assumed that the antenna panel is relatively small so it is less practical to divide the panel into two sections. When using transmission ranks greater than 4 then the second solution would require the antenna panel to be divided into 3 or more sections. This becomes less practical because each individual section would be relatively small and the associated beams would become less directional and have lower gain

★ Closed loop MIMO can also be implemented using a hybrid PMI reporting solution. The Base Station can use the *CSI-reportConfig* parameter structure presented in Table 293 (section 13.6) to set *reportQuantity* to '*cri-RI-i1*'. This means that the UE reports RI and a partial PMI for MIMO, in combination with the CRI for Beam Management. The UE is not required to report CQI at this stage. The general expectation is that this first stage relies upon CSI Reference Signal transmissions which are not beamformed. The UE measures the propagation channel for each CSI Reference Signal transmission and then identifies the PMI codebook entry which would generate a beam (or group of beams) directed towards the UE. However, it is also possible for the CSI Reference Signal transmissions to be beamformed. Beamforming is transparent to the UE, so the UE would follow the same process irrespective of any beamforming

★ The partial PMI allows the Base Station to generate a coarse beam towards the UE (or a group of beams if the partial PMI has been used to identify a group of beams). The UE can then be instructed to provide a second PMI report, for example using '*cri-RI-PMI-CQI*' with the Type 2 Port Selection codebook. This codebook assumes that beamforming has already been applied to the CSI Reference Signal transmissions. The UE then reports a refined PMI, RI and CQI based upon the beamformed CSI Reference Signal transmissions

4.3.4 MULTI-USER MIMO

★ Single User MIMO (SU-MIMO) provides dedicated Resource Block allocations to each UE, i.e. resource allocations are separated in the time and frequency domains. In contrast, Multi-User MIMO (MU-MIMO) allows Resource Blocks to be shared by a group of UE. The group of UE are carefully selected to ensure that transmissions towards those UE are separated in the spatial domain. This means that the co-scheduled UE must be distributed across the cell area. The performance of MU-MIMO is likely to be compromised if all of the UE are clustered together at one location

★ MU-MIMO is an effective solution for increasing spectral efficiency. Spectral efficiency can be doubled if the complete set of Resource Blocks is allocated to 2 UE. Similarly, spectral efficiency can be quadrupled if the complete set of Resource Blocks is allocated to 4 UE. Higher order MU-MIMO becomes more challenging because it is necessary for the Base Station to identify an increased number of UE with adequate spatial separation. Sharing Resource Blocks between UE which have inadequate spatial separation will lead to interference between the transmissions belonging to each UE

★ Massive MIMO solutions are able to generate significant performance gains from MU-MIMO because the highly directional beams are able to increase the spatial separation between UE. However, MU-MIMO is not restricted to massive MIMO and can also be supported using smaller antenna systems, e.g. an 8Tx8Rx solution based upon a combination of Remote Radio Heads (RRH) and a passive antenna. Smaller antenna systems will generate wider beams which will be less capable of providing spatial separation between UE

★ MU-MIMO is typically associated with lower order MIMO, e.g. 2×2 MIMO. It is challenging to support both MU-MIMO and higher order MIMO simultaneously because it becomes difficult to identify sufficient uncorrelated propagation paths towards each UE within the group of co-scheduled UE

★ MU-MIMO is applicable to both the uplink and downlink so the spectral efficiency can be improved in both directions. The Base Station is able to generate directional receive beams, similar to generating directional transmit beams. These directional receive beams help to achieve spatial separation in the uplink direction

★ Digital beamforming is able to support MU-MIMO, whereas analogue beamforming is not able to support MU-MIMO. Figure 209 illustrates the use of digital beamforming for MU-MIMO. The Resource Blocks allocated to each UE are precoded separately for both MIMO and beamforming. This allows separate beams to be generated for each UE. The outputs are then summed before digital to analogue conversion

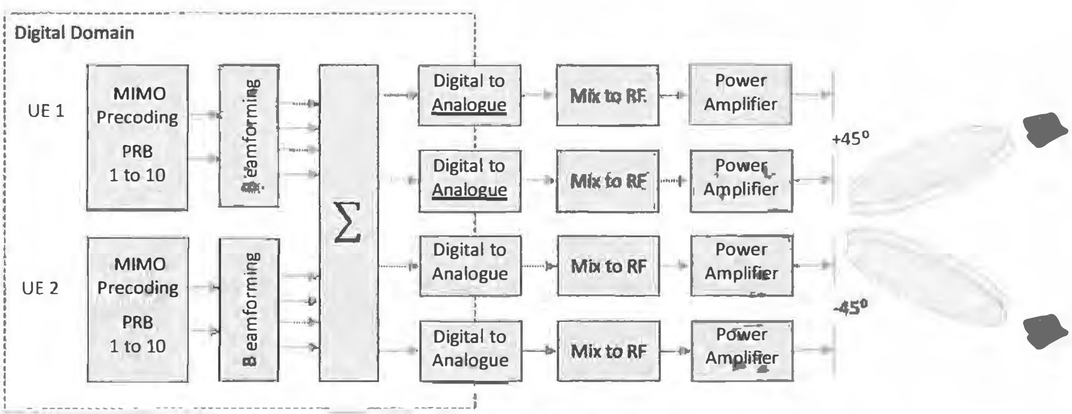


Figure 209 – Multi-User MIMO with digital beamforming

★ Figure 210 illustrates an equivalent diagram for Single User MIMO with analogue beamforming. In this case, the beamforming is completed after the RF signal has been generated. It is not possible to apply UE specific beamforming because the transmissions towards each individual UE cannot be separated once the RF signal has been generated

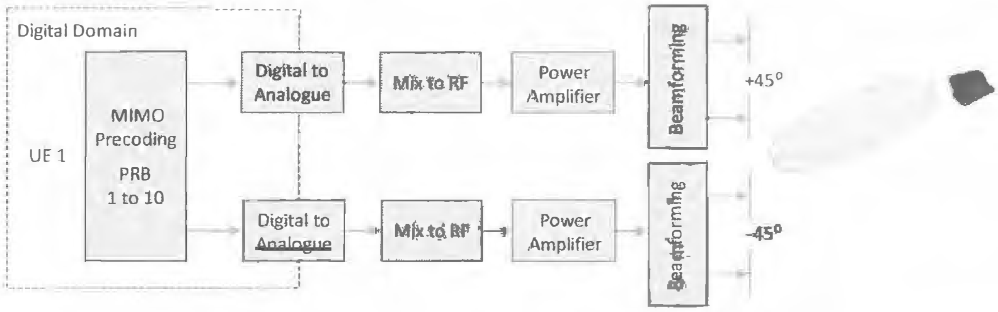


Figure 210 – Single User MIMO with analogue beamforming

★ The Base Station is responsible for allocating different PDSCH Demodulation Reference Signals (DMRS) to co-scheduled UE. The DMRS is described in section 3.7.3:

  - Configuration Type 1 supports up to 4 antenna ports when using single symbol transmission, and up to 8 antenna ports when using double symbol transmission. 2 Code Division Multiplexing (CDM) groups are available to allow the re-use of DMRS Resource Elements across antenna ports

  - Configuration Type 2 supports up to 6 antenna ports when using single symbol transmission, and up to 12 antenna ports when using double symbol transmission. 3 CDM groups are available to allow the re-use of DMRS Resource Elements across antenna ports

★ Each UE which is allocated rank 2 transmission requires 2 DMRS antenna ports. This means that Configuration Type 1 can support up to 4 co-scheduled UE with rank 2 without having to re-use DMRS antenna ports. Similarly, Configuration Type 2 can support up to 6 co-scheduled UE with rank 2 without having to re-use DMRS antenna ports. It is possible for the DMRS ports to be re-used if the co-scheduled UE have high spatial isolation

★ Downlink Control Information (DCI) Format 1_1 can be used to allocate specific DMRS antenna ports to the UE. The '*Antenna Ports*' field shown in Table 80 (section 3.5.7) specifies the allocated antenna ports and also indicates whether or not the PDSCH can be frequency multiplexed with the DMRS. In the case of Single User MIMO, the DMRS can be frequency multiplexed with the DMRS because the Resource Elements between the DMRS are not used by other UE. In the case of MU-MIMO, the UE can be informed that the Resource Elements between the DMRS are not used by the PDSCH because they are potentially used by the DMRS belonging to other co-scheduled UE

★ Other than the information regarding the frequency multiplexing of the PDSCH and DMRS, a UE does not have any knowledge regarding the presence of co-scheduled UE. In the case of MU-MIMO, beamforming can be used for both beam steering and null steering, i.e. the beam is directed towards the UE, while nulls are directed towards other co-scheduled UE. The null steering helps to minimise interference (cross-talk) between co-scheduled UE

★ The performance of MU-MIMO is sensitive to the quality of the Channel State Information (CSI) reported by the UE. The Type 2 PMI codebooks described in section 13.6.3 have been designed to provide the increased accuracy required for MU-MIMO. These codebooks support a maximum transmission rank of 2 which is aligned with the normal requirement for MU-MIMO

4.3.5 RECIPROCITY BASED

★ Reciprocity based transmission schemes rely upon uplink propagation channel measurements to determine the downlink precoding. The Base Station can measure the propagation channel from uplink Sounding Reference Signal (SRS) transmissions. This approach is capable of generating results with a high frequency domain resolution. When using Closed Loop MIMO, the UE provides sub-band PMI reports but the frequency domain resolution is restricted by the signalling overhead generating by those reports. 3GPP has specified sub-band sizes which increase as a function of the Bandwidth Part size. When using a Reciprocity based transmission scheme, the Base Station has the freedom to determine an appropriate frequency domain resolution

★ The Base Station can use the *CSI-reportConfig* parameter structure to set *reportQuantity* to '*cri-RI-CQI*'. This means that the UE reports RI and CQI for MIMO, in combination with the CSI Reference Signal Resource Indicator (CRI) for Beam Management. It remains necessary for the UE to report CQI because the Base Station does not have visibility of the downlink interference conditions, i.e. SRS measurements do not quantify the downlink signal to noise ratio.

4.3.6 MULTIPLE TRP

★ UE receiving downlink data at cell edge are vulnerable to inter-cell interference originating from neighbouring cells. Solutions based upon Coordinated Scheduling can help to reduce co-channel interference by ensuring that neighbouring cells allocate different sets of Resource Blocks whenever possible. This type of solution can improve performance when the cell load is low to moderate, but is less likely to improve performance when the cell load is high and all cells need to use all Resource Blocks. Solutions based upon Coordinated Beamforming can help to reduce co-channel interference by ensuring that neighbouring cells do not simultaneously use beams which are directed towards each other. This can help to maximise the system level benefit of the directional beams. However, it may compromise the flexibility of the Packet Scheduler and is likely to be more challenging when using Multi-User MIMO which requires each cell to simultaneously transmit multiple beams in different directions

★ Transmission schemes based upon multiple Transmit and Receive Points (TRP) represent another solution for improving cell edge performance. These transmission schemes are introduced within this section but they have not been standardised within the release 15 version of the 3GPP specifications. The release 15 version of the specifications provides support for solutions which are transparent to the UE (and the specifications) but other solutions are planned for subsequent releases. Figure 211 illustrates 3 categories of multiple TRP solution

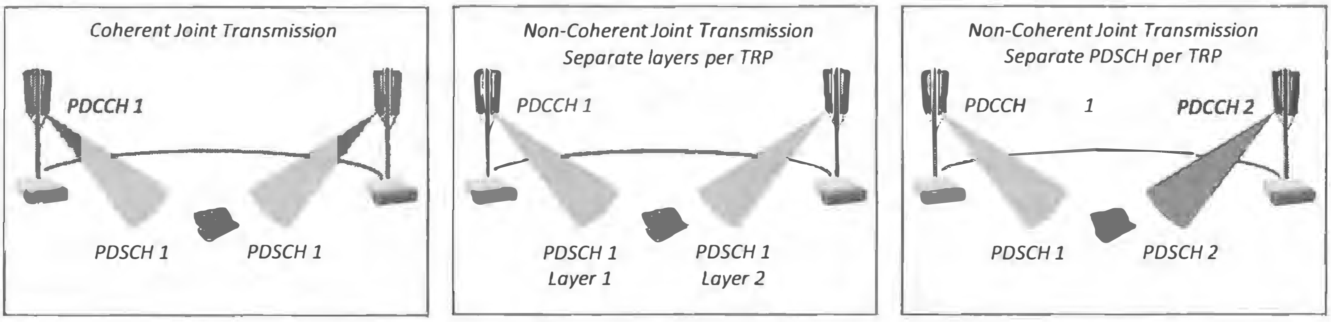


Figure 211 – Transmission schemes using multiple TRP

★ Coherent Joint Transmission uses a single PDCCH to allocate a single set of PDSCH resources. This is followed by multiple TRP simultaneously transmitting the same PDSCH. From the UE perspective, the additional downlink transmissions appear similar to additional downlink delay spread components originating from a single TRP. However, there may be differences in frequency offset due to each TRP using independent local oscillators, and differences in the UE mobility relative to each TRP, e.g. the UE could be moving away from one TRP and towards the other TRP, thus experiencing a negative Doppler offset from one TRP and a positive Doppler offset towards the other TRP. Both TRP transmit the same DMRS so the UE is able to estimate the composite propagation channel. The primary challenges associated with Coherent Joint Transmission are the requirement for an almost ideal transport connection and the requirement for stringent synchronisation. Coherent Joint Transmission also requires accurate Channel State Information (CSI) to ensure that the downlink transmissions sum constructively at the UE. Coherent Joint Transmission is transparent to the UE and the 3GPP specifications but is generally viewed as being less practical due to the stringent transport and synchronisation requirements

★ Non-Coherent Joint Transmission can be based upon a solution which involves each TRP transmitting different layers belonging to the same PDSCH resource allocation. A single PDCCH can be used to allocate a single set of PDSCH resources. It is assumed that the UE is allocated more than a single layer and that the layers are divided across the TRP. For example, a first TRP can transmit layer 1 while a second TRP can transmit layer 2. It is not necessary for the UE to coherently combine the 2 layers because separate layers are intended to have uncorrelated propagation paths and are decoded separately. This type of solution can increase the transmission rank available to the UE. For example, a UE may have line-of-sight to the first TRP and thus be restricted to rank 1 transmission. Use of the second TRP provides an additional and uncorrelated propagation path which can be used to increase the allocated rank and thus, increase the connection throughput. The release 15 version of the 3GPP specifications uses DCI Format 1_1 to allocate PDSCH resources with multiple layers. A single Modulation and Coding Scheme (MCS) value is assigned for all layers when allocating up to 4 layers. This single MCS may not be optimal for both TRP because the path loss and propagation channels from each TRP are likely to be different

★ Non-Coherent Joint Transmission can be based upon a solution which involves each TRP transmitting its own PDCCH. This allows each TRP to generate its own resource allocations and to operate relatively independently. The use of separate PDCCH transmissions allows separate MCS to be allocated by each TRP. Similar to the previous solution, the use of multiple TRP allows the total transmission rank and the corresponding connection throughput to be increased. It may be necessary to have some level of co-ordination to avoid the separate resource allocations exceeding the UE capability. For example, if a UE supports a maximum transmission rank of 4 then the set of TRP should ensure that the total number of allocated layers summed across all TRP does not exceed 4

5 FLOW OF DOWNLINK DATA

★ Figure 212 illustrates the user plane protocol stack for a standalone Base Station. The figure assumes that the base station uses the Centralised Unit (CU) - Distributed Unit (DU) higher layer split architecture, i.e. the DU hosts the RLC, MAC and Physical layers, while the CU hosts the SDAP and PDCP layers

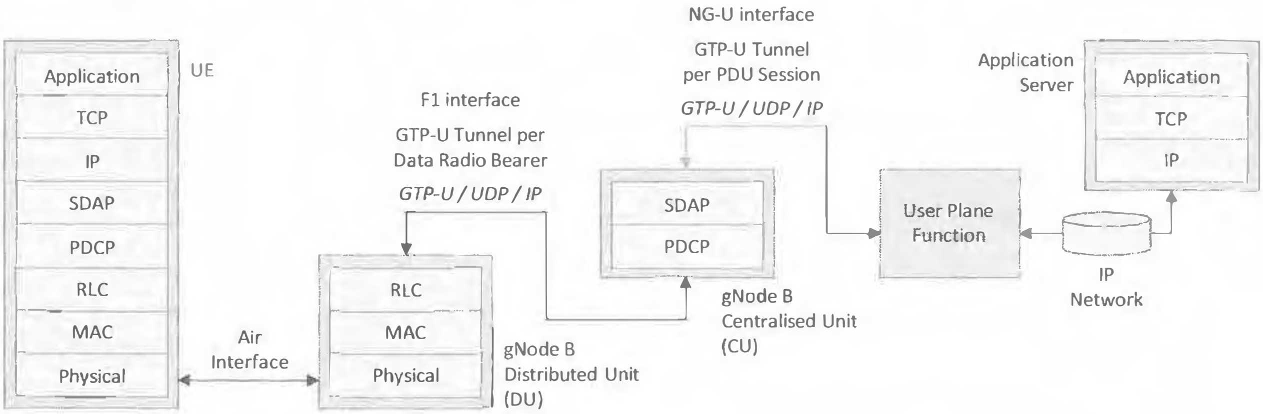


Figure 212 – User Plane protocol stack for Standalone Base Station

★ Consider the example of an end-user browsing the internet and downloading a web page. Internet browsers use the HyperText Transfer Protocol (HTTP) at the Application layer. Assume that the end-user has just sent an HTTP GET command to the server hosting the web page to be downloaded. The application server will proceed to start downloading the web page towards the end-user using Transmission Control Protocol (TCP) / Internet Protocol (IP) packets

★ Figure 213 illustrates the header added by the TCP layer. The standard header size is 20 bytes although it can be larger when optional header fields are included. The TCP header specifies both the Source and Destination Ports to identify the higher layer application. By default, HTTP uses port number 80. The header also includes a Sequence Number to allow re-ordering and packet loss detection at the receiver. The Acknowledgement Number provides a mechanism to acknowledge packets, while the Data Offset defines the size of the header. The Window Size specifies the number of bytes which the sender is willing to receive. The Checksum allows bit error detection across both the header and payload. The Urgent Pointer can be used to indicate that some data needs to be handled with a high priority

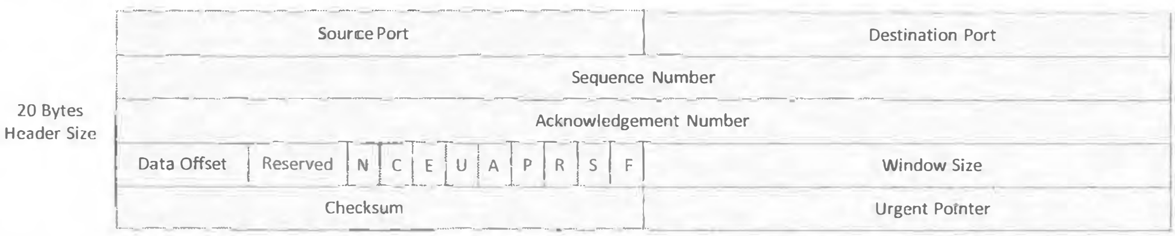


Figure 213 – TCP Header (20 bytes)

★ Figure 214 illustrates the header added by the IP layer (assuming IPv4). The standard header size is 20 bytes although it can be larger when optional header fields are included. The IP header specifies both the Source and Destination IP Addresses. Routers use the Destination IP address to forward packets in an appropriate direction. The Version header field has a value of 4 when using IPv4. The Header (HDR) Length field specifies the size of the header, while the Total Length field specifies the size of the packet. The Differentiated Services Code Point (DSCP) can be used to prioritise the packet, whereas the Explicit Congestion Notification (ECN) can be used to indicate network congestion. The Protocol field specifies the type of content within the payload of the packet. TCP is identified using a protocol number of 6

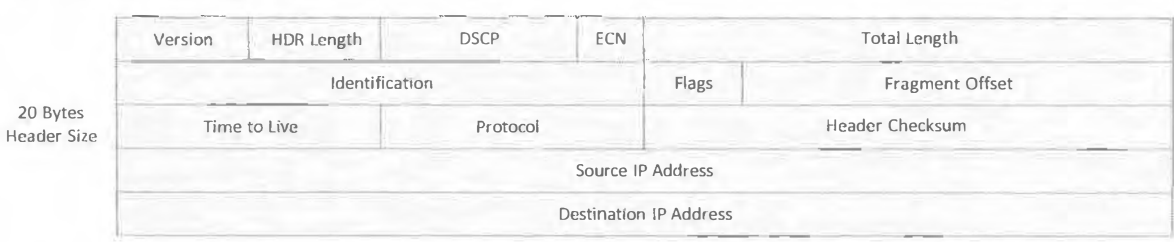


Figure 214 – IP Header (20 bytes)

- ★ Once the IP header has been added, the packet is routed across the IP network towards the User Plane Function (UPF) which provides the point of entry into the 5G Core Network. The IP network relies upon its lower layers to transport packets between routers. For example, Ethernet could be used as a layer 2 protocol to transfer IP packets between routers
- ★ The UPF is responsible for mapping the TCP/IP packet onto a specific QoS Flow belonging to a specific PDU Session. The UPF uses packet inspection to extract various header fields. These header fields are compared against the set of Service Data Flow (SDF) Templates to identify the appropriate PDU Session and QoS Flow. For example, packets can be mapped onto a specific PDU Session and QoS Flow using a unique combination of {source IP address 'X'; destination IP address 'Y'; source port number 'J'; destination port number 'K'}. The UPF receives the set of SDF Templates from the Session Management Function (SMF) during the setup of the PDU Session
- ★ After identifying the appropriate PDU Session and QoS Flow, the UPF uses a GTP-U tunnel to forward the data towards the gNode B (the 5G Core Network architecture may chain multiple UPFs so the first UPF may have to use a GTP-U tunnel to forward the data towards another UPF before it is forwarded towards the gNode B). A GTP-U tunnel is setup for each PDU Session. This means that the Tunnel Endpoint Identifier (TEID) within the GTP-U header identifies the PDU Session but does not identify the QoS Flow. A 'PDU Session Container' is added to the GTP-U header to provide information which identifies the QoS Flow. Figure 215 illustrates the structure of a GTP-U header which includes the 'PDU Session Container'. The structure of the GTP-U header is specified within 3GPP TS 29.281, whereas the content of the 'PDU Session Container' is specified within 3GPP TS 38.415

20 Bytes Header Size

Version	PT	0	E	S	PN	Message Type	Length
Tunnel Endpoint Identifier (TEID)							
Sequence Number						N-PDU Number	Next Extension Header Type
Extension Header Length						**PDU Session Container**	
PDU Session Container							Next Extension Header Type

Figure 215 – GTP-U Header with PDU Session Container

- ★ The content of the 'PDU Session Container' is presented in Figure 216. The 'PDU Type' value of '0' indicates that the PDU is a downlink packet rather than an uplink packet. The Paging Policy Presence (PPP) field indicates whether or not a Paging Policy Indicator (PPI) is included within the header. The UPF can provide a PPI to the gNode B to influence the priority of the paging procedure which may be triggered by the arrival of the downlink packet, i.e. when the UE is RRC Inactive. The Reflective QoS Indicator (RQI) specifies whether or not Reflective QoS should be applied for this QoS Flow

PDU Type = 0		Spare
PPP	RQI	QoS Flow Identifier
PPI		Spare

Figure 216 – PDU Session Container included within GTP-U header

- ★ A GTP-U tunnel uses a UDP/IP protocol stack so UDP and IP headers are added before forwarding the packet across the transport network. UDP provides simple connectionless data transfer. Figure 217 illustrates the structure of a UDP header. The Source and Destination Ports identify the higher layer application. In this case, the higher layer application is GTP-U which has a registered port number of 2152

8 Bytes Header Size

Source Port	Destination Port
Length	Checksum

Figure 217 – UDP Header (8 bytes)

- ★ The addition of an IP header for routing across the GTP-U tunnel means that the data packet now has two IP headers. These are commonly referred to as inner and outer IP headers. Both headers are illustrated in Figure 218. The UPF can prioritise packets using the DSCP field within the outer IP header. The headers associated with the GTP-U tunnel are removed at the far end of the tunnel, i.e. at the gNode B, or at another UPF if the Core Network architecture uses chained UPFs

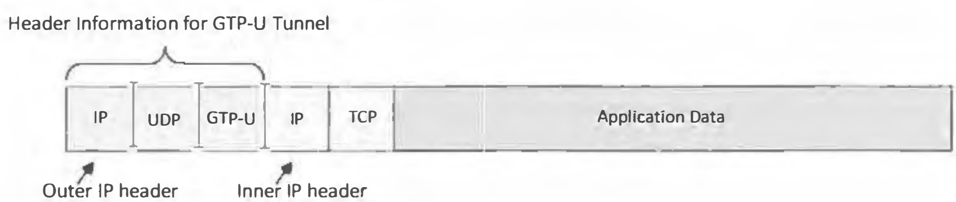


Figure 218 – Headers for data transfer across GTP-U tunnel

★ The gNode B Centralised Unit (CU) uses the GTP-U header information to identify the PDU Session and QoS Flow associated with the data packet. The packet is then processed by the Service Data Adaptation Protocol (SDAP) layer which is responsible for mapping the packet onto a specific Data Radio Bearer (DRB). This mapping is illustrated in Figure 219. The SDAP layer can be configured to transfer data without the addition of an SDAP header. Alternatively, the SDAP layer can add a header to allow the use of Reflective QoS. In this case, the SDAP header specifies the QoS Flow associated with the packet. The UE can use this information to deduce the mapping between QoS Flow and DRB for its uplink transmissions. The SDAP layer is specified in 3GPP TS 37.324 and is described in greater detail in section 5.1. The SDAP layer passes the packet to the PDCP layer using its allocated DRB

★ The PDCP layer provides security in terms integrity protection and ciphering. Integrity protection is provided by calculating an authentication code which is appended to the packet as header information (MAC-I field). This authentication code is used by the receiver to verify that the packet is genuine, and has not been inserted by an intruder. Ciphering is applied to the payload of each PDCP packet after the authentication code has been calculated. Ciphering scrambles the sequence of bits to make the packet unreadable unless the receiver knows the ciphering key to reverse the scrambling. The PDCP layer also adds header information which includes the PDCP sequence number. This sequence number is used for re-ordering at the receiver. In some cases, the PDCP layer can provide header compression. This depends upon the end-user application and is typically applied to speech packets rather than data packets

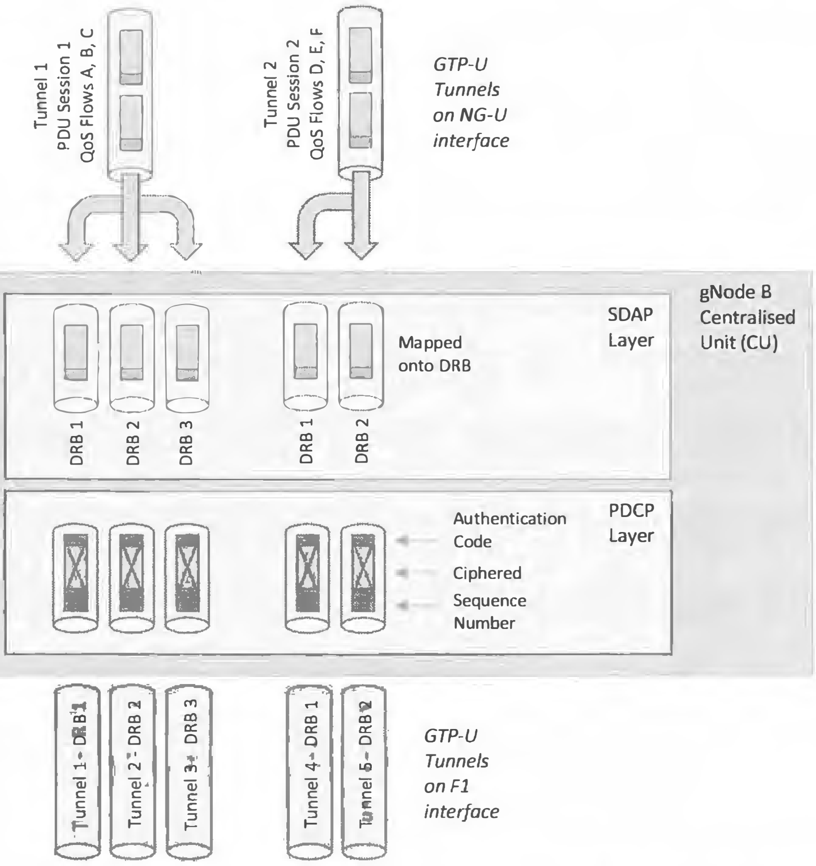


Figure 219 – SDAP and PDCP processing within the gNode B Centralised Unit (CU)

★ The gNode B Centralised Unit forwards the PDCP PDU to the appropriate gNode B Distributed Unit. This involves transferring the packets across the F1 interface using GTP-U tunnels. At this stage, packets are mapped onto their Data Radio Bearer (DRB) so GTP-U tunnels are setup 'per DRB' rather than 'per PDU Session' The GTP-U header is modified to accommodate the 'NR RAN Container', rather than the 'PDU Session Container' used for the NG-U interface. The GTP-U header used for the F1 interface is illustrated in Figure 220. The 'NR RAN Container' accommodates the header information generated by the New Radio User Plane Protocol specified in 3GPP TS 38.425

20 Bytes Header Size	Version	PT	0	E	S	PN	Message Type	Length	
	Tunnel Endpoint Identifier (TEID)								
	Sequence Number							N-PDU Number	Next Extension Header Type
	Extension Header Length						NR RAN Container		
	NR RAN Container								Next Extension Header Type

Figure 220 – GTP-U Header with NR RAN Container

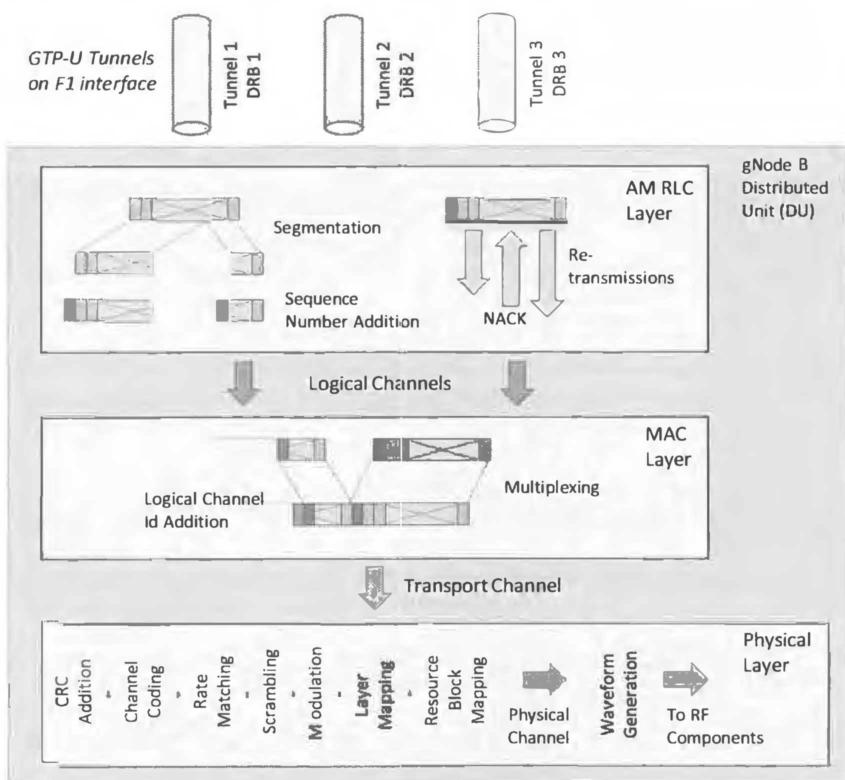
- ★ Packets received by the gNode B Distributed Unit are processed by the RLC layer after removing the GTP-U/UDP/IP header information, i.e. after removing the headers belonging to the GTP-U tunnel. The RLC layer can be configured to operate using either Transparent Mode (TM), Unacknowledged Mode (UM) or Acknowledged Mode (AM). Transparent Mode is only applicable to control channels so it cannot be used for downloading a web page. Unacknowledged Mode is typically used for time sensitive applications, e.g. voice and video. Acknowledged Mode is typically used for non-time sensitive applications, e.g. web browsing, file transfer, instant messenger applications. Acknowledged mode is assumed for this example web page download

- ★ The RLC layer is responsible for segmentation and potentially re-segmentation. RLC SDU belonging to data applications may be too large to transfer across the air-interface using a single resource allocation. The RLC layer segments packets when necessary to allow them to be accommodated by the allocated air-interface resources. The packet scheduler within the gNode B Distributed Unit informs the RLC layer of the appropriate packet size, i.e. the allocated transport block size which must also accommodate the RLC and MAC headers. Re-segmentation is applicable to Acknowledged Mode RLC when the resource allocation for a re-transmission is reduced relative to the original transmission, i.e. the packet has to be segmented again to be accommodated by the new resource allocation. The receiving RLC entity is responsible for re-assembling the higher layer packets

- ★ The RLC layer provides a reliable data transfer service when using Acknowledged Mode. This is achieved by supporting Automatic Repeat reQuest (ARQ) re-transmissions. RLC re-transmissions are relatively slow compared to MAC re-transmissions. They are only triggered if MAC re-transmissions are unable to successfully deliver a packet. ARQ refers to a re-transmission protocol in which the receiver checks for errors within the received data and if an error is detected than the receiver discards the data and requests a re-transmission from the sender

- ★ The size of the RLC header is dependent upon the configured Sequence Number (SN) size. 12 bit or 18 bit Sequence Number sizes can be configured. The larger size generates a larger overhead but may be required to support higher throughput services, i.e. to avoid the Sequence Number range becoming exhausted. The Sequence Number is used for packet loss detection at the receiver and also for packet re-assembly if segmentation has been applied. The RLC header can also include a Segmentation Offset (SO) field to support segmentation and re-assembly

- ★ The RLC PDU belonging to the allocated DRB is mapped onto a logical channel and is then transferred to the MAC layer. In the case of application data, the Dedicated Traffic Channel (DTCH) is selected as the logical channel. The RLC PDU then becomes the MAC SDU



- The MAC layer is responsible for prioritising the set of logical channels. For example, if the gNode B Distributed Unit has downlink data to transmit for both the Dedicated Control Channel (DCCH) and the DTCH, then it will prioritise the DCCH. The quantity of resources allocated by the Packet Scheduler may be greater than the resources required by the DCCH logical channel. The MAC layer can then multiplex MAC SDU belonging to different logical channels, e.g. MAC SDU belonging to both the DCCH and DTCH can be multiplexed within a single MAC PDU. If the end-user application generates relatively small MAC SDU then the MAC layer can multiplex MAC SDU belonging to a single logical channel

- The MAC layer provides a reliable data transfer service by supporting Hybrid Automatic Repeat reQuest (HARQ) re-transmissions. HARQ re-transmissions at the MAC layer are relatively fast compared to ARQ re-transmissions at the RLC layer. HARQ re-transmissions can be used for both real time and non-real time applications. HARQ refers to a re-transmission protocol in which the receiver checks for errors in the received data and if an error is detected then the receiver buffers the data and requests a re-transmission from the sender. A HARQ receiver is then able to combine the buffered data with the re-transmitted data prior to channel decoding and error detection. This improves the performance of the re-transmissions

- The MAC layer can include one or more Control Elements (CE) within the MAC PDU. Control Elements can be used as a solution for rapid signalling, i.e. sending control information from the MAC layer is faster than sending control information from the RRC layer. Examples of downlink CE include: Timing Advance Command CE, DRX Command CE and Secondary Cell Activation CE

- The MAC layer includes a subheader for each MAC SDU which is multiplexed within the MAC PDU. The subheader identifies the logical channel (Logical Channel Identity (LCID) field) and quantifies the number of bytes within the MAC SDU (Length (L) field)

- The MAC PDU is mapped onto a transport channel which is then transferred to the Physical layer. In the case of downlink application data, the Downlink Shared Channel (DL-SCH) is selected as the transport channel. The MAC PDU then becomes a transport block which will be processed by the Physical layer before transmission across the air-interface

- 3GPP References: TS 38.300, TS 29.281, TS 38.415, TS 38.425, TS 37.324, TS 38.323, TS 38.322, TS 38.321

5.1 SDAP LAYER

★ The 'Service Data Adaptation Protocol' (SDAP) layer is required when a Base Station is connected to the 5G core network. It is only applicable to the user plane, and is the highest layer within the Radio Access Network protocol stack. The SDAP layer receives downlink data from the User Plane Function (UPF) across the NG-U interface

★ Downlink user plane data is linked to a specific QoS Flow belonging to a specific PDU Session. The QoS Flow is identified using an identity within the 'PDU Session Container' which is included within the GTP-U header. The PDU Session is identified using the GTP-U Tunnel Endpoint Identifier (TEID)

★ The primary task of the SDAP layer is to map each QoS Flow onto a specific Data Radio Bearer (DRB). This mapping is illustrated in Figure 221. Multiple QoS Flows can be mapped onto a single DRB, or a single QoS Flow can be mapped onto a single DRB. QoS Flows belonging to different PDU Sessions are mapped onto different DRB

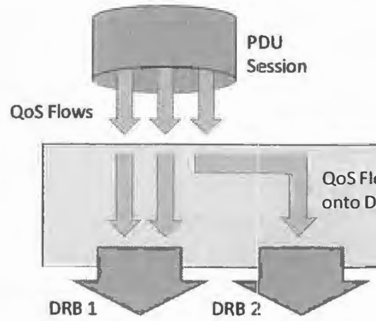


Figure 221 – SDAP layer mapping QoS Flows onto DRB

★ The SDAP layer adds header information to the downlink data packets when reflective QoS is enabled at either the Access Stratum or Non-Access Stratum layers. Reflective QoS at the Access Stratum refers to the mapping between QoS Flows and DRB, whereas Reflective QoS at the Non-Access Stratum layers refers to the mapping between QoS Flows and the higher layer IP traffic or Ethernet traffic. Reflective QoS allows the UE to deduce the uplink mapping rules from the downlink mappings, i.e. the uplink rules are copied from the downlink. Downlink data packets can be sent without a header when reflective QoS is not used. Figure 222 illustrates downlink data PDU with and without header information

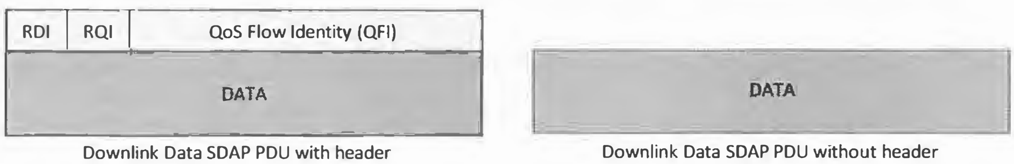


Figure 222 – Format of SDAP SDU (without and with header information)

★ The header information has a size of 1 byte. The 'Reflective QoS Flow to DRB Mapping Indication' (RDI) instructs the UE to apply Reflective QoS at the Access Stratum, whereas the 'Reflective QoS Indication' (RQI) instructs the UE to apply Reflective QoS at the Non-Access Stratum layer. In both cases, the QoS Flow Identity (QFI) is required to deduce the mapping

★ The SDAP layer is configured individually for each DRB within the *DRB-ToAddMod* parameter structure. The SDAP-Config belonging to this parameter structure is presented in Table 134. The DRB is linked to a specific PDU Session and the UE is informed whether or not SDAP headers are to be included in the uplink and downlink directions. There is also a flag to indicate whether or not the DRB is to be used as a 'Default DRB' for the PDU Session. Only a single DRB can be configured as the 'Default DRB' for each PDU Session. A PDU is mapped onto the 'Default DRB' if there is no rule to map the packet onto a specific DRB. An uplink SDAP header is always included when mapping a PDU onto the 'Default DRB'

SDAP-Config			
pdu-Session	0 to 255		
sdap-HeaderDL	present, absent		
sdap-HeaderUL	present, absent		
defaultDRB	BOOLEAN		
mappedQoS-FlowsToAdd	{1 to 64 instances} of QFI	QFI	0 to 63
mappedQoS-FlowsToRelease	{1 to 64 instances} of QFI	QFI	0 to 63

Table 134 – Content of *SDAP-Config* for a specific DRB

★ 3GPP References: TS 37.324, TS 23.501, TS 38.300

5.2 PDCP LAYER

★ The 'Packet Data Convergence Protocol' (PDCP) layer receives user plane packets belonging to Data Radio Bearers (DRB) from the SDAP layer, and control plane packets belonging to specific Signalling Radio Bearers (SRB) from the RRC layer. Examples of these SRB and DRB are illustrated in Figure 223. The PDCP layer serves DRB which are mapped onto the Dedicated Traffic Channel (DTCH) and SRB which are mapped onto the Dedicated Control Channel (DCCH), i.e. SRB 1 and SRB 2. The PDCP layer does not serve SRB which are mapped onto the Common Control Channel (CCCH), i.e. SRB 0. Messages belonging to SRB 0 are passed directly to the RLC layer

★ The PDCP layer supports a maximum SDU size of 9000 bytes. This allows the transfer of Ethernet Jumbo frames which have a maximum size of 9000 bytes and are typically used on networks supporting at least 1 Gbps (standard Ethernet frames have a maximum size of 1522 bytes)

★ Each Radio Bearer is allocated a single PDCP Entity which is responsible for processing both the uplink and downlink data. PDCP entities are linked to RLC entities. A single PDCP entity is linked to a single RLC entity when using Acknowledged Mode (AM) RLC. A single PDCP entity is linked to a pair of RLC entities when using Unacknowledged Mode (UM) RLC

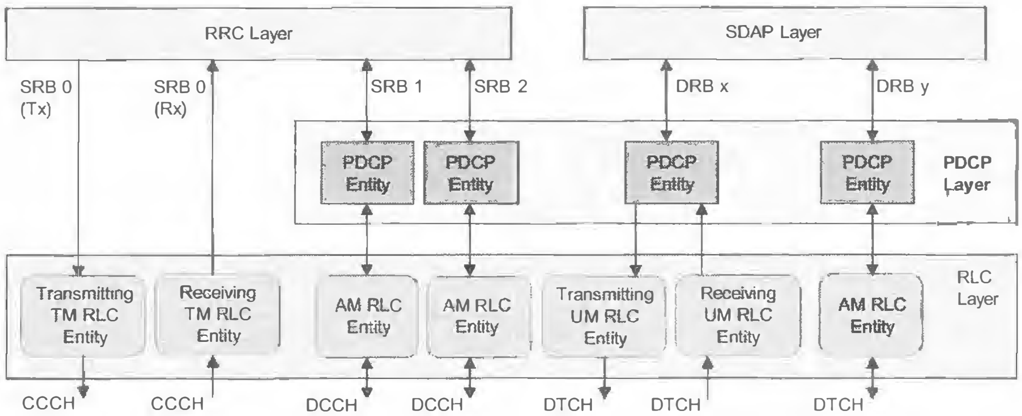


Figure 223 – PDCP layer serving DRB, SRB 1 and SRB 2

★ The main tasks associated with the PDCP layer are illustrated in Figure 224. Higher layer packets are buffered within a transmission buffer until either a status report is received indicating successful reception, or the *discardTimer* expires. The *discardTimer* (presented in Table 135) represents the maximum time permitted by the Radio Access Network to successfully deliver a packet

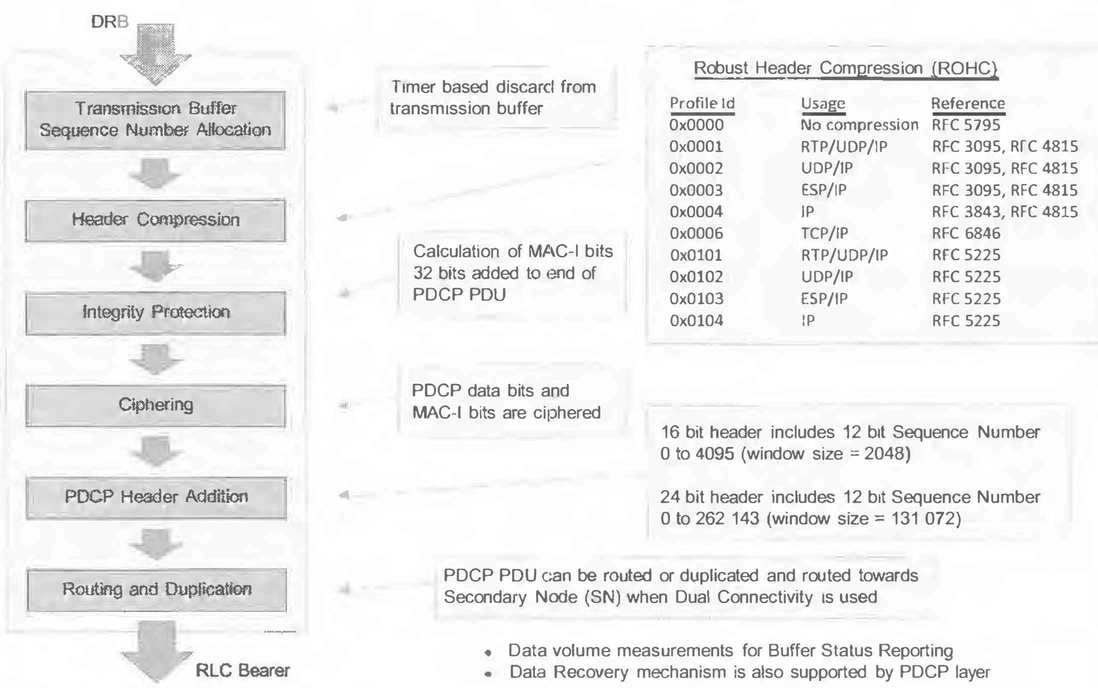


Figure 224 – Processing applied by PDCP layer

★ Header Compression can be enabled for DRB in both the uplink and downlink directions, or only in the uplink direction. This choice of configurations is visible within Table 135. If Header Compression is enabled only in the uplink direction, the compression algorithm is restricted to the TCP/IP protocol stack. Otherwise, the Header Compression algorithm can target a relatively broad range of protocol stacks including TCP/IP, UDP/IP and RTP/UDP/IP. Header Compression is completed using the Robust Header Compression (RoHC) protocol. Header Compression is important because the overheads generated by the higher layers can become large and without compression they would consume valuable air-interface resources. Header Compression is less important across the fixed network because bandwidths are significantly greater

★ The receiver uses Integrity Protection to ensure that packets are authentic and have not been inserted by a rogue source. In general, packets belonging to SRB 1 and SRB 2 always have Integrity Protection applied (an exception is permitted for emergency calls in Limited Service Mode). Integrity Protection can be enabled or disabled for a DRB using the flag shown in Table 135. The PDCP layer adds a set of 32 MAC-I bits to the end of the packet when using Integrity Protection

★ Ciphering is used to scramble the bits belonging to the payload of the PDCP packet and the MAC-I bits added by Integrity Protection. However, ciphering is not applied to the SDAP header (when included), nor is it applied to SDAP Control PDU nor PDCP Control PDU. Ciphering is used to improve security by helping to ensure that only the intended recipient is able to interpret the data. The *cipheringDisabled* flag allows ciphering to be disabled for a specific DRB

★ The PDCP layer is responsible for routing packets towards the appropriate RLC entities. In the case of Dual Connectivity, these RLC entities may belong to a different Base Station. For example, when using the EN-DC Non-Standalone Base Station architecture, the PDCP layer within the 5G Base Station may route packets across the X2 interface towards RLC entities within the 4G Base Station

★ The PDCP layer can also be configured to generate duplicate packets. These duplicate packets can be routed to different RLC entities for separate parallel transmission, e.g. across both the 4G and 5G air-interfaces when using the EN-DC Non-Standalone Base Station architecture. Packet duplication generates an overhead but increases reliability. The receiver discards duplicate packets if both transmissions are received successfully

★ Table 135 presents the *PDCP-Config* parameter set which is provided to the UE when configuring either an SRB or DRB, i.e. it is provided within either the *SRB-To-AddMod* or *DRB-ToAddMod* parameter structures

★ If the UE is configured with more than a single uplink RLC entity, the UE can be provided with an *ul-DataSplitThreshold*. A default value of 'infinity' is assumed if the *ul-DataSplitThreshold* is excluded. The value of 'infinity' means that only the primary RLC entity is used for transmission and so uplink transmission is not split. The primary RLC entity is identified by the *primaryPath* information element. Otherwise, the UE is permitted to split the stream of uplink packets between the primary and secondary RLC entities when the total PDCP and RLC data volume pending initial transmission exceeds the value of *ul-DataSplitThreshold*

<table>
<tr><th colspan="7">PDCP-Config</th></tr>
<tr><td rowspan="11">drb</td><td>discardTimer</td><td colspan="5">10, 20, 30, 40,50, 60, 75, 100, 150, 200, 250, 300, 500, 750, 1500 ms, infinity</td></tr>
<tr><td>pdcp-SN-SizeUL</td><td colspan="5">12, 18 bits</td></tr>
<tr><td>pdcp-SN-SizeDL</td><td colspan="5">12, 18 bits</td></tr>
<tr><td rowspan="5">headerCompression</td><td colspan="5">CHOICE</td></tr>
<tr><td rowspan="4">notUsed</td><td colspan="2">rohc</td><td colspan="2">uplinkOnlyROHC</td></tr>
<tr><td>maxCID</td><td>1 to 16383</td><td>maxCID</td><td>1 to 16383</td></tr>
<tr><td>profiles</td><td>1, 2, 3, 4, 6, 101, 102, 103, 104</td><td>profiles</td><td>6</td></tr>
<tr><td>drb-ContinueROHC</td><td>true</td><td>drb-ContinueROHC</td><td>true</td></tr>
<tr><td>integrityProtection</td><td colspan="5">enabled</td></tr>
<tr><td>statusReportRequired</td><td colspan="5">true</td></tr>
<tr><td>outOfOrderDelivery</td><td colspan="5">true</td></tr>
<tr><td rowspan="4">moreThanOneRLC</td><td rowspan="2">primaryPath</td><td>cellGroup</td><td colspan="4">0 to 3</td></tr>
<tr><td>logicalChannel</td><td colspan="4">1 to 32</td></tr>
<tr><td>ul-DataSplitThreshold</td><td colspan="5">0, 100, 200, 400, 800, 1600, 3200, 6400, 12800, 25600, 51200, 102400, 204800, 409600, b819200, b1228800, 1638400, 2457600, 3276800, 4096000, 4915200, 5734400, 6553600 bytes, infinity</td></tr>
<tr><td>pdcp-Duplication</td><td colspan="5">BOOLEAN</td></tr>
<tr><td>t-Reordering</td><td colspan="6">0, 1, 2, 4, 5, 8, 10, 15, 20, 30, 40, 50, 60, 80, 100, 120, 140, 160, 180, 200, 220, 240, 260, 280, 300, 500, 750, 1000, 1250, 1500, 1750, 2000, 2250, 2500, 2750 ms</td></tr>
<tr><td>cipheringDisabled</td><td colspan="6">true</td></tr>
</table>

Table 135 – Content of *PDCP-Config* for a specific DRB or SRB

★ The *outOfOrderDelivery* flag can be used to specify that that receiving PDCP entity is not required to provide in-sequence delivery of the higher layer packets. In this case, packets can be delivered to the higher layers without having to wait for missing packets, i.e. latency can be improved if the higher layers are able to operate without in-sequence delivery. When using in-sequence delivery, the *t-Reordering* timer defines an upper limit on the duration that received packets are buffered at the PDCP layer while waiting for missing packets. The buffered packets are passed to the higher layers if this timer expires

- ★ The PDCP layer is able to provide data recovery when requested. This involves the re-transmission of all PDCP data PDU which have been previously transmitted without confirmation of successful delivery, i.e. it does not involve the re-transmission of specific individual packets, as done by the ARQ and HARQ re-transmission protocols provided by the RLC and MAC layers. Data recovery can be used for handovers between Base Station Distributed Units (DU). This is necessary to achieve lossless handovers when the source DU has buffered packets which are lost when the source DU is released as part of the handover procedure. There is no interface between DU for data forwarding

- ★ The PDCP layer can also provide data volume measurements for Buffer Status Reporting (BSR). Buffer Status Reporting is described in section 13.7.2

- ★ Figure 225 illustrates the format of the PDCP Data and Control PDU (there is also an 'Interspersed ROHC Feedback' Control PDU which is not shown in Figure 225). The PDCP header always includes a 12 bit Sequence Number when transferring data belonging to SRB 1 or SRB 2, i.e. when using the DCCH logical channel

- ★ The PDCP header can have a length of 12 or 18 bits when transferring data belonging to a DRB, i.e. when using the DTCH logical channel. The Base Station configures the header length using the *pdcp-SN-SizeUL* and *pdcp-SN-SizeDL* information elements shown in Table 135

- ★ The PDCP Status Report includes a 'PDU Type' field which is used to differentiate between a 'PDCP Status Report' and an 'Interspersed ROHC Feedback' packet. The PDCP Status Report specifies the First Missing COUNT (FMC) value at the receiver. The COUNT value is a concatenation of the Hyper Frame Number (HFN) and PDCP Sequence Number. The Bitmap is used to indicate which COUNT values following the FMC are missing. This information allows the transmitter to delete all packets which have been successfully received from its transmit buffer

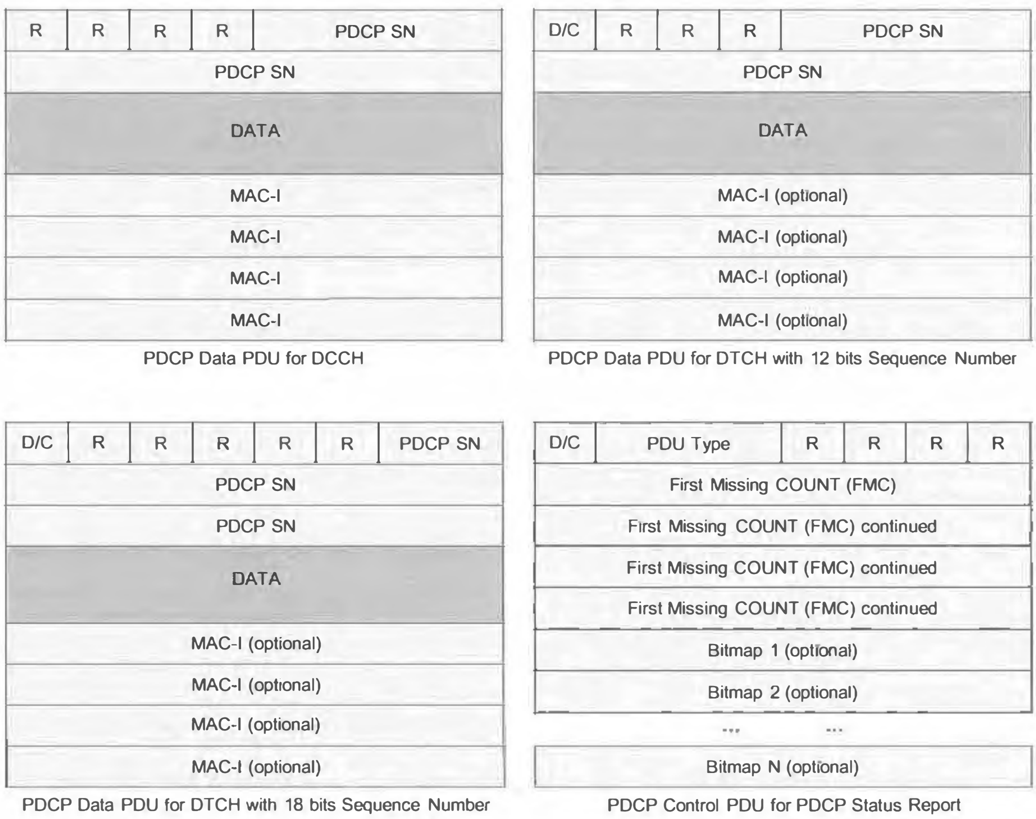


Figure 225 – Format of PDCP Data and Control PDU

- ★ The DTCH is used to transfer both Data and Control PDU so the 'D/C' header field is required to differentiate between them. The DCCH is only used to transfer Data PDU so the 'D/C' header field is not required

- ★ 3GPP References: TS 38.323, TS 38.331

5.3 RLC LAYER

★ The 'Radio Link Control' (RLC) layer receives both user plane and control plane packets from the PDCP layer. Each packet is processed by a specific RLC Entity. An RLC Entity can support one of three modes:

- o Transparent Mode (TM) RLC
- o Unacknowledged Mode (UM) RLC
- o Acknowledged Mode (AM) RLC

★ Packets are associated with a specific logical channel after being processing by the RLC layer, i.e. logical channels are used to pass packets from the RLC layer to the MAC layer. Packets are only passed to the MAC layer after a resource allocation has been received. Table 136 presents the logical channels supported by each RLC mode

RLC Mode	BCCH	PCCH	CCCH	DCCH	DTCH
TM	✓	✓	✓	-	-
UM	-	-	-	-	✓
AM	-	-	-	✓	✓

Table 136 – Logical channels supported by each RLC mode

★ Transparent Mode RLC is only applicable to the control plane. A specific set of RRC messages make use of Transparent Mode (see section 5.3.1). User plane transmissions on the DTCH can use either Unacknowledged Mode or Acknowledged Mode RLC

★ Unacknowledged Mode RLC is appropriate for real time applications which have a strict delay budget and are able to cope with at least some packet loss. The strict delay budget means that these applications do not allow time for the relatively slow Automatic Repeat Request (ARQ) re-transmissions from the RLC layer (they normally rely upon faster Hybrid Automatic Repeat Request (HARQ) re-transmissions from the MAC layer). Voice over NR (VoNR) is a typical application which uses Unacknowledged Mode RLC. Some packet loss is acceptable although voice quality will degrade as the quantity of packet loss increases

★ Acknowledged Mode RLC is appropriate for non-real time applications which require reliable data transfer. These applications have a delay budget which allows time for the relatively slow ARQ re-transmissions from the RLC layer. These re-transmissions provide a back-up mechanism after the faster HARQ re-transmissions from the MAC layer, i.e. an RLC re-transmission is triggered after the MAC layer has already attempted its set of HARQ re-transmissions

★ ARQ re-transmissions from the RLC layer can be more adaptive than HARQ re-transmissions from the MAC layer. HARQ re-transmissions can be adaptive from the perspective of air-interface resource allocation, i.e. Resource Blocks 1 to 5 may be allocated for the original transmission while Resource Blocks 25 to 35 may be allocated for a re-transmission. This allows the resource allocation to move in case one part of the channel bandwidth is experiencing interference or fading channel conditions. It also allows the number of allocated Resource Blocks to change in case there is a requirement to adjust the coding rate, e.g. increase the number of allocated Resource Blocks to increase channel coding redundancy (a lower coding rate)

★ ARQ re-transmissions also allow the packet size to change between re-transmissions. If channel conditions are becoming worse over time then the RLC layer can re-segment packets before completing re-transmissions. This means that the payload associated with the re-transmissions can be smaller, i.e. a lower RLC layer throughput is targeted to provide a more relaxed link budget. These differences between RLC and MAC layer re-transmissions are summarised in Table 137

Re-transmission Mechanism	Adaptive Air-Interface Resource Allocation between transmissions	Adaptive Packet Size between transmissions
RLC Layer Re-transmission (ARQ)	✓	✓
MAC Layer Re-transmission (HARQ)	✓	-

Table 137 – Adaptation between RLC and MAC re-transmissions

★ Both UM and AM RLC modes support segmentation. AM RLC supports both segmentation and re-segmentation. Re-segmentation is not applicable to UM RLC because re-transmissions are not supported, i.e. re-segmentation can be applied to re-transmissions

★ The segmentation solutions for 4G and 5G are different. 4G uses a 'Framing Information' (FI) solution for segmentation and a 'Segment Offset' (SO) solution for re-segmentation. 5G uses an SO solution for both segmentation and re-segmentation. The benefit of the SO solution is that it allows an increased quantity of pre-processing to be completed, i.e. packets can be largely prepared in advance of their transmission. This is an important benefit when supporting high throughputs because it helps to reduce the quantity of real time processing. The drawback of the SO solution is that it increases the size of the RLC header relative to the FI solution

★ Some examples of the SO solution used for 5G are illustrated in Figure 226. In the first example, there is no segmentation so the RLC header includes a Sequence Number (SN) and Segmentation Information (SI) to indicate that the RLC PDU includes a complete RLC SDU

★ In the second example, segmentation is used to generate 3 segments. Each segment is allocated the same Sequence Number (the Sequence Number is linked to the RLC SDU rather than the RLC PDU when using the SO solution). The RLC header for the first segment includes Segmentation Information to indicate that it is the first segment. The RLC header for the second segment includes Segmentation Information to indicate that it is a middle segment. The header also includes a Segment Offset to indicate the position of the segment within the original RLC SDU. The RLC header for the third segment includes Segmentation Information to indicate that it is the final segment, and also a Segment Offset to indicate the position of the segment within the original SDU

★ In the third example, segmentation is used to generate 3 segments, and then re-segmentation is used to generate 4 segments. This example illustrates that re-segmentation allows data from multiple original segments to be combined when generating the new set of segments. All segments have the same Sequence Number because the Sequence Number is allocated to the RLC SDU and all segments originate from that RLC SDU

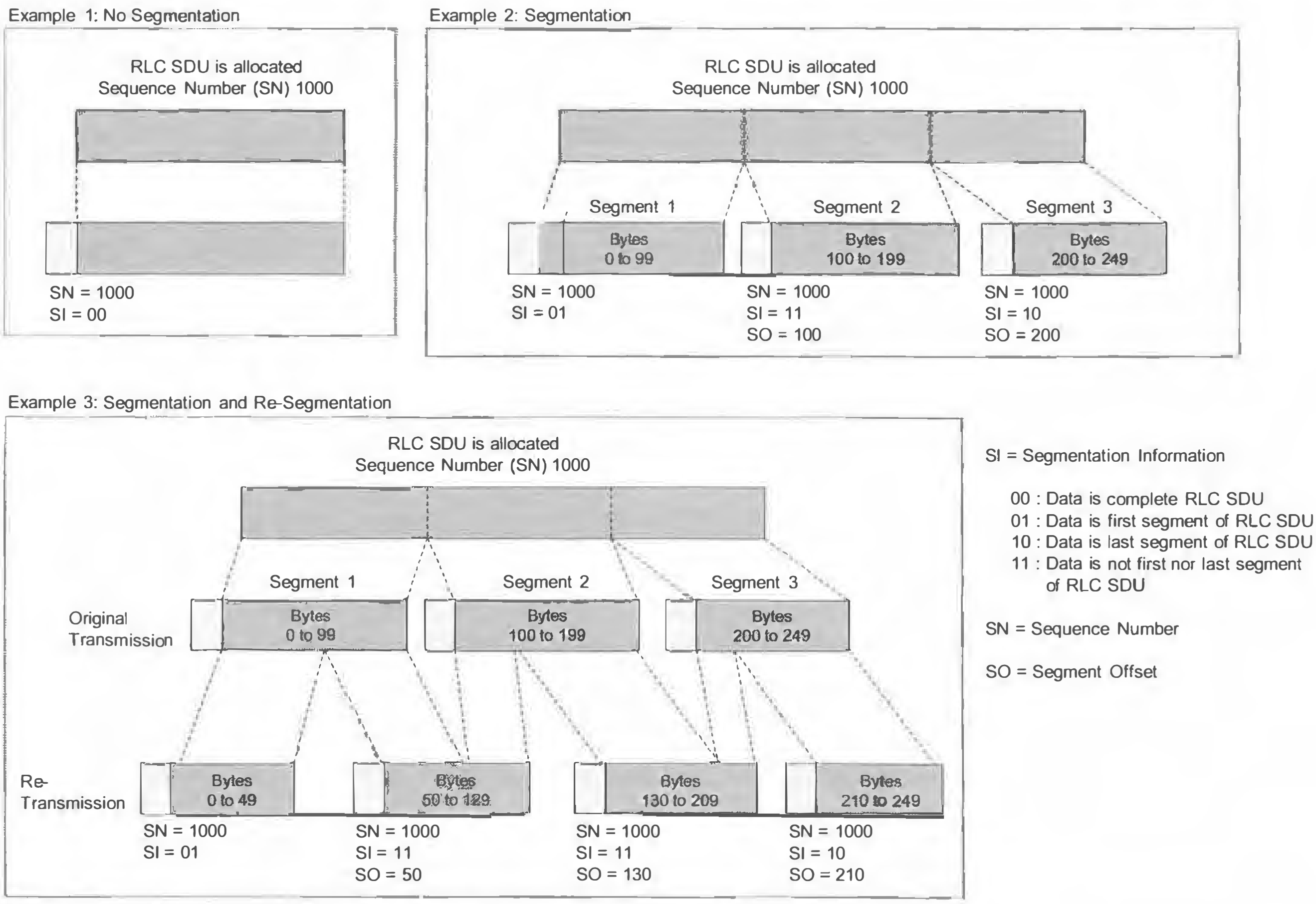


Figure 226 – Examples of RLC layer Segmentation

★ The 4G RLC layer supports concatenation to allow multiple RLC SDU to be combined within a single RLC PDU. The 5G RLC layer does not support concatenation so an RLC PDU contains a single RLC SDU (or segment of a single RLC SDU)

★ The RLC layer can also provide data volume measurements for Buffer Status Reporting (BSR). Buffer Status Reporting is described in section 13.7.2

★ 3GPP References: TS 38.322

5.3.1 TRANSPARENT MODE

★ Transparent Mode RLC is only applicable to the Control Plane, i.e. a subset of RRC messages can be sent using Transparent Mode RLC. Transparent Mode RLC is used to send the following messages:

- o Broadcast Control Channel (BCCH): *MIB*, *SIB1*, *SystemInformation*
- o Paging Control Channel (PCCH): *Paging*
- o Common Control Channel (CCCH): *RRCSetupRequest*, *RRCSetup*, *RRCReject*, *RRCReestablishmentRequest*, *RRCResumeRequest*, *RRCResumeRequest1*, *RRCSystemInfoRequest*

★ Transparent Mode means that the RLC layer does not modify the higher layer packet in any way, i.e. it is not segmented and no header information is added so the RLC PDU is the same as the RLC SDU

★ 3GPP References: TS 38.322, TS 38.331

5.3.2 UNACKNOWLEDGED MODE

★ Unacknowledged Mode (UM) RLC is only applicable to the User Plane, i.e. it cannot be used to transfer RRC signalling messages. UM RLC is able to segment packets at the sender and reassemble those packets at the receiver. RLC SDU can be discarded at the receiver if it has not been possible to reassemble the SDU within a specific time window

★ The Base Station uses the *RLC-Config* parameter structure presented in Table 138 to provide the UE with information regarding UM RLC. There is an instance of this parameter structure for each mapping between SRB/DRB and logical channel (SRB is not applicable when *RLC-Config* specifies UM RLC)

★ UM RLC can be configured as bi-directional, uplink only or downlink only. Thus, a DRB may use only a downlink UM RLC entity or only an uplink UM RLC entity. *RLC-Config* specifies the Sequence Number (SN) length for the uplink RLC entity, and both the SN length and reassembly timer for the downlink RLC entity. The Base Station is likely to have its own reassembly timer but this information is not provided to the UE

RLC-Config				
RLC-Config	CHOICE			
	am	*(see next section)*		
	um-Bi-Directional	ul-UM-RLC	sn-FieldLength	6, 12 bits
		dl-UM-RLC	sn-FieldLength	6, 12 bits
			t-Reassembly	0, 5, 10,15, 20, 25, 30, 35, 40, 45, 50, 55, 60, 65, 70, 75, 80, 85, 90, 95, 100, 110, 120, 130, 140, 150, 160, 170, 180, 190, 200 ms
	um-Uni-Directional-UL	ul-UM-RLC	sn-FieldLength	6, 12 bits
	um-Uni-Directional-DL	dl-UM-RLC	sn-FieldLength	6, 12 bits
			t-Reassembly	0, 5, 10,15, 20, 25, 30, 35, 40, 45, 50, 55, 60, 65, 70, 75, 80, 85, 90, 95, 100, 110, 120, 130, 140, 150, 160, 170, 180, 190, 200 ms

Table 138 – Content of *RLC-Config* for Unacknowledged Mode RLC

★ Figure 227 illustrates the set of UM RLC PDU formats ('R' header fields are 'Reserved' and are not used to convey information). The RLC header includes only the 'Segmentation Information' (SI) field when the RLC PDU contains a complete RLC SDU. The SI field uses a value of '00' to indicate that a complete SDU is included. In this case, the header does not include a Sequence Number (SN). This highlights the fact that the RLC layer is not responsible for in-sequence delivery (the PDCP layer is responsible for providing in-sequence delivery when required)

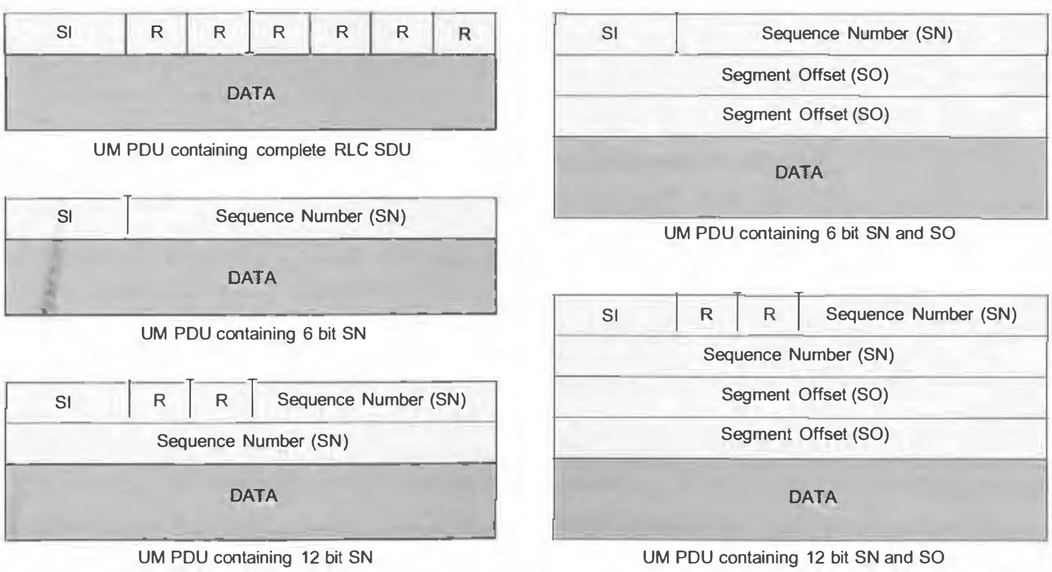


Figure 227 – RLC header fields for Unacknowledged Mode Data PDU

★ The UM RLC header field includes a combination of 'Segmentation Information' (SI) and 'Sequence Number' (SN) when the RLC PDU includes the first segment belonging to an RLC SDU. In this case, the SI is set to '01' and the SN is used to identify the RLC SDU, i.e. the SN allows all segments belonging to the same RLC SDU to be linked together

★ In other cases, the UM RLC header field also includes the 'Segment Offset' (SO) to allow correct reassembly of the SDU at the receiver. The SO specifies the position of the data within the RLC SDU using a byte number. The set of 16 bits provides a relatively large range from 0 to 65 535 bytes (considering that the PDCP layer supports a maximum SDU size of 9 000 bytes)

★ 3GPP References: TS 38.322, TS 38.331

5.3.3 ACKNOWLEDGED MODE

★ Acknowledged Mode (AM) RLC is applicable to both the Control Plane and User Plane. Table 16 in section 1.12 presents the set of RRC messages which are transferred using AM RLC

★ AM RLC relies upon Automatic Repeat Request (ARQ) to allow re-transmissions and thus provide reliable data transfer. Status Reports are used to trigger re-transmissions of RLC SDU or segments of RLC SDU. Status Reports are a category of Control PDU, in contrast to Data PDU which transfer the actual payload from the higher layers

★ Reaching the maximum permitted number of RLC re-transmissions at the Master Cell Group (MCG) can trigger a Radio Link Failure (RLF). This causes the UE to release itself to RRC Idle if the Security Mode procedure has not been completed and the UE has not been configured with SRB 2 and at least one DRB. Otherwise, the UE initiates the RRC Connection Re-establishment procedure. Reaching the maximum permitted number of RLC re-transmissions at a Secondary Cell Group (SCG) can trigger the 'SCG Failure Information' procedure which allows the UE to report the event to the MCG

★ The Base Station uses the *RLC-Config* parameter structure presented in Table 139 to provide the UE with information regarding AM RLC. There is an instance of this parameter structure for each mapping between SRB/DRB and logical channel

RLC-Config				
RLC-Config	CHOICE			
	am	ul-AM-RLC	sn-FieldLength	12, 18 bits
			t-PollRetransmit	5, 10, 15, 20, 25, ..., 400, 450, 500, 800, 1000, 2000, 4000 ms
			pollPDU	4, 8, 16, 32, 64, 128, ..., 49152, 57344, 65536 PDU, infinity
			pollByte	1, 2, 5, 8, 10, 15, 25, 50, 75, ..., 6500, 7000, 7500 kBytes, 8, 9, 10, 11, 12, 13, 14, ..., 18, 20, 25, 30, 40 MBytes, infinity
			maxRetxThreshold	1, 2, 3, 4, 6, 8, 16, 32 re-transmissions
		dl-AM-RLC	sn-FieldLength	12, 18 bits
			t-Reassembly	0, 5, 10,15, 20, 25, 30, 35, 40, 45, 50, 55, 60, 65, 70, 75, 80, 85, 90, 95, 100, 110, 120, 130, 140, 150, 160, 170, 180, 190, 200 ms
			t-StatusProhibit	0, 5, 10, 15, 20, 25, 30, 35, ..., 1200, 1600, 2000, 2400 ms
	um-Bi-Directional	(see previous section)		
	um-Uni-Directional-UL	*(see previous section)*		
	um-Uni-Directional-DL	*(see previous section)*		

Table 139 – Content of *RLC-Config* for Acknowledged Mode RLC

★ The transmitting side of an AM RLC entity uses a transmit window to limit the number of RLC SDU which are transmitted while waiting for an acknowledgement. The general concept of the transmit window is illustrated in Figure 228. The transmit window starts at the oldest transmitted RLC SDU which has not been fully acknowledged. This oldest transmitted RLC SDU may have been partly acknowledged if it was segmented prior to transmission. The transmit window advances as acknowledgements are received

★ The first example illustrates a scenario where SDU 0 to 5 have been fully acknowledged, whereas SDU 6 to 11 have been transmitted but have not been fully acknowledged. In this case, the transmitter is able to continue sending packets because the transmit window is not full, i.e. SDU 12 to 17 can be transmitted while waiting for older packets to be acknowledged

★ The second example illustrates a scenario where SDU 0, 1, 2, 4 and 5 have been fully acknowledged but SDU 3 has not been fully acknowledged. Re-transmissions for SDU 3 are ongoing. The transmitter is able to continue sending new packets because the transmit window is not full, i.e. SDU 12 to 14 can be transmitted while waiting for SDU 3 to be acknowledged

★ The third example, illustrates a scenario where the transmit window has become full, causing the RLC entity to stall, i.e. no further SDU can be transmitted until SDU 3 has been fully acknowledged. Stalling has an impact upon application layer throughput so should be avoided whenever possible. High air-interface throughputs potentially increase the risk of stalling because the transmit window is filled more rapidly. In general, high throughputs require large transmit window sizes to avoid stalling

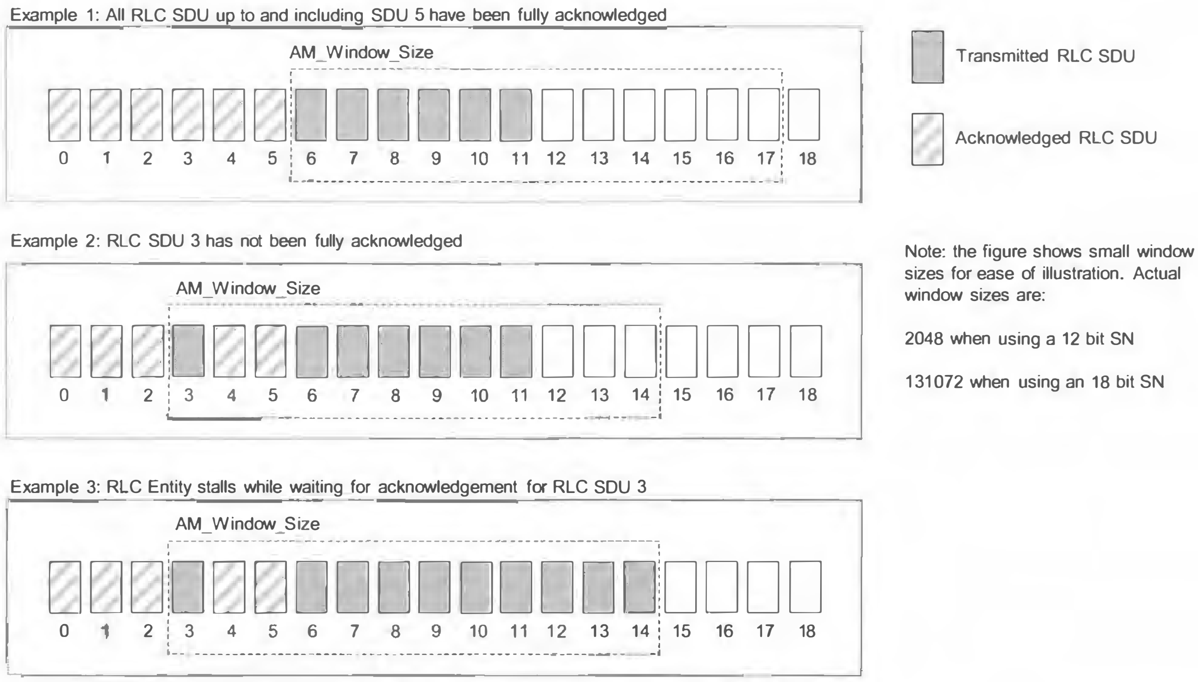


Figure 228 – Examples of the transmit window for AM RLC

- The maximum transmit window size is limited by the Sequence Number range. The transmit window is used to prevent Sequence Number ambiguity at the receiver (same concept as the transmit window used by TCP). 3GPP has specified that the transmit window size is half of the Sequence Number range because this is the upper limit of the window size which avoids ambiguity. For example, the 12 bit Sequence Number supports a range from 0 to 4095 so the transmit window size is 2048
- Figure 229 illustrates how ambiguity can occur when the window size is greater than half of the Sequence Number range. It requires consideration of both the transmit and receive windows. The start of the receive window advances to the oldest RLC SDU which has not been fully received. Ideally, the transmit and receive windows remain synchronised, i.e. an RLC SDU is successfully received so the receive window advances, and an acknowledgement is returned to the transmitter so the transmit window also advances. In practice, Status Reports are not sent to the transmitter after the reception of every SDU so the two windows become unsynchronised
- The example in Figure 229 illustrates a scenario where the transmit window is stuck on an 'old' RLC SDU 3 while re-transmissions are ongoing and the transmitter is waiting for a positive acknowledgement. The receiver has in fact successfully received 'old' RLC SDU 3 and has advanced its receive window such that a 'new' RLC SDU 3 is expected. In this scenario, if the transmitter makes a further re-transmission of 'old' RLC SDU 3 then the receiver will think it is the 'new' RLC SDU 3

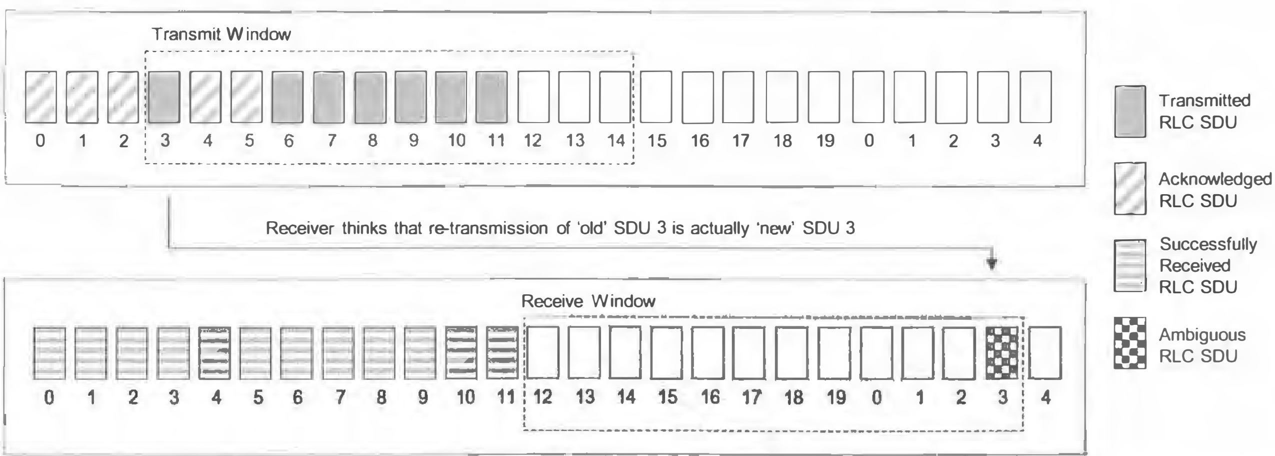


Figure 229 – Sequence Number ambiguity when using window sizes > sequence number range / 2

- Figure 230 illustrates the set of AM RLC Data PDU formats ('R' header fields are 'Reserved' and are not used to convey information). The pair of formats on the left are based upon a 12 bit Sequence Number (SN), whereas the pair on the right are based upon an 18 bit SN. The SN length is configured using the *RLC-Config* parameter structure presented in Table 139. The pair of formats at the top exclude the Segment Offset (SO) so these PDU either include a complete RLC SDU, or they include the first segment belonging to an RLC SDU. In the case of Unacknowledged Mode (UM) RLC, a SN is not required when an RLC PDU includes a complete RLC SDU. In contrast, Acknowledged Mode PDU always require a SN to allow each PDU to be identified when returning acknowledgements

★ The RLC header includes a 'Data/Control' (D/C) field to identify the PDU as a Data PDU rather than a Control PDU. The 'Segmentation Information' (SI) indicates whether or not the RLC SDU has been segmented. In the case of segmentation, the SI field indicates if the RLC PDU includes the first segment, a central segment or the last segment. Segmentation and re-segmentation are described in section 5.3

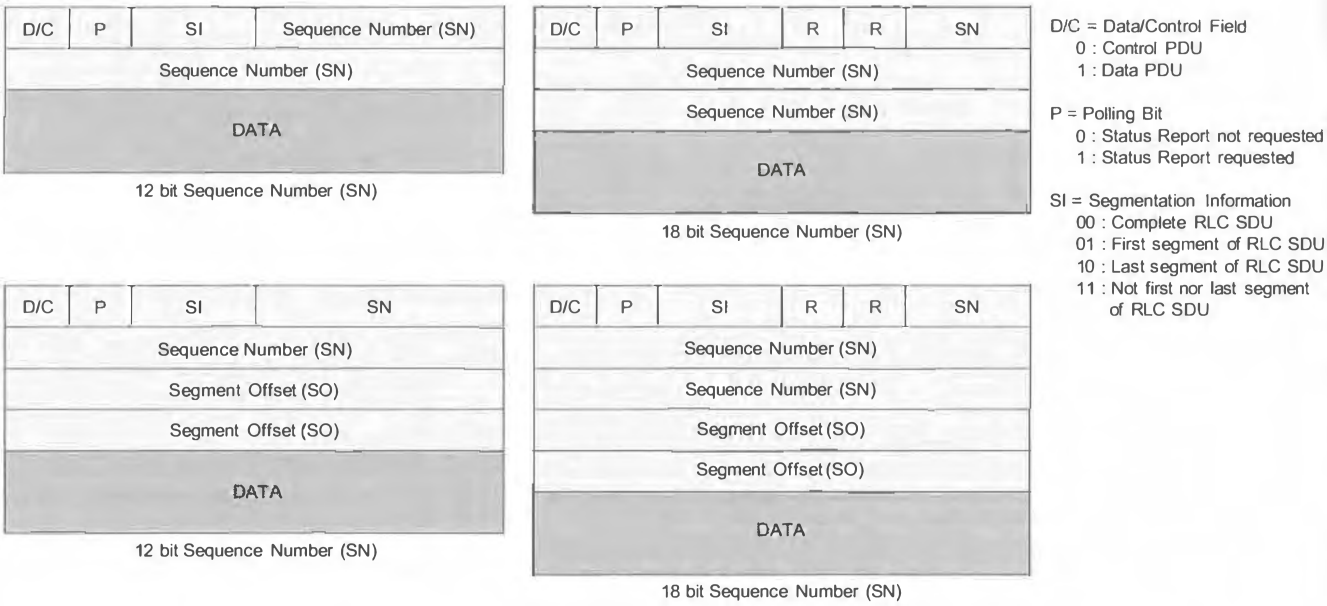


Figure 230 – RLC header fields for Acknowledged Mode Data PDU

★ The 'Polling' (P) bit can be used to request a Status Report from the receiving RLC entity. The transmitting RLC entity can trigger Polling based upon either the number of PDU which have been sent since a previous Poll, or the data volume which has been sent since a previous Poll. The *RLC-Config* parameter structure provides *pollPDU* to quantify the number of PDU which triggers a Poll, and *pollByte* to quantify the data volume which triggers a Poll

★ The transmitting RLC entity also triggers a Poll if the transmit buffer becomes empty (with the exception of the packets awaiting acknowledgement). In addition, the transmitting RLC entity triggers a Poll if no new RLC SDU can be sent due to reaching the limit of the transmit window

★ If the UE triggers a poll but does not receive a Status Report after waiting a period of time defined by *t-PollRetransmit*, the UE re-transmits the poll. The Base Station will also have a Poll re-transmission timer but its value is not provided to the UE.

★ Once the UE has sent a Status report, then it does not send another Status report until requested, and only after the *t-StatusProhibit* timer has expired

★ A Status Report specifies the Sequence Number up to which all RLC SDU have been successfully received, with the exception of RLC SDU specified within the remainder of the Status Report. The Status Report can specify the requirement to re-transmit complete RLC SDU, or the requirement to re-transmit specific segments of specific RLC SDU

★ The transmitting side of an RLC entity prioritises Control PDU over Data PDU. Similarly, re-transmissions of Data PDU are prioritised over new transmissions of Data PDU

★ The transmitting side of an RLC entity discards an RLC SDU if instructed to do so by the PDCP layer, e.g. the PDCP layer discard timer expires before the SDU has been successfully transmitted

★ 3GPP References: TS 38.322, TS 38.331

5.4 MAC LAYER

★ The 'Medium Access Control' (MAC) layer receives both user plane and control plane data from the set of logical channels provided by the RLC layer. The MAC layer is responsible for processing this data and mapping onto the Transport Channels which allow data transfer towards the Physical layer

★ The high level architecture of the MAC layer is illustrated in Figure 231. The MAC layer is transparent to some logical channels, i.e. the PCCH and BCCH. The BCCH uses HARQ when mapped onto the DL-SCH but no header information is added by the MAC layer

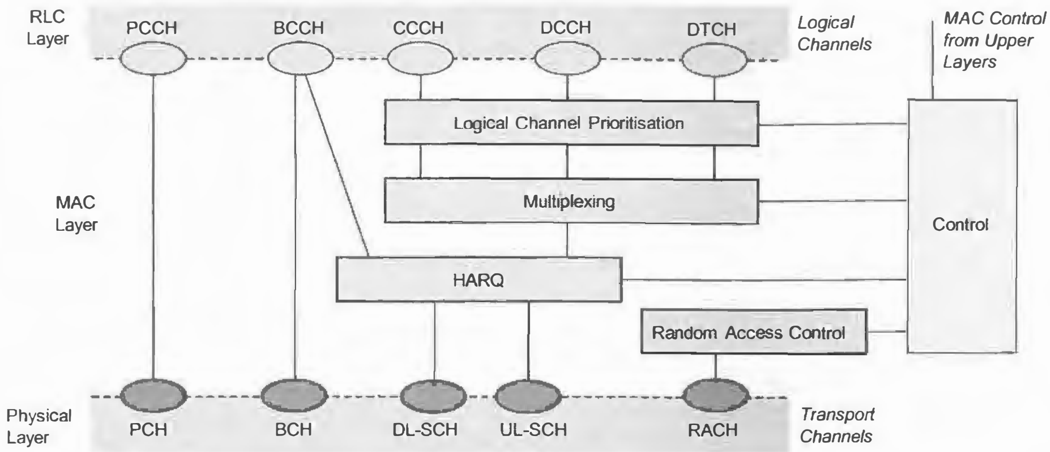


Figure 231 – High level architecture of the MAC layer

★ The MAC layer prioritises data belonging to the CCCH, DCCH and DTCH logical channels. Prioritisation of uplink data at the UE is achieved using a parameter set provided by the Base Station. Table 140 presents the *LogicalChannelConfig* which includes the *priority*, *prioritisedBitRate* and *bucketSizeDuration* parameters (a low numerical *priority* corresponds to a high priority)

★ A variable known as *Bj* is initialised to zero when logical channel 'j' is established. The value of *Bj* is incremented by the product of *prioritisedBitRate* × T, in advance of each logical channel prioritisation. The value of 'T' is equal to the time period since the value of *Bj* was previously updated. The result from this multiplication represents the volume of data which the logical channel is required to transfer to achieve its *prioritisedBitRate.* If the calculated value of *Bj* exceeds the Bucket Size = *prioritisedBitRate* × *bucketSizeDuration* then the value of *Bj* is rounded down to the value of the Bucket Size

★ Logical channel prioritisation is then completed by selecting the logical channel which has the lowest numerical *priority* and a positive value for *Bj*. If the selected logical channel has *prioritisedBitRate* = 'infinity' then the buffer belonging to that logical channel is emptied before serving any other logical channel. Otherwise, the selected logical channel is provided with sufficient resources to achieve the Prioritised Bit Rate, i.e. the transmit buffer for the logical channel is emptied by at least the value of *Bj*. The value of Bj is then updated by subtracting the quantity of data emptied from the buffer

★ If the resource allocation has capacity remaining after serving the first logical channel, additional logical channels are served based upon their *priority* value without accounting for the value of *Bj*. Logical channels with equal priority are served equally

LogicalChannelConfig			
ul-Specific Parameters	priority	1 to 16	
	prioritisedBitRate	0, 8, 16, 32, 64, 128, 256, ..., 8192, 16384, 32768, 65536 kBytes per second, infinity	
	bucketSizeDuration	5, 10, 20, 50, 100, 150, 300, 500, 1000 ms	
	allowedServingCells	{1 to 31 instances of ServCellIndex}	0 to 31
	allowedSCS-List	{1 to 5 instances of SubcarrierSpacing}	15, 30, 60, 120 kHz
	maxPUSCH-Duration	0.02, 0.04, 0.0625, 0.125, 0.25, 0.5 ms	
	configuredGrantType1Allowed	true	
	LogicalChannelGroup	0 to 7	
	schedulingRequestID	0 to 7	
	logicalChannelSR-Mask	BOOLEAN	
	logicalChannelSR-DelayTimerApplied	BOOLEAN	
	bitRateQueryProhibitTimer	0, 0.4, 0.8, 1.6, 3, 6, 12, 30 seconds	

Table 140 – Content of *LogicalChannelConfig*

★ In all cases, when allocating resources for a logical channel, checks are completed to ensure that the logical channel is permitted to use the serving cell and subcarrier spacing associated with the resource allocation. These checks are based upon the *allowedServingCells* and *allowedSCS-List* parameters shown in Table 140. It is also necessary to check that the duration of the PUSCH resource allocation does not exceed the value of *maxPUSCH-Duration*

★ A MAC PDU is generated by multiplexing the data from one or more logical channels. A MAC PDU can also include one or more MAC Control Elements (MAC CE). MAC CE which can be sent in the downlink direction are presented in Table 86 (section 3.6), whereas MAC CE which can be sent in the uplink direction are presented in Table 194 (section 7.4)

★ Figure 232 and Figure 233 present the structures of uplink and downlink MAC PDU. In the uplink direction, the MAC CE are multiplexed at the end of the PDU, whereas in the downlink direction they are multiplexed at the start of the PDU. Each MAC SDU and variable size MAC Control Element uses an 'R/F/LCID/L' subheader. The Reserved (R) field does not convey any information. The Format (F) field specifies the size of the Length (L) field. A value of '0' indicates that the Length field occupies 8 bits, whereas as a value of '1' indicates that the Length field occupies 16 bits. The Logical Channel Identity (LCID) has a size of 6 bits and is used to identify the Logical channel, or a MAC Control Element or the inclusion of padding. The Length (L) field quantifies the size of the MAC SDU in bytes. A fixed size MAC Control Element uses a simplified 'R/LCID' subheader because length information is not required

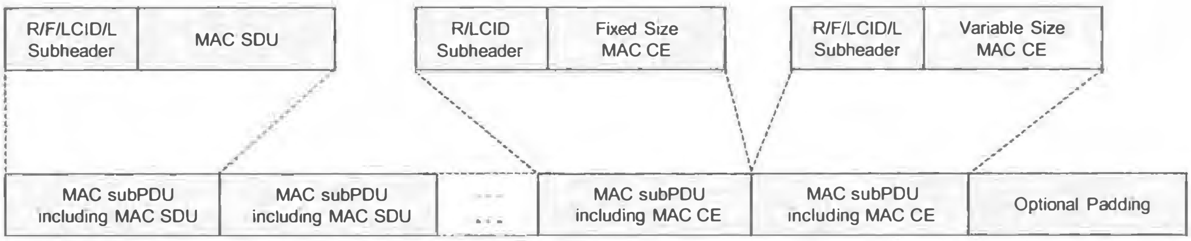


Figure 232 – Structure of uplink MAC PDU

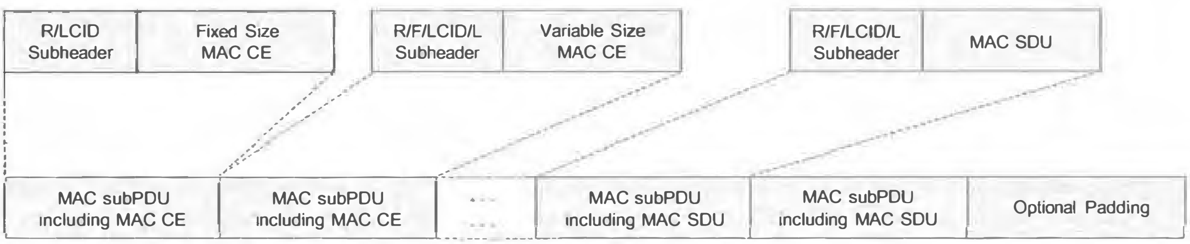


Figure 233 – Structure of downlink MAC PDU

★ The MAC layer at the Base Station is responsible for allocating air-interface resources, i.e. the Packet Scheduler and Link Adaptation algorithms belong to the MAC layer. The details of these algorithms depend upon the network implementation

★ The Base Station can use the *MAC-CellGroupConfig* parameter structure to provide the UE with a *dataInactivityTimer*. This inactivity timer is presented in Table 141. In general, the Base Station is responsible for monitoring periods of inactivity and releasing the UE to RRC Idle or RRC Inactive. The *dataInactivityTimer* provides a solution for a mis-match between the RRC State at the UE and the RRC State at the Base Station. If the inactivity timer at the Base Station expires and the Base Station sends an *RRCRelease* message while the UE is in poor coverage, the UE may fail to receive the message and remain in RRC Connected while the Base Station releases all resources. In this case, it can be useful to have an inactivity timer within the UE which allows the UE to release itself to RRC Idle. *dataInactivityTimer* should be configured with a value which is larger than the Base Station inactivity timer to ensure that the normal release mechanism is always attempted first. If *dataInactivityTimer* expires, the UE releases itself to RRC Idle and informs the NAS layer that an RRC Release has occurred with a cause value of 'RRC Connection Failure'. This triggers the NAS layer to initiate a Registration procedure towards the Core Network

Extract from *MAC-CellGroupConfig*	
dataInactivityTimer	1, 2, 3, 5, 7, 10, 15, 20, 40, 50, 60, 80, 100, 120, 150, 180 seconds

Table 141 – *dataInactivitytimer* within *MAC-CellGroupConfig*

★ The MAC layer is also responsible for the following procedures:

- o Buffer Status Reporting (BSR) described in section 13.7.2, and Power Headroom Reporting (PHR) described in section 13.8
- o the Random Access procedure described in section 13.1, and the Paging procedure described in section 12.4
- o Timing Advance described in section 13.2, and Connected Mode DRX described in section 13.10
- o HARQ re-transmissions described in section 13.5, and the Scheduling Request procedure described in section 13.7.1

★ 3GPP References: TS 38.321, TS 38.331

6 SYSTEM INFORMATION

★ UE read system information in RRC Idle mode to acquire the parameters necessary to complete cell selection and cell reselection. System information also provides the parameters necessary to access the network and detect paging messages

★ System information is broadcast using a Master Information Block (MIB) and a series of System Information Blocks (SIB). Figure 234 illustrates the logical, transport and physical channels used to transfer the MIB and SIB. The MIB is the only system information transferred using the BCH and PBCH. SIB are transferred using the DL-SCH and PDSCH. SIB1 has its own RRC message whereas SIB2 to SIB9 are encapsulated within the more general System Information RRC message

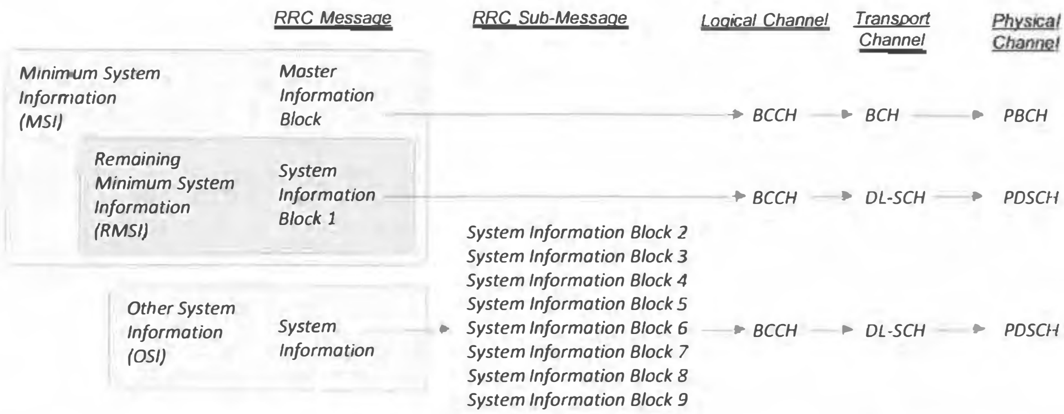


Figure 234 – System Information messages mapped onto Logical, Transport and Physical Channels

★ Minimum System Information (MSI) includes the MIB and SIB1. Remaining Minimum System Information (RMSI) includes SIB1, whereas Other System Information (OSI) includes SIB 2 to 9

★ During the initial cell search procedure, a UE acquires the MIB after scanning the set of Global Synchronisation Channel Numbers (GSCN) and discovering an SS/PBCH Block. The MIB is found directly on the PBCH without the requirement for any resource allocations on the PDCCH. During cell reselection, SIB4 provides the UE with information regarding the GSCN belonging to inter-frequency neighbouring cells. In the case of RRC Connected Mode, the Base Station can use dedicated signalling to provide the UE with information regarding the position of the SS/PBCH belonging to neighbouring cells, e.g. for handovers or Secondary Cell Group (SCG) addition

★ The MIB provides the UE with information regarding the Control Resource Set (CORESET) and Search Space used by the PDCCH when making a resource allocation for SIB1. SIB1 provides the UE with scheduling information for all Other System Information

★ 5G supports both the regular periodic broadcast of SIB and 'on-demand' SIB, i.e. some SIB may not be broadcast using the usual periodic transmission pattern but may be broadcast upon request by individual UE. SIB1 includes a flag to indicate which SIB are broadcast using a regular periodic pattern and which SIB can be requested 'on-demand'

★ 'On-demand' SIB can be configured to be requested using either MSG1 or MSG3. The signalling associated with both of these options is illustrated in Figure 235

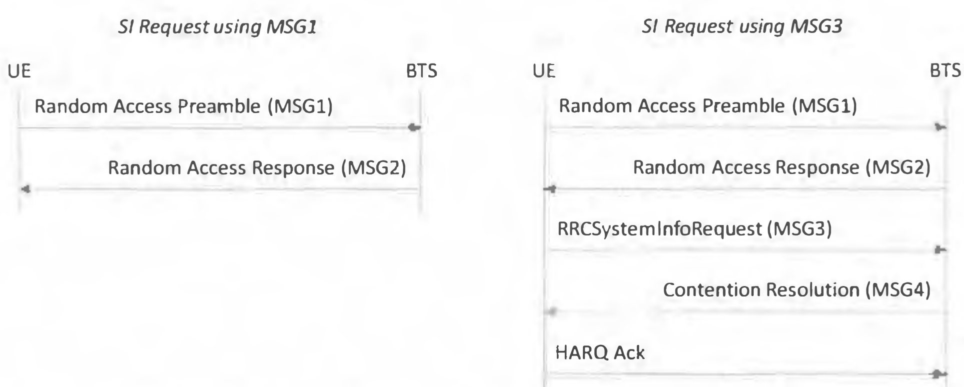


Figure 235 – Requesting 'On-demand' System Information using either MSG1 or MSG3

★ In the case of MSG1 System Information requests, the Base Station allocates a specific set of PRACH preambles for requesting System Information. The Base Station can allocate a single PRACH preamble to request all 'on-demand' SIB. Alternatively, the Base Station can allocate a separate PRACH preamble for each 'on-demand' SIB. This allows the UE to request specific individual SIB with each preamble transmission. When using MSG1 to request 'on-demand' SIB, the Base Station acknowledges the request at the MAC layer using a MSG2 transmission

★ In the case of MSG3 System Information requests, the UE completes a normal contention based random access procedure but populates MSG3 with an *RRCSystemInfoRequest* message (Table 142). This message includes a bit string, where each bit is linked to a specific SIB. This allows the UE to request a specific SIB transmission by setting a specific bit to '1'

RRCSystemInfoRequest	
requested-SI-List	BIT STRING {32 bits}
spare	BIT STRING {12 bits}

Table 142 – *RRCSystemInfoRequest* message

★ The *RRCSystemInfoRequest* message is not acknowledged at the RRC layer but is acknowledged at the MAC layer when the Base Station transmits a 'UE Contention Resolution Identity' MAC Control Element (MSG4). The UE completes the procedure by returning a HARQ acknowledgement for MSG4

★ The SI-RNTI is used to scramble the CRC bits belonging to DCI Format 1_0 when allocating PDSCH resources for the transmission of System Information. The content of DCI Format 1_0 is presented in section 3.5.6

★ A summary of the information included within the MIB and each of the SIB is provided in Table 143. More detailed information is provided within the following sections

System Information	3GPP Release	Content
Master Information Block	15	SFN, cell barred flag, information required to receive SIB1
System Information Block 1	15	Cell selection information, Tracking Area Code (TAC), RAN Notification Area Code (RANAC), Cell Identity, cell reserved flag, scheduling information for Other System Information (OSI), serving cell information (Bandwidth Part, RACH and Paging information), UE timers and constants, Unified Access Control (UAC) information
System Information Block 2	15	General cell reselection information and intra-frequency cell reselection information
System Information Block 3	15	Cell specific information for intra-frequency cell reselection
System Information Block 4	15	Information regarding inter-frequency cell reselection
System Information Block 5	15	Information regarding inter-system cell reselection towards LTE
System Information Block 6	15	Earthquake and Tsunami Warning System (ETWS) primary notifications
System Information Block 7	15	ETWS secondary notifications
System Information Block 8	15	Commercial Mobile Alert Service (CMAS) notification
System Information Block 9	15	Timing information for UTC, GPS and local time

Table 143 – Summary of System Information content

★ 3GPP References: TS 38.331, TS 38.321

6.1 MASTER INFORMATION BLOCK

★ The Master Information Block (MIB) is transmitted using the BCCH logical channel, the BCH transport channel and the PBCH physical channel. The PBCH is transmitted as part of an SS/PBCH Block described in section 3.4

★ During the initial cell selection procedure, a UE assumes that a burst of SS/PBCH Blocks is transmitted every 20 ms, i.e. each beam transmits the PBCH once every 20 ms. Other transmission periods can be configured after initial cell selection. Either SIB1 or UE specific signalling can be used to configure PBCH periods of 5, 10, 20, 40, 80 or 160 ms. Cells supporting initial access should have PBCH periods of 5, 10 or 20 ms, whereas cells belonging to the EN-DC Non-Standalone Base Station architecture can have PBCH periods of 5, 10, 20, 40, 80 or 160 ms (EN-DC cells are not used for initial cell selection)

★ In the case of the Centralised Unit (CU) – Distributed Unit (DU) Base Station architecture, the DU is responsible for generating the content of both the MIB and SIB1. The DU forwards the MIB and SIB1 to the CU using the *gNB-DU System Information* parameter structure which can be included within either the F1AP: 'F1 Setup Request' or F1AP: 'gNB-DU Configuration Update' message

★ The MIB and SIB1 are known as 'Minimum System Information' because they provide the basic parameter set required for initial access and acquiring any other System Information. The MIB contains information which allows a UE to subsequently receive SIB1

★ The content of the MIB is presented in Table 144. The actual payload of the MIB occupies 23 bits but an additional 1 bit is required to indicate the BCCH message type. Thus, the MIB requires a total of 24 bits

MIB			Number of bits
systemFrameNumber	BIT STRING {6 bits}		6
subCarrierSpacingCommon	scs15or60, scs30or120		1
ssb-SubcarrierOffset	0 to 15		4
dmrs-TypeA-Position	pos2, pos3		1
pdcch-ConfigSIB1	controlResourceSetZero	0 to 15	4
	searchSpaceZero	0 to 15	4
cellBarred	barred, notBarred		1
intraFreqReselection	allowed, notAllowed		1
spare	BIT STRING {1 bit}		1
			Total of 23 bits

Table 144 – Content of the Master Information Block (MIB)

★ *systemFrameNumber* provides the 6 Most Significant Bits (MSB) of the current System Frame Number (SFN). The SFN uses a total of 10 bits to provide a range from 0 to 1023 (corresponding to a time window of 10.24 seconds). Inclusion of the 6 MSB means that the value changes once every 160 ms. The 4 Least Significant Bits (LSB) are also transferred using the PBCH but are added outside the MIB (presented later in this section)

★ *subCarrierSpacingCommon* defines the subcarrier spacing to be used for the reception of SIB1, other broadcast System Information, paging messages and the MSG2/MSG4 transmitted during initial access. The 'scs15or60' value indicates a subcarrier spacing of 15 kHz when the MIB is received within Frequency Range 1 (450 MHz to 6 GHz), and a subcarrier spacing of 60 kHz when the MIB is received within Frequency Range 2 (24.25 GHz to 52.6 GHz). Similarly, the 'scs30or120' value indicates a subcarrier spacing of 30 kHz for Frequency Range 1 and a subcarrier spacing of 120 kHz for Frequency Range 2

★ *ssb-subcarrierOffset* defines the 4 Least Significant Bits of the subcarrier offset (k_{SSB}). In the case of Frequency Range 2, the subcarrier offset requires a range from 0 to 11 and these 4 bits are sufficient. In the case of Frequency Range 1, the subcarrier offset requires a range from 0 to 23 so a 5th bit is required. This 5th bit (the Most Significant Bit) is also transferred using the PBCH but is added outside the MIB (presented later in this section). k_{SSB} defines the subcarrier offset between the Common Resource Block grid and the SS/PBCH. Examples of this subcarrier offset are illustrated in Figure 109 and Figure 110 (section 2.3.1). This highlights the fact that the Resource Blocks belonging to the PBCH are not always aligned with the Physical Resource Blocks used to transfer information on the PDCCH and PDSCH. However subcarrier alignment is maintained to achieve orthogonality between the transmissions

★ The value of k_{SSB} which is derived from *ssb-subcarrierOffset* can also be used to indicate whether or not the MIB has an associated CORESET which can be used by the PDCCH when allocating PDSCH resources for SIB1:

- in the case of Frequency Range 1, k_{SSB} has a range from 0 to 31, while values 0 to 23 are required to signal the subcarrier offset when a CORESET for SIB1 is present. This means that values 24 to 31 are available for other purposes. 3GPP TS 38.213 provides a look-up table which is indexed by values 24 to 29. Each row within the look-up table specifies a range of Global Synchronisation Channel Number (GSCN) offsets. For example, value 24 maps onto GSCN offsets of 1 to 256. This indicates that there is another SS/PBCH Block, and that SS/PBCH Block has a GSCN within the range {current GSCN + 1, current GSCN + 256}. The UE can then complete a scan for this additional SS/PBCH Block to acquire SIB1. The k_{SSB} value of 31 is used to indicate that there is no SS/PBCH Block with an associated CORESET for SIB1 within the range {current GSCN - N_{GSCN}^{Start}, current GSCN + N_{GSCN}^{End}}. *controlResourceSetZero* defines the value of N_{GSCN}^{Start}, whereas *searchSpaceZero* defines the value of N_{GSCN}^{End}

- in the case of Frequency Range 2, k_{SSB} has a range from 0 to 15, while values 0 to 11 are required to signal the subcarrier offset when a CORESET for SIB1 is present. This means that values 12 to 15 are available for other purposes. 3GPP TS 38.213 provides a look-up table which is indexed by values 12 and 13. Value 12 maps onto GSCN offsets of 1 to 256, while value 13 maps onto GSCN offsets of -1 to -256. The UE can then complete a scan for an additional SS/PBCH Block within the specified range of GSCN offsets. The k_{SSB} value of 15 is used to indicate that there is no SS/PBCH Block with an associated CORESET for SIB1 within the range {current GSCN - N_{GSCN}^{Start}, current GSCN + N_{GSCN}^{End}}. The value *controlResourceSetZero* is used to define the value of N_{GSCN}^{Start}, whereas the value of *searchSpaceZero* is used to define the value of N_{GSCN}^{End}

★ *dmrs-TypeA-Position* specifies the first symbol used by the Demodulation Reference Signal (DMRS) when using 'Mapping Type A'. This information element is applicable to the DMRS for both the PDSCH and PUSCH. Mapping Type A is described for the PDSCH within section 3.7.3 and for the PUSCH within section 7.5.1. The value of 'dmrs-TypeA-Position' is also used in combination with the 'Time Domain Resource Assignment' field received within Downlink Control Information (DCI). The combination of these two parameters is used to differentiate the set of rows belonging to 3GPP standardised look-up tables for time domain resource allocations. An example based upon standardised loop-up table 'A' is presented in Table 95 (section 3.6.4.1)

★ *controlResourceSetZero* defines a pointer to a row belonging to a look-up table standardised by 3GPP TS 38.213. The look-up table includes columns which define the SS/PBCH and CORESET multiplexing pattern, the number of Resource Blocks belonging to the CORESET, the number of symbols belonging to the CORESET and the frequency domain offset between the SS/PBCH Block and the CORESET. This look-up table is described in section 3.5.3. As described above, *controlResourceSetZero* has a different interpretation when k_{SSB} has a value of 31 in Frequency Range 1, and a value of 15 in Frequency Range 2

★ *searchSpaceZero* defines a pointer to a row belonging to a look-up table standardised by 3GPP TS 38.213. The look-up table includes columns which define the time domain offset between the SS/PBCH Block and the Search Space for SIB1, the number of Search Space Sets per Slot and the first symbol belonging to the Search Space Sets. This look-up table is described in section 3.5.3. As described above, *searchSpaceZero* has a different interpretation when k_{SSB} has a value of 31 in Frequency Range 1, and a value of 15 in Frequency Range 2

★ *cellBarred* indicates whether or not the cell is barred. A UE is not permitted to complete cell selection nor cell reselection onto a cell which is barred, i.e. a UE cannot camp on the cell for normal services nor emergency services. This restriction applies for a period of 300 seconds after which the UE can re-check the MIB to determine whether or not the cell remains barred

★ *intraFreqReselection* is applicable when the current cell is to be treated as barred. A value of 'notAllowed' indicates that the UE is not permitted to reselect another cell on the same frequency. In contrast, a value of 'allowed' indicates that the UE is permitted to reselect another cell on the same frequency

★ Figure 236 illustrates the additional information added by the Physical layer prior to processing the MIB for transmission on the PBCH. An additional 8 bits are added so the PBCH has a combined payload size of 32 bits

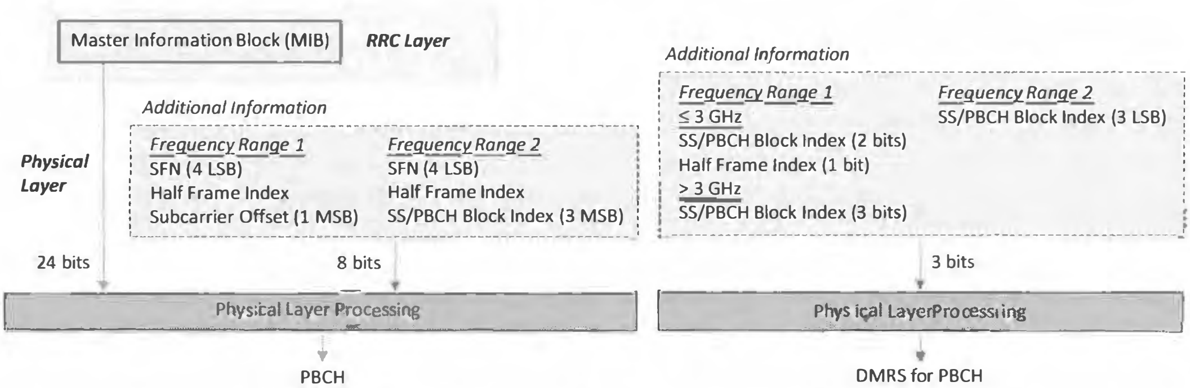


Figure 236 – Information transferred by the PBCH and DMRS for PBCH

★ The additional information added by the Physical layer is also presented in Table 145

★ The 4 Least Significant Bits (LSB) of the *System Frame Number* (SFN) are used in combination with the 6 MSB of the SFN included within the MIB. The Least Significant Bit changes every 10 ms because radio frames have a duration of 10 ms

★ The *Half Frame Index* is used as a flag to indicate whether the SS/PBCH Block is transmitted during the first 5 ms of a radio frame or the second 5 ms of a radio frame. This information allows the UE to achieve radio frame synchronisation after receiving the PBCH

★ In the case of Frequency Range 1, the Most Significant Bit of the subcarrier offset (k_{SSB}) is added by the Physical layer. This single bit is combined with the 4 Least Significant Bits provided by the MIB (generating a total of 5 bits with a range from 0 to 31)

PBCH Content generated by Physical layer		Number of bits
System Frame Number	BIT STRING {4 bits}	4
Half Frame Index	0, 1	1
CHOICE		3
Frequency Range 1	*Frequency Range 2*	
1 MSB of subcarrier offset (k_{SSB}) 2 reserved bits	3 MSB of SS/PBCH Block Index	
		Total of 8 bits

Table 145 – Additional information added to the PBCH by the Physical layer

★ In the case of Frequency Range 2, the 3 Most Significant Bits of the SS/PBCH Block Index are added by the Physical layer. Frequency Range 2 supports up to 64 SS/PBCH Blocks within a single burst, i.e. up to 64 SS/PBCH beams. Indexing all 64 SS/PBCH Blocks requires 6 bits. The remaining 3 bits are transferred by the DMRS for the PBCH. Frequency Range 1 supports a maximum of 8 SS/PBCH Blocks within a single burst so the 3 bits transferred by the DMRS are sufficient. SS/PBCH Block Indices are presented in section 3.4 (Figure 144)

★ Table 146 presents additional information which can be deduced from the PBCH Demodulation Reference Signal (DMRS). This information is used to initialise the pseudo random sequence which populates the DMRS Resource Elements. The set of 3 bits can generate 8 different sequences. A UE can use blind detection to identify which sequence has been generated for the DMRS and thus deduce the set of 3 bits. Blind detection is relatively demanding in terms of UE processing because it can require the UE to correlate each of the 8 sequences with the DMRS

CHOICE		
Frequency Range 1 ≤3 GHz	*Frequency Range 1 > 3 GHz*	*Frequency Range 2*
SS/PBCH Block Index (2 bits) Half Frame Index (1 bit)	SS/PBCH Block Index (3 bits)	SS/PBCH Block Index (3 LSB)
Total of 3 bits		

Note : the threshold of 3 GHz is replaced by a threshold of 2.4 GHz for some cases. See Table 56 (section 3.4)

Table 146 – Information which can be deduced from the pseudo-random sequence belonging to the PBCH DMRS

★ Operating bands below 3 GHz support up to 4 SS/PBCH Blocks within a single burst. Indexing these 4 SS/PBCH requires 2 bits of information. The third bit is used to indicate the Half Frame Index which is also transferred within the PBCH payload

★ Operating bands within Frequency Range 1 above 3 GHz support up to 8 SS/PBCH Blocks within a single burst. Indexing these 8 SS/PBCH requires 3 bits of information

★ Operating bands within Frequency Range 2 support up to 64 SS/PBCH Blocks within a single burst. Indexing these 64 SS/PBCH requires 6 bits of information. 3 bits can be deduced from the DMRS, while the remaining 3 bits are transferred within the PBCH payload

★ 3GPP References: TS 38.211, TS 38.212, TS 38.331

6.2 SYSTEM INFORMATION BLOCK 1

★ System Information Block 1 (SIB1) is transmitted using the BCCH logical channel, the DL-SCH transport channel and the PDSCH physical channel. It contains information which allows a UE to determine whether or not it is permitted to access the cell. SIB1 also provides scheduling information for all remaining SIB and some radio resource configuration information, e.g. timers and constants

★ The MIB and SIB1 are known as 'Minimum System Information' because they provide the basic parameter set required for initial access and acquiring any other System Information. SIB1 is also known as 'Remaining Minimum System Information' (RMSI) which can be received after decoding the content of the MIB on the PBCH

★ In the case of cells belonging to the EN-DC Non-Standalone Base Station architecture, it is not necessary to broadcast SIB1. This is because the initial access procedure uses a 4G cell rather than a 5G cell. Dedicated signalling can be used to provide the UE with all of the relevant configuration information once the UE has connected to the 4G cell

★ PDSCH resources for SIB1 are allocated using a PDCCH DCI Format 1_0 transmission within a 'Type 0' Common Search Space Set. This Search Space Set and its associated CORESET are configured by the MIB. Section 3.5.3 describes the Search Space Set for SIB1

★ When using the SS/PBCH Block and CORESET multiplexing pattern 1, the repetition period for SIB1 is 20 ms. Multiplexing pattern 1 is always used by operating bands within Frequency Range 1. Operating bands within Frequency Range 2 can use multiplexing patterns 1, 2 or 3. In the case of Multiplexing patterns 2 and 3, SIB1 has a repetition period which equals the repetition period of the SS/PBCH Block (SS/PBCH Block and CORESET multiplexing patterns are described in section 3.5.3)

★ In the case of the Centralised Unit (CU) – Distributed Unit (DU) Base Station architecture, the DU is responsible for generating the content of both the MIB and SIB1. The DU forwards the MIB and SIB1 to the CU using the *gNB-DU System Information* parameter structure which can be included within either the F1AP: 'F1 Setup Request' or F1AP: 'gNB-DU Configuration Update' message

★ The content of SIB1 is presented in Table 147. *q-RxLevMin* defines the minimum RSRP for cell selection and reselection. The actual value of *Qrxlevmin* is 2 × the signalled value. This means that the actual value has a step size of 2 dBm. The RSRP for cell selection and reselection is measured from the Secondary Synchronisation Signal

★ *q-RxLevMinOffset* is applicable to UE which are completing periodic searches for a higher priority PLMN while camped on a Visited PLMN. The offset is added to the value of *Qrxlevmin* to increase the minimum RSRP requirement

★ *q-RxLevMinSUL* is used instead of *q-RxLevMin* if the UE supports a Supplemental Uplink (SUL) for this cell. The link budget for the Supplemental Uplink is likely to be different when compared to the Normal Uplink (NUL). This means that it might be appropriate to configure a different Qrxlevmin. For example, a Supplemental Uplink in a lower operating band may provide an improved uplink link budget so the value of Qrxlevmin could be reduced if coverage is uplink limited

★ *q-QualMin* defines the minimum RSRQ for cell selection and reselection. This information element is optional and excluding it from SIB1 means that the UE applies a default value of minus infinity, i.e. the RSRQ check is always passed. The RSRQ is measured from the Secondary Synchronisation Signal

★ *q-QualMinOffset* is applicable to UE which are completing periodic searches for a higher priority PLMN while camped on a Visited PLMN. The offset is added to the value of *Qqualmin* to increase the minimum RSRQ requirement

★ *cellAccessRelatedInfo* allows multiple PLMN Identities to be listed (each PLMN Identity is defined by its Mobile Country Code (MCC) and Mobile Network Code (MNC)). Each PLMN Identity has an associated Tracking Area Code (TAC), RAN Area Code (RANAC), Cell Identity and flag to indicate whether or not the cell is reserved for operator use

SIB1				
cellSelectionInfo	q-RxLevMin	-70 to – 22 dBm (actual value = signalled value × 2)		
	q-RxLevMinOffset	1 to 8 dB (actual value = signalled value × 2)		
	q-RxLevMinSUL	-70 to – 22 dBm (actual value = signalled value × 2)		
	q-QualMin	-43 to -12 dB		
	q-QualMinOffset	1 to 8		
cellAccessRelatedInfo	1 to 12 instances of PLMN-IdentityInfo	1 to 12 instances of PLMN-Identity	mcc	SEQUENCE {3 digits}
			mnc	SEQUENCE {2 or 3 digits}
		trackingAreaCode	BIT STRING {24 bits}	
		ranac	0 to 255	
		cellIdentity	BIT STRING {36 bits}	
		cellReservedForOperatorUse	Reserved, notReserved	
	cellReservedForOtherUse	true		
connEstFailureControl	connEstFailCount	1, 2, 3, 4		
	connEstFailOffsetValidity	30, 60, 120, 240, 300, 420, 600, 900 seconds		
	connEstFailOffset	0 to 15		
si-SchedulingInfo	see Table 148			
servingCellConfigCommon	see Table 151			
ims-EmergencySupport	true			
eCallOverIMS-Support	true			
ue-TimerAndConstants	t300	100, 200, 300, 400, 600, 1000, 1500, 2000 ms		
	t301	100, 200, 300, 400, 600, 1000, 1500, 2000 ms		
	t310	0, 50, 100, 200, 500, 1000, 2000 ms		
	n310	1, 2, 3, 4, 6, 8, 10, 20		
	t311	1000, 3000, 5000, 10 000, 15 000, 20 000, 30 000 ms		
	n311	1, 2, 3, 4, 5, 6, 8, 10		
	t319	100, 200, 300, 400, 600, 1000, 1500, 2000 ms		
uac-BarringInfo	see Table 152			
useFullResumeID	true			

Table 147 – Content of System Information Block 1 (SIB1)

★ *trackingAreaCode* has a length of 24 bits providing a range from 0 to 16 777 215. In contrast, 4G uses Tracking Area Codes which have a length of 16 bits providing a range from 0 to 65 535. This highlights that 5G allows greater flexibility and scope for planning large numbers of Tracking Areas

★ *ranac* defines the RAN Area Code which can be used when configuring a RAN Notification Area for the RRC Inactive state, i.e. a RAN Notification Area can be defined as a set of 'PLMN Identity/Tracking Area Code/RAN Area Code' combinations. A UE in the RRC Inactive State can read the content of SIB1 when reselecting a new cell to determine whether or not the UE has remained within the same RAN Notification Area, or the UE has changed RAN Notification Area and needs to trigger an update procedure

★ *cellIdentity* is used to uniquely identify a cell within the PLMN. The combination of PLMN Identity and *cellIdentity* generates the New Radio Cell Global Identity (NCGI). The *cellIdentity* has a length of 36 bits which are used to identify both the Base Station and the cell. The Base Station Identity can occupy between 22 and 32 bits, leaving between 14 and 4 bits to identify the cell within the Base Station. Allocating an increased number of bits for the Base Station Identity allows more Base Stations to be deployed within the PLMN but reduces the number of cells which can be configured at each Base Station

★ 4G uses cell identities which have a length of 28 bits rather than 36 bits. The complete set of 28 bits can be used to identify the Base Station when deploying a Home eNode B with a single cell. Otherwise, the Base Station Identity can occupy 18, 20 or 21 bits from the set of 28 bits. These figures illustrate that 5G networks are able to support increased numbers of Base Stations and cells

★ The *cellIdentity* also provides an alternative solution for defining RAN Notification Areas, i.e. a RAN Notification Area can be defined as a set of 'PLMN Identity/Cell Identity' combinations. In this case, the RAN Notification Area can include up to 32 cells within a specific PLMN

★ The structure of SIB1 illustrates that multiple *cellIdentity* values and multiple *trackingAreaCode* values can be listed. This approach provides additional flexibility for network sharing deployment scenarios. It means that each operator sharing a cell can plan its own Tracking Area Codes (TAC) and its own cell identities. This helps to minimise the co-ordination required between operators

★ *cellReservedForOperatorUse* indicates whether or not the cell is reserved such that only UE which have Access Identities 11 or 15, and are camped on their Home PLMN or an Equivalent Home PLMN are permitted access to the cell. Access Identity 11 is mapped directly from Access Class 11 and is intended for 'PLMN Use'. Similarly, Access Identity 15 is mapped directly from Access Class 15 and is intended for 'PLMN Staff'. UE with other Access Identities treat the cell as barred. Unified Access Control is described in section 1.11

★ *cellReservedForOtherUse* does not have a specific purpose within the release 15 version of the 3GPP specifications but has been introduced to provide forward compatibility with services which may be introduced in the future. If this flag is set to 'true' then all UE treat the cell as barred, i.e. it has the same impact as the *cellBarred* flag within the MIB. The example of Closed Subscriber Group (CSG) cells can be used to illustrate how this flag provides forward compatibility. The release 15 version of the 3GPP specifications does not support CSG cells for New Radio. If the release 16 version of the specifications introduces support for CSG cells then a release 16 UE will understand the rules for accessing a CSG cell (only subscribers belonging to the closed subscriber group are permitted to access the cell). Release 15 UE will not have any knowledge of these rules but the *cellReservedForOtherUse* flag can be used to ensure that a release 15 UE does not attempt to access the CSG cell

★ The *connEstFailureControl* parameter set is used to manage UE which experience repeated failures when attempting to establish an RRC connection. A UE starts timer T300 after sending an *RRCSetupRequest* message. The connection establishment attempt fails if T300 expires before the UE receives a response from the Base Station. The UE counts the number of times that T300 expires after consecutive connection establishment attempts on a specific cell. If this counter reaches the value of *connEstFailCount* then a timer is started with a duration defined by *connEstFailOffsetValidity*. While this timer is running, the UE subtracts the value of *connEstFailOffset* from its RSRP and RSRQ measurements for the cell it is attempting to access. This makes the cell appear less attractive and more likely to fail the cell selection criteria. The offset is also applied to neighbouring intra-frequency cells and inter-frequency cells with equal priority. A UE is permitted to ignore the offset if the UE cannot find an alternative cell after being forced to leave the current cell due to the offset causing the cell selection criteria to fail

★ *ims-EmergencySupport* indicates whether or not the cell supports IMS emergency services for UE which are in limited service mode. Limited service mode means that the UE is camped on an 'acceptable' cell rather than a 'suitable' cell. Both 'acceptable' and 'suitable' cells require the cell selection criteria to be fulfilled

★ *eCallOverIMS-Support* indicates whether or not the cell supports emergency calls over IMS. A UE which is in limited service mode has to check both the *ims-EmergencySupport* and *eCallOverIMS-Support* flags

★ *t300* is started after sending an *RRCSetupRequest* message. *t300* is stopped if the UE receives an *RRCSetup* or *RRCReject* message, or if the UE completes a cell reselection, or if the higher layers decide to abort the connection establishment attempt. The connection establishment attempt fails if *t300* expires

★ *t301* is started after sending an *RRCReestablishmentRequest* message. *t301* is stopped if the UE receives an *RRCReestablishment* or *RRCSetup* message, or if the selected cell becomes 'unsuitable'. The UE moves to RRC IDLE mode if *t301* expires

★ *t310* is started after receiving *n310* consecutive 'out-of-sync' indications from the Physical layer of the primary serving cell belonging to either the Master Cell Group (MCG) or Secondary Cell Group (SCG). *t310* is stopped if the UE receives *n311* consecutive 'in-sync' indications from the Physical layer. Radio Link Failure (RLF) is detected if *t310* expires for the primary serving cell belonging to the MCG. If security has not yet been activated, the UE moves to RRC IDLE mode. Otherwise, the UE initiates the RRC Connection Re-establishment procedure. If *t310* expires for the primary serving cell belonging to the SCG, the UE informs the MCG using the RRC: *SCGFailureInformationNR* message (assuming the SCG is New Radio)

★ *t311* is started after initiating the RRC Connection Re-establishment procedure. *t311* is stopped if the UE manages to select a suitable New Radio cell. The UE is then able to initiate the transmission of the *RRCReestablishmentRequest* message. *t311* is also stopped if the UE manages to select a suitable cell belonging to another Radio Access Technology. However, in this case the UE does not attempt to transmit the *RRCReestablishmentRequest* message. A UE moves to RRC IDLE if *t311* expires

★ *t319* is started after sending an *RRCResumeRequest* or *RRCResumeRequest1* message. *t319* is stopped if the UE receives an *RRCResume, RRCSetup, RRCRelease* or *RRCReject* message, or if the UE completes a cell reselection, or if the higher layers decide to abort the resume connection attempt. A UE moves to RRC IDLE if *t319* expires

★ *useFullResumeID* represents a flag which is applicable to UE in the RRC Inactive state. A UE uses this flag to determine whether it should use the *RRCResumeRequest* or the *RRCResumeRequest1* message when requesting a transition back to RRC Connected mode. *RRCResumeRequest* includes the short I-RNTI so it is a relatively small message which offers good coverage performance. *RRCResumeRequest1* includes the full I-RNTI so it is a longer message with more restricted coverage (these messages cannot be segmented because they are transmitted as MSG3 during the random access procedure)

★ Table 148 presents the *si-SchedulingInfo* parameter set belonging to SIB1. *schedulingInfoList* specifies the set of SIB which are available for transmission by the serving cell. Each SIB is associated with an instance of *si-BroadcastStatus* which indicates whether the SIB is broadcast using a regular periodic pattern, or requires the UE to request transmission using the 'on-demand' procedure

★ *si-Periodicity* defines the period between SIB transmissions, and is used as an input when calculating the specific radio frames during which the Base Station will transmit a SIB

★ *valueTag* is an integer value which is used to indicate that the content of a specific SIB has changed, and that the UE should re-acquire the SIB. The *valueTag* is incremented if the content of the SIB is changed. This solution allows the UE to identify changes to the set of SIB without having to decode and check each individual transmission. There are some exceptions which allow SIB content to be modified without incrementing the *valueTag*. For example, the timing information within SIB9 can be updated without impacting the *valueTag*

★ *areaScope* is applicable when a UE has already acquired one of more SIB and has stored those SIB for future reference. If *areaScope* is excluded then the SIB has a scope of the serving cell. This means the UE must re-acquire that SIB when moving to a neighbouring cell. In this case, the UE uses the combination of PLMN identity, cell identity and *valueTag* to determine when the SIB needs to be re-acquired, i.e. the SIB needs to be re-acquired if any of those three variables change. If *areaScope* is included then the SIB has a scope of a 'System Information Area'. This means that the UE only needs to re-acquire the SIB when moving outside the current 'System Information Area', i.e. the same SIB content can be applied across a group of cells. The 'System Information Area' is identified using the *systemInformationAreaID* (shown at the base of Table 148). In this case, the UE uses the combination of PLMN identity, System Information Area identity and *valueTag* to determine when the SIB needs to be re-acquired

si-SchedulingInfo					
schedulingInfoList	1 to 32 instances of SchedulingInfo	si-BroadcastStatus	broadcasting, notBroadcasting		
		si-Periodicity	8, 16, 32, 64, 128, 256, 512 radio frames		
		sib-MappingInfo	1 to 32 instances of SIB-TypeInfo	type	SIB 2, 3, 4, 5, 6, 7, 8, 9
				valueTag	0 to 31
				areaScope	true
si-WindowLength	5, 10, 20, 40, 80, 160, 320, 640, 1280 slots				
si-RequestConfig	rach-OccasionsSI	rach-ConfigSI	prach-ConfigurationIndex		0 to 255
			msg1-FDM		1, 2, 4, 8
			msg1-FrequencyStart		0 to 274
			zeroCorrelationZoneConfig		0 o 15
			preambleReceivedTargetPower		-202 to -60
			preambleTransMax		3, 4, 5, 6, 7, 8, 10, 20, 50, 100, 200
			powerRampingStep		0, 2, 4, 6 dB
			ra-ResponseWindow		1, 2, 4, 8, 10, 20, 40, 80 slots
		ssb-perRACH-Occasion	oneEighth, oneFourth, oneHalf, one, two, four, eight, sixteen		
	si-RequestPeriod	1, 2, 4, 6, 8, 10, 12, 16			
	si-RequestResources	1 to 32 instances of SI-RequestResources	ra-PreambleStartIndex		0 to 63
			ra-AssociationPeriodIndex		0 to 15
			ra-ssb-OccasionMaskIndex		0 to 15
si-RequestConfigSUL	same parameter structure as used for *si-RequestConfig*				
systemInformationAreaID	BIT STRING (24 bits)				

Table 148 – *si-SchedulingInfo* parameter set

★ *si-WindowLength* defines the duration of the time window during which a SIB will be scheduled for transmission. A single value is applied to all SIB. The transmission time window for each SIB occurs once per SI period (defined by *si-Periodicity*). Figure 237 illustrates an example of the SIB transmission windows for a set of 3 SIB. Within each window, a UE checks for PDCCH transmissions using the SI-RNTI. The *servingCellConfigCommon* section of SIB1 provides the UE with information regarding the CORESET and Search Space Sets to be checked for PDCCH transmissions (the CORESET and Search Space Sets define the Resource Blocks and symbols where the PDCCH may be transmitted)

★ *si-RequestConfig* is included within SIB1 if the Base Station supports 'On-demand' SIB requests using MSG1, i.e. the reception of a specific PRACH preamble serves as a request for a specific SIB, or a specific set of SIB. This requires at least one SIB to have *si-BroadcastStatus* set to 'notBroadcasting'. If *si-RequestConfig* is excluded and at least one SIB has *si-BroadcastStatus* set to 'notBroadcasting', then 'On-demand' SIB requests are based upon MSG3 transmissions, i.e. the *RRCSystemInfoRequest* message. Figure 235 illustrates the use of MSG1 and MSG3 for 'On-demand' SIB requests

★ *rach-ConfigSI* defines the PRACH configuration to be used for MSG1 'On-demand' System Information requests. The combination of *prach-ConfigurationIndex*, *msg1-FDM* and *msg2-FrequencyStart* define the time domain and frequency domain positions of the PRACH occasions. The configuration index also determines the PRACH Format to be used for MSG1. *msg1-FDM* defines the number of PRACH occasions which are multiplexed in the frequency domain, while *msg1-FrequencyStart* specifies the first Resource Block belonging to the first of the frequency multiplexed PRACH occasions. *zeroCorrelationZoneConfig* determines the number of PRACH preambles which can be generated from each root sequence. The root sequence itself is not configured within this part of SIB1 but is included within *ServingCellConfigCommon*

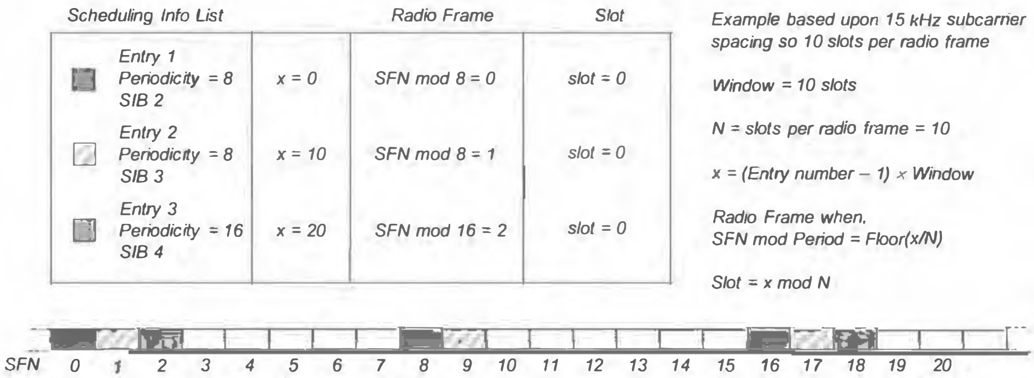


Figure 237 – Example timing of transmission windows for a set of SIB

★ *preambleReceivedTargetPower* is used within the open loop power control calculation for each PRACH preamble transmission. This parameter will impact the UE transmit power, uplink interference levels and the number of preambles required for successful reception. *preambleTransMax* defines the maximum number of preambles which can be used during a specific PRACH procedure, while *powerRampingStep* defines the increase in transmit power between successive PRACH preamble transmissions. The *ra-ResponseWindow* defines the number of slots that the UE waits for reception of MSG2 before sending another PRACH preamble

★ *ssb-perRACH-Occasion* defines the number of SS/PBCH Blocks associated with each PRACH occasion. This equates to the number of beams associated with each PRACH occasion. If more than one SS/PBCH Block is associated with each PRACH occasion, the set of 64 PRACH preambles belonging to each occasion are shared between beams. If less than one SS/PBCH Block is associated with each PRACH occasion, each beam uses multiple sets of 64 PRACH preambles

★ *si-RequestPeriod* determines the period between PRACH resources used for 'On-demand' System Information requests. The Request Period is specified in terms of 'Association Periods'. A single 'Association Period' is a time window which allows each SS/PBCH Block to have access to at least one PRACH occasion

★ *si-RequestResources* defines the specific MSG1 resources associated with each 'On-demand' SIB. If there is only a single entry within the list, then that entry is used to request all 'On-demand' SIB. Otherwise, there is a separate entry for each SIB

★ *ra-PreambleStartIndex* specifies the first PRACH preamble allocated to request the 'On-demand' SIB. If multiple SS/PBCH Blocks share the same PRACH occasion, then multiple consecutive PRACH preambles will be allocated. *ra-AssociationPeriodIndex* specifies the 'Association Period' within the *si-RequestPeriod* that the PRACH preamble can be transmitted. *ra-ssb-OccasionMaskIndex* determines the set of PRACH occasions which are available for use

★ Table 149 presents the first part of the *ServingCellConfigCommonSIB* parameter set. This first part includes *downlinkConfigCommon*

★ *frequencyBandList* is used within the context of 'Multiple Frequency Bands', which refers to operating bands which overlap, i.e. a specific carrier frequency can belong to multiple operating bands. The configuration of 'Multiple Frequency Bands' allows a UE to use an operating band which is not normally supported by the UE. For example, a UE used within its home country may support operating band 'Home'. That UE may roam into a different country which offers services using operating band 'Roam'. The UE may not normally support operating band 'Roam'. However, if operating band 'Roam' overlaps with operating band 'Home', the UE is physically capable of using at least some of the carriers belonging to operating band 'Roam'

★ *frequencyBandList* allows up to 8 compatible operating bands to be listed. In each case, it is possible to specify up to 8 pairs of {*additionalPmax*, *additionalSpectrumEmission*}, i.e. for a specific maximum transmit power, the UE must achieve a specific additional spectrum emission requirement

★ *offsetToPointA* specifies the Resource Block offset between Common Resource Block 0 and the Common Resource Block which overlaps with the start of the SS/PBCH. The numerology used for the Common Resource Block numbering is set equal to the value of *subCarrierSpacingCommon* provided within the MIB. *offsetToPointA* is used in combination with the subcarrier offset (k_{SSB}) which is derived from the MIB (and PBCH Physical layer payload in the case of Frequency Range 1). The subcarrier offset (k_{SSB}) represents an offset from subcarrier 0 of the Common Resource Block identified by *offsetToPointA* to subcarrier 0 of the SS/PBCH. The combination of these parameters allows the UE to identify the frequency domain position of the lower edge of the channel bandwidth

★ SIB1 includes an instance of *scs-SpecificCarrierList* for each of the supported numerologies. The *offsetToCarrier* value specifies the number of Resource Blocks between Point A and subcarrier 0 within the lowest usable Resource Block, i.e. it is possible that not all Common Resource Blocks are available for transmission, e.g. due to guard band requirements. Figure 111 in section 2.3.1 illustrates an example of unused Common Resource Blocks at the edge of the channel bandwidth. The *carrierBandwidth* value specifies the number of Resource Blocks which are available for that numerology

★ *txDirectCurrentLocation* provides the UE with information regarding the position of the DC subcarrier. The value specifies the subcarrier index which can range from 0 to 3299, i.e. 275 × 12 = 3300 values. A special value of 3300 indicates that the DC subcarrier is outside the channel bandwidth. As described in section 2.9.1 (Figure 130), local oscillator leakage can impact the performance of the DC subcarrier. The UE receiver can benefit from knowing the position of the DC subcarrier, i.e. knowing which subcarrier may have degraded performance

ServingCellConfigCommonSIB						
downlinkConfig Common	frequencyInfoDL	frequencyBandList	SEQUENCE {1 to 8 instances}			
			freqBandIndicatorNR	1 to 1024		
			nr-NS-PmaxList	SEQUENCE {1 to 8 instances}		
				additionalPmax	-30 to 33 dBm	
				additionalSpectrumEmission	0 to 7	
		offsetToPointA	0 to 2199			
		scs-SpecificCarrierList	SEQUENCE {1 to 5 instances}			
			offsetToCarrier	0 to 2199		
			subcarrierSpacing	15, 30, 60, 120 kHz		
			carrierBandwidth	1 to 275		
			txDirectCurrentLocation	0 to 4095		
	initialDownlinkBWP	genericParameters	locationAndBandwidth	0 to 37949		
			subcarrierspacing	15, 30, 60, 120 kHz		
			cyclicPrefix	extended		
		pdcch-ConfigCommon	SetupRelease { PDCCH-ConfigCommon }			
		pdsch-ConfigCommon	SetupRelease { PDSCH-ConfigCommon }			
	bcch-Config	modificationPeriodCoeff	2, 4, 8, 16			
	pcch-Config	defaultPagingCycle	32, 64, 128, 256 radio frames			
		nAndPagingFrameOffset	CHOICE			
			oneT	halfT	oneEigthT	oneSixteenthT
			0, 1	0 to 3	0 to 7	0 to 15
		ns	four, two, one			
		firstPDCCH-MonitoringOccasionOfPO				

Table 149 – *servingCellConfigCommon* parameter set – Part 1

- A UE uses an 'Initial' Bandwidth Part when first accessing a cell. The *initialDownlinkBWP* parameter structure uses the *locationAndBandwidth* information element to specify the set of contiguous Common Resource Blocks belonging to the Initial Downlink Bandwidth Part. The value is coded using Resource Indication Value (RIV) rules with N_{BWP}^{size} = 275 (these rules are described in section 3.6.4.2.2 within the context of allocating Resource Blocks for the PDSCH). The RB_{start} value which is derived from the *locationAndBandwidth* value is added to the value of *offsetToCarrier*, i.e. the starting position of the Bandwidth Part is relative to the first usable Resource Block. The *initialDownlinkBWP* parameter structure also specifies the subcarrier spacing and cyclic prefix to be used for the Bandwidth Part

- *pdcch-ConfigCommon* and *pdsch-ConfigCommon* provide the UE with cell level information for receiving the PDCCH and PDSCH within the initial Bandwidth Part. The content of *PDCCH-ConfigCommon* is presented in Table 66 within section 3.5.2. This parameter structure provides the UE with information regarding Control Resource Sets (CORESETs) and Search Space Sets. These can be used when completing the random access procedure and when receiving paging messages. The content of *PDSCH-ConfigCommon* is presented in Table 87 within section 3.6. This parameter structure provides the UE with a look-up table for the allocation of PDSCH time domain resources, i.e. the time domain resource allocation field within Downlink Control Information (DCI) provides a pointer to a row within this table

- *bcch-Config* provides the modification period coefficient which is used to calculate the actual modification period in terms of radio frames: BCCH Modification Period = *modificationPeriodCoeff* × *defaultPagingCycle*. Modification period boundaries occur when SFN mod m = 0, where 'm' is the BCCH Modification Period. UE are notified of System Information changes using the 'Short Messages' field within DCI Format 1_0. This field can be included when the CRC bits belonging to DCI Format 1_0 are scrambled using the P-RNTI. Use of the P-RNTI means that UE in RRC Idle or RRC Inactive can receive System Information change notifications when 'waking-up' to receiving paging messages (based upon the paging DRX cycle pattern). If a UE receives a change notification during modification period 'x', the change itself is applied during modification period 'x+1'

- *pcch-Config* provides the parameter set which allows a UE to identify its Paging Frames (PF) and Paging Occasions (PO). The use of this parameter set is described in section 12.4.2

- Table 150 presents the second part of *ServingCellConfigCommonSIB*. This second part includes the *uplinkConfigCommon* and *supplementaryUplink* parameter sets

- *frequencyInfoUL* provides similar information to *frequencyInfoDL* but with the addition of *p-Max* and *frequencyShift7p5khz*

- *p-Max* defines the maximum UE transmit power permitted within the current cell. *p-Max* impacts the cell selection criteria if the UE transmit power capability is below the value of *p-Max*. It is assumed that the coverage of the cell has been planned based upon the value of *p-Max*. This means that the Base Station would not be able to receive a cell edge UE with a lower transmit power capability. In this case, *Qrxlevmin* is increased to ensure that the UE can only camp on the cell when the UE is closer to the Base Station. This corresponds to the value of 'Pcompensation' within the cell selection equation for *Srxlev*

★ *frequencyShift7p5khz* indicates whether or not the uplink center frequency should be increased by 7.5 kHz. This is an optional offset which can be applied depending upon the deployment scenario. The objective of this 7.5 kHz offset is to allow coexistence with legacy 4G transmissions. The uplink of 4G applies a 7.5 kHz offset when generating the SC-FDMA waveform to avoid having a 0 Hz subcarrier (also known as the DC subcarrier). The uplink of 5G does not apply this offset when generating its waveform so a 7.5 kHz frequency shift is required to achieve subcarrier alignment with 4G (assuming that 5G uses the 15 kHz subcarrier spacing). This frequency shift can be applied to either Supplemental Uplink operating bands and to the uplink of FDD operating bands

ServingCellConfigCommonSIB (continued)					
uplinkConfig Common	frequencyInfoUL	frequencyBandList	SEQUENCE {1 to 8 instances}		
			freqBandIndicatorNR	1 to 1024	
			nr-NS-PmaxList	SEQUENCE {1 to 8 instances}	
				additionalPmax	-30 to 33 dBm
				additionalSpectrumEmission	0 to 7
		absoluteFrequencyPointA	0 to 3279165		
		scs-SpecificCarrierList	SEQUENCE {1 to 5 instances}		
			offsetToCarrier	0 to 2199	
			subcarrierSpacing	15, 30, 60, 120, 240	
			carrierBandwidth	1 to 275	
		p-Max	-30 to 33 dBm		
		frequencyShift7p5khz	true		
	initialUplinkBWP	genericParameters	BWP	locationAndBandwidth	0 to 37949
				subcarrierSpacing	15, 30, 60, 120, 240
				cyclicPrefix	extended
			SetupRelease { RACH-ConfigCommon }		
			SetupRelease { PUSCH-ConfigCommon }		
			SetupRelease { PUCCH-ConfigCommon }		
	timeAlignmentTimerCommon	500, 750, 1280, 1920, 2560, 5120, 10240 ms, infinity			
supplementaryUplink	same parameter structure as used for uplink*ConfigCommon*				

Table 150 – *servingCellConfigCommon* parameter set – Part 2

★ Similar to the downlink, the *initialUplinkBWP* parameter structure uses the *locationAndBandwidth* information element to specify the set of contiguous Common Resource Blocks belonging to the Initial Uplink Bandwidth Part. The value is coded using Resource Indication Value (RIV) rules with N_{BWP}^{size} = 275 (these rules are described in section 3.6.4.2.2 within the context of allocating Resource Blocks for the PDSCH). The RB_{start} value which is derived from the *locationAndBandwidth* value is added to the value of *offsetToCarrier*, i.e. the starting position of the Bandwidth Part is relative to the first usable Resource Block. The *initialUplinkBWP* parameter structure also specifies the subcarrier spacing and cyclic prefix to be used for the Bandwidth Part

★ The content of *RACH-ConfigCommon* is presented in Table 255 within section 13.1.1. This parameter structure provides the UE with the information required to complete the random access procedure. For example, it specifies the PRACH Configuration Index, the Zero Correlation Zone configuration, the PRACH Root Sequence, the grouping of PRACH preambles, PRACH power control parameters and RSRP thresholds for initiating the random access procedure with a specific beam

★ The content of *PUSCH-ConfigCommon* is presented in Table 195 within section 7.4. This parameter structure provides the UE with a look-up table for the allocation of PUSCH time domain resources, i.e. the time domain resource allocation field within Downlink Control Information (DCI) provides a pointer to a row within this table. The parameter structure also provides some power control information and a flag to indicate whether or not group hopping is to be applied when selecting a Zadoff-Chu sequence for the PUSCH DMRS (group hopping is applicable when Transform Precoding is enabled (DFT-S-OFDM waveform is used))

★ The content of *PUCCH-ConfigCommon* is presented in Table 181 within section 7.3. This structure provides the *pucch-ResourceCommon* information element which defines a pointer towards a cell specific PUCCH resource. It also provides power control information and group/sequence hopping information

★ *timeAlignmentTimerCommon* specifies the maximum time that a UE remains synchronised in the uplink direction after receiving a Timing Advance Command. A UE re-starts the Time Alignment Timer whenever a Timing Advance Command is received, i.e. the Base Station must send Timing Advance Commands using a period which is less than the Time Alignment Timer. If the Time Alignment Timer expires, the UE assumes that it has lost uplink synchronisation. The UE must then use the random access procedure to re-synchronise before continuing to transmit on the PUSCH, PUCCH or SRS. Timing Advance is described in section 13.2

- Table 151 presents the third part of *ServingCellConfigCommonSIB*

- *n-TimingAdvanceOffset* specifies the value of N_{TA_offset} within the uplink frame timing calculation. Uplink frame timing starts in advance of the downlink frame timing using a margin defined by $(N_{TA} + N_{TA\_offset}) \times T_c$. The Timing Advance Command, N_{TA} is dynamically updated by the Base Station using MAC Control Elements (MAC CE). The semi-static value of N_{TA_offset} depends upon the deployment scenario. By default, Frequency Range 1 uses *n-TimingAdvanceOffset* = 25600, while Frequency Range 2 uses *n-TimingAdvanceOffset* = 13792. However, if 4G/5G spectrum sharing is configured, it is necessary to ensure that the 4G and 5G uplink frames are time aligned. 4G uses an offset of 0 for FDD and an offset of 624 T_s for TDD. 624 T_s equates to 39936 T_c. Thus, SIB1 can broadcast a value of 0 or 39936 when spectrum sharing is applied to FDD or TDD respectively. It is not necessary to broadcast a value for Frequency Range 2 because only a single value is possible (spectrum sharing is not applicable to Frequency Range 2)

ServingCellConfigCommonSIB (continued)		
n-TimingAdvanceOffset	0, 25600, 39936	
ssb-PositionsInBurst	inOneGroup	BIT STRING {8 bits}
	groupPresence	BIT STRING {8 bits}
ssb-PeriodicityServingCell	5, 10, 20, 40, 80, 160 ms	
tdd-UL-DL-ConfigurationCommon	see Table 33 in section 2.2	
ss-PBCH-BlockPower	-60 to 50 dBm	

Table 151 – *servingCellConfigCommon* parameter set – Part 3

- *ssb-PositionsInBurst* specifies the set of SS/PBCH Blocks which are broadcast by the cell. When using an operating band below 3 GHz, the 4 leftmost bits of *inOneGroup* are used to indicate which SS/PBCH Blocks are active. When using an operating band between 3 and 6 GHz, all 8 bits of *inOneGroup* are used to indicate which SS/PBCH Blocks are active. When using an operating band above 6 GHz, the 64 SS/PBCH Blocks are divided into 8 groups. The *inOneGroup* bit string indicates which SS/PBCH Blocks within a group are active, while the *groupPresence* bit string indicates which groups are active

- *ssb-PeriodicityServingCell* specifies the periodicity of the SS/PBCH Burst, i.e. each beam transmits an SS/PBCH Block with this periodicity. During the initial cell selection procedure, a UE assumes that a burst of SS/PBCH Blocks is transmitted every 20 ms, i.e. each beam transmits the PBCH once every 20 ms. This means that cells supporting initial access should have SS/PBCH Block periods of 5, 10 or 20 ms

- *ss-PBCH-BlockPower* specifies the downlink transmit power of a single Resource Element used by the Secondary Synchronisation Signal (SSS), the PBCH and the PBCH Demodulation Reference Signal (DMRS). 3GPP specifies that the Primary Synchronisation Signal (PSS) can be transmitted with the same power as the SSS/PBCH/DMRS, or it can be transmitted with 3 dB more power. There is scope to increase the transmit power of the PSS because there are unused Resource Elements both above and below the PSS. Increasing the power by 3 dB means that the total power within each symbol of the SS/PBCH Block remains approximately constant. The network vendor selects the PSS power relative to the SSS/PBCH/DMRS power. The UE is not provided with information regarding the selection between 0 dB and 3 dB so the UE is required to deduce the offset

- Table 152 presents the *uac-BarringInfo* parameter set belonging to SIB1. This parameter set provides information which is applicable to cell barring based upon Unified Access Control (UAC). Unified Access Control is introduced within section 1.11

- *uac-BarringForCommon* is used to link Access Categories to UAC Barring parameter sets. *accessCategory* identifies the specific Access Category using the numbering scheme presented in section 1.11. *uac-barringInfoSetIndex* acts as a pointer towards an instance of *uac-BarringInfoSetList* specified later within the parameter set

- *uac-BarringperPLMN-List* and *uac-BarringForCommon* provide similar information but the former provides information which is applicable to specific PLMN. *plmn-IdentityIndex* points towards a specific PLMN Identity based upon the order in which the PLMN are listed within SIB1. Explicit listing of the barring list uses the same format as the common barring information, i.e. each Access Category is linked with a pointer towards an instance of *uac-BarringInfoSetList*. Implicit listing of the barring list specifies a pointer towards an instance of *uac-BarringInfoSetList* for each of the 63 Access Categories

- Unified Access Control specifies 64 Access Categories (0 to 63) whereas the *uac-BarringInfo* parameter set references only 63 Access Categories. Access Category 0 corresponds to 'Mobile Terminated' connection requests. These requests are not barred from the UE perspective. The network is responsible for managing this Access Category by deciding whether or not to broadcast specific paging messages

- *uac-BarringInfoSetList* provides the parameter set which is used when completing an access barring check. A UE starts by determining whether or not its Access Identity is subject to the access barring check. *uac-BarringForAccessIdentity* defines a bitmap where each bit maps onto a specific Access Identity (AI). The mapping is specified as: {bit 0, AI1}, {bit 1, AI2}, {bit 2, AI11}, {bit 3, AI12}, {bit 4, AI13}, {bit 5, AI14}, {bit 6, AI15}. A value of '0' within the bitmap indicates that an access attempt is allowed for the corresponding Access Identity. UE with Access Identity 0 must always complete the access barring check

- The access barring check involves the UE generating a uniformly distributed random number between 0 and 1. If the random number is less than the value of *uac-BarringFactor*, then the access attempt is permitted. Otherwise, the access attempt is barred. Configuring a value of '0' for *uac-BarringFactor* means that all checks will lead to barred access attempts

★ If an access attempt is barred, the UE generates a second uniformly distributed random number between 0 and 1. The value of T390 is then set equal to (0.7 + 0.6 × *rand*) × *uac-BarringTime* seconds, where 'rand' is the random number. T390 defines the duration that the UE treats the cell as barred for the corresponding Access Category. The UE can maintain a separate instance of T390 for each Access Category

★ *uac-AccessCategory1-SelectionAssistanceInfo* is intended to determine whether or not Access Category 1 is applicable to a specific UE. However, this parameter set is not applied when using the release 15 version of the 3GPP specifications

<table>
<tr><th colspan="6">uac-BarringInfo</th></tr>
<tr><td rowspan="18">uac-BarringInfo</td><td rowspan="3">uac-BarringForCommon</td><td colspan="4">SEQUENCE {1 to 63 instances}</td></tr>
<tr><td>accessCategory</td><td colspan="3">1 to 63</td></tr>
<tr><td>uac-barringInfoSetIndex</td><td colspan="3">1 to 8</td></tr>
<tr><td rowspan="7">uac-BarringperPLMN-List</td><td colspan="4">SEQUENCE {1 to 12 instances}</td></tr>
<tr><td>plmn-IdentityIndex</td><td colspan="3">1 to 12</td></tr>
<tr><td rowspan="5">uac-ACBarringListType</td><td colspan="3">CHOICE</td></tr>
<tr><td>uac-ImplicitACBarringList</td><td colspan="2">uac-ExplicitACBarringList</td></tr>
<tr><td>SEQUENCE {63}</td><td colspan="2">SEQUENCE {1 to 63}</td></tr>
<tr><td rowspan="2">1 to 8</td><td>accessCategory</td><td>1 to 63</td></tr>
<tr><td>uac-barringInfoSetIndex</td><td>1 to 8</td></tr>
<tr><td rowspan="4">uac-BarringInfoSetList</td><td colspan="4">SEQUENCE {1 to 8 instances}</td></tr>
<tr><td>uac-BarringFactor</td><td colspan="3">0, 0.05, 0.1, 0.15, 0.2, 0.25, 0.3, 0.4, 0.5, 0.6, 0.7, 0.75, 0.8, 0.85, 0.9, 0.95</td></tr>
<tr><td>uac-BarringTime</td><td colspan="3">4, 8, 16, 32, 64, 128, 256, 512 seconds</td></tr>
<tr><td>uac-BarringForAccessIdentity</td><td colspan="3">BIT STRING {7 bits}</td></tr>
<tr><td rowspan="4">uac-AccessCategory1-SelectionAssistanceInfo</td><td colspan="4">CHOICE</td></tr>
<tr><td colspan="2">plmnCommon</td><td colspan="2">individualPLMNList</td></tr>
<tr><td colspan="2" rowspan="2">a, b, c</td><td colspan="2">SEQUENCE {2 to 12 instances}</td></tr>
<tr><td colspan="2">a, b, c</td></tr>
</table>

Table 152 – *uac-BarringInfo* parameter set

6.3 SYSTEM INFORMATION BLOCK 2

★ SIB2 provides information which is common to intra-frequency, inter-frequency and inter-system cell reselection. It also provides information which is specifically applicable to intra-frequency cell reselection. The first part of the content belonging to SIB2 is presented in Table 153

★ Cell reselection can be based upon a combination of cell level and beam level measurements. When the Base Station transmits multiple beams, a UE is required to generate a cell level measurement from one or more beam level measurements

★ A UE derives a cell level measurement by calculating the linear average of the measurements belonging to a maximum of *nrofSS-BlocksToAverage* beams, where each beam has a measurement which exceeds *absThreshSS-BlocksConsolidation*. If SIB2 excludes either of these parameters, the UE generates the cell level measurement using only the strongest beam level measurement. The UE also generates the cell level measurement using only the strongest beam level measurement if the strongest beam has a measurement below the value of *absThreshSS-BlocksConsolidation*

★ The values of *thresholdRSRP*, *thresholdRSRQ* and *thresholdSINR* are translated into actual values using the mappings presented in section 0

★ When completing cell reselection towards an intra-frequency cell, or an equal priority inter-frequency cell, the UE starts by identifying the highest ranked cell based upon Rs = Qmeas,s + Qhyst - $\text{Qoffset}_{\text{temp}}$ for the serving cell, and Rn = Qmeas,n - Qoffset - $\text{Qoffset}_{\text{temp}}$ for the neighbouring cell. The UE then identifies the cells which have a rank > 'highest rank - *rangeToBestCell*'. For each of those cells, the UE counts the number of beams which have a measurement result greater than *absThreshSS-BlocksConsolidation*. Cell reselection is then completed towards the cell with the highest beam count. If SIB2 excludes *rangeToBestCell*, the UE completes cell reselection towards the highest ranked cell

★ *q-Hyst* is used when calculating the rank of the serving cell for cell reselection towards either an intra-frequency cell, or an equal priority inter-frequency cell

SIB2				
cellReselection InfoCommon	nrofSS-BlocksToAverage	2 to 16		
	absThreshSS-BlocksConsolidation	thresholdRSRP	0 to 127	
		thresholdRSRQ	0 to 127	
		thresholdSINR	0 to 127	
	rangeToBestCell	-24, -22, -20, -18, -16, -14, -12, -10, -8, -6, -5, -4, -3, -2, -1, 0, 1, 2, 3, 4, 5, 6, 8, 10, 12, 14, 16, 18, 20, 22, 24 dB		
	q-Hyst	0, 1, 2, 3, 4, 5, 6, 8, 10, 12, 14, 16, 18, 20, 22, 24 dB		
	speedStateReselectionPars	mobilityStateParameters	t-Evaluation	30, 60, 120, 180, 240 s
			t-HystNormal	30, 60, 120, 180, 240 s
			n-CellChangeMedium	1 to 16
			n-CellChangeHigh	1 to 16
		q-HystSF	sf-Medium	-6, -4, -2, 0 dB
			sf-High	-6, -4, -2, 0 dB
cellReselection ServingFreqInfo	s-NonIntraSearchP	0 to 31 dB (actual value = signalled value × 2)		
	s-NonIntraSearchQ	0 to 31 dB		
	threshServingLowP	0 to 31 dB (actual value = signalled value × 2)		
	threshServingLowQ	0 to 31 dB		
	cellReselectionPriority	0 to 7		
	cellReselectionSubPriority	0.2, 0.4, 0.6, 0.8		

Table 153 – Content of System Information Block 2 (SIB2) – Part 1

- ★ The UE uses the *mobilityStateParameters* to determine the current mobility state. The high mobility state is detected if the number of cell reselections within the *t-Evaluation* time window exceeds *n-CellChangeHigh*. Otherwise, the medium mobility state is detected if the number of cell reselections within the *t-Evaluation* time window exceeds *n-CellChangeMedium*. Otherwise, the UE adopts the normal mobility state. A UE makes the transition from the high or medium mobility states to the normal mobility state if the conditions for those states are not achieved during a time window defined by *t-HystNormal*

- ★ *q-HystSF* defines an offset which is added to *q-Hyst* for the medium and high mobility states. The negative offset values reduce the value of Qhyst which makes the current serving cell less attractive, i.e. cell reselection towards a neighbouring cell can occur earlier when the UE has medium or high mobility

- ★ *s-NonIntraSearchP* and *s-NonIntraSearchQ* define measurement triggering thresholds for RSRP and RSRQ respectively. A UE measures higher priority inter-frequency and inter-system layers irrespective of these thresholds. If Srxlev > *s-NonIntraSearchP* and Squal > *s-NonIntraSearchQ* then a UE does not have to measure inter-frequency layers with an equal or lower priority. Similarly, a UE does not have to measure inter-system layers with a lower priority (it is not permitted to configure inter-system layers with an equal priority). Otherwise, the UE has to measure inter-frequency layers with an equal or lower priority, and inter-system layers with a lower priority

- ★ If *s-NonIntraSearchP* is not broadcast within SIB2, the UE assumes a value of infinity which means that measurements are always triggered from the perspective of RSRP. If *s-NonIntraSearchQ* is not broadcast within SIB2, the UE assumes a value of 0 dB which means that measurements are always triggered from the perspective of RSRQ

- ★ *theshServingLowP* and *threshServingLowQ* define the RSRP and RSRQ serving cell thresholds which are applied when completing cell reselection towards a lower priority layer. A UE is only permitted to reselect a lower priority layer when the current serving cell is providing weak coverage, i.e. Srxlev < *theshServingLowP* if RSRP based cell reselection is configured, and Squal < *threshServingLowQ* if RSRQ based cell reselection is configured. RSRQ based cell reselection is configured by broadcasting a value for *threshServingLowQ*. RSRP based cell reselection is configured by excluding *threshServingLowQ* from SIB2

- ★ *cellReselectionPriority* and *cellReselectionSubPriority* are summed to generate the Absolute Priority for the serving cell

- ★ The second part of the content belonging to SIB2 is presented in Table 154. This part of SIB2 is applicable to intra-frequency cell reselection

- ★ *q-RxLevMin* defines the minimum RSRP requirement for the target intra-frequency cell. *q-RxLevMinSUL* is used instead of *q-RxLevMin* when it is broadcast and when the UE supports a Supplemental Uplink (SUL) for the current carrier. The link budget belonging to a Supplemental Uplink may differ from the link budget for the Normal Uplink. If coverage is uplink limited then *q-RxLevMinSUL* can be adjusted relative to *q-RxLevMin* to reflect the difference in link budgets

- ★ *q-QualMin* defines the minimum RSRQ requirement for the target intra-frequency cell. The UE assumes a value of minus infinity if this information element is not broadcast, i.e. the UE always passes the RSRQ check

SIB2 continued				
intraFreq CellReselectionInfo	q-RxLevMin	-70 to -22 dBm (actual value = signalled value × 2)		
	q-RxLevMinSUL	-70 to -22 dBm (actual value = signalled value × 2)		
	q-QualMin	-43 to -12 dB		
	s-IntraSearchP	0 to 31 dB (actual value = signalled value × 2)		
	s-IntraSearchQ	0 to 31 dB		
	t-ReselectionNR	0 to 7 s		
	frequencyBandList	SEQUENCE {1 to 8 instances}		
		freqBandIndicatorNR	1 to 1024	
		nr-NS-PmaxList	SEQUENCE {1 to 8 instances}	
			additionalPmax	-30 to 33 dBm
			additionalSpectrumEmission	0 to 7
	frequencyBandListSUL	SEQUENCE {1 to 8 instances}		
		freqBandIndicatorNR	1 to 1024	
		nr-NS-PmaxList	SEQUENCE {1 to 8 instances}	
			additionalPmax	-30 to 33 dBm
			additionalSpectrumEmission	0 to 7
	p-Max	-30 to 33 dBm		
	smtc	periodicityAndOffset	CHOICE	
			5 subframes	0 to 4
			10 subframes	0 to 9
			20 subframes	0 to 19
			40 subframes	0 to 39
			80 subframes	0 to 79
			160 subframes	0 to 159
		duration	1, 2, 3, 4, 5 subframes	
	ss-RSSI-Measurement	measurementSlots	BIT STRING {1 to 80 bits}	
		endSymbol	0 to 3	
	ssb-ToMeasure	CHOICE		
		Short Bitmap	BIT STRING {4 bits}	
		Medium Bitmap	BIT STRING {8 bits}	
		Long Bitmap	BIT STRING {64 bits}	
	deriveSSB-IndexFromCell	BOOLEAN		
	t-ReselectionNR-SF	sf-Medium	0.25, 0.5, 0.75, 1.0	
		sf-High	0.25, 0.5, 0.75, 1.0	

Table 154 – Content of System Information Block 2 (SIB2) – Part 2

★ *s-IntraSearchP* and *s-IntraSearchQ* define intra-frequency measurement triggering thresholds for RSRP and RSRQ respectively. If Srxlev > *s-IntraSearchP* and Squal > *s-IntraSearchQ* then a UE does not have to measure intra-frequency neighbours. A UE needs to be measuring its neighbours to complete cell reselection. These thresholds should be configured with values which ensure that the UE always starts measurements before needing to complete a cell reselection, i.e. the UE should start measuring before approaching cell edge. Initiating measurements too early may have a negative impact upon UE battery life

★ If *s-IntraSearchP* is not broadcast within SIB2, the UE assumes a value of infinity which means that measurements are always triggered from the perspective of RSRP. If *s-IntraSearchQ* is not broadcast within SIB2, the UE assumes a value of 0 dB which means that measurements are always triggered from the perspective of RSRQ

★ *t-ReselectionNR* defines the time-to-trigger for intra-frequency cell reselection. *sf-Medium* and *sf-High* (broadcast at the end of SIB2) define scaling factors for medium and high mobility conditions. *t-ReselectionNR* is multiplied by the appropriate scaling factor when medium or high mobility is detected

★ *frequencyBandList* and *frequencyBandListSUL* are used within the context of 'Multiple Frequency Bands', which refers to operating bands which overlap, i.e. a specific carrier frequency can belong to multiple operating bands. The configuration of 'Multiple Frequency Bands' allows a UE to use an operating band which is not normally supported by the UE. For example, a UE used within its home country may support operating band 'Home'. That UE may roam into a different country which offers services using operating band 'Roam'. The UE may not normally support operating band 'Roam'. However, if operating band 'Roam' overlaps with operating band 'Home', the UE is physically capable of using at least some of the carriers belonging to operating band 'Roam'

★ *frequencyBandList* and *frequencyBandListSUL* allow up to 8 compatible operating bands to be listed. In each case, it is possible to specify up to 8 pairs of {*additionalPmax*, *additionalSpectrumEmission*}, i.e. for a specific maximum transmit power, the UE must achieve a specific additional spectrum emission requirement

★ *p-Max* defines the maximum UE transmit power permitted within intra-frequency neighbouring cells. *p-Max* impacts the cell selection criteria if the UE transmit power capability is below the value of *p-Max*. It is assumed that the coverage of the neighbouring cell has been planned based upon the value of *p-Max*. This means that the Base Station would not be able to receive a cell edge UE with a lower transmit power capability. In this case, Qrxlevmin is increased to ensure that the UE can only camp on the cell when the UE is closer to the Base Station. This corresponds to the value of 'Pcompensation' within the cell selection equation for Srxlev

★ *smtc* defines the SS/PBCH Block Measurement Timing Configuration (SMTC). The SMTC specifies the time window during which the UE measures the SS/PBCH Blocks for intra-frequency cell reselection. The *periodicityAndOffset* is used to calculate the SFN and subframe associated with the start of each measurement window. The System Frame Numbers (SFN) which include the start of a measurement window satisfy the following condition: *SFN* mod *T* = FLOOR(*Offset* / 10), where *T* = CEIL(*Periodicity* / 10). The starting subframe is defined by *Offset* mod 10, if *Periodicity* is greater than 5 subframes. Otherwise, the starting subframes are defined by *Offset* and *Offset* + 5 (there are 2 windows per radio frame when the period is 5 ms). *duration* defines the length of the measurement window

★ *ss-RSSI-Measurement* is used to configure the RSSI measurements which are required to calculate RSRQ, i.e. RSRQ = SS-RSRP / (RSSI / N), where 'N' is the number of Resource Blocks used for the RSSI measurement

★ *measurementSlots* provides a bit string where each bit corresponds to a slot within the SMTC *duration*. For example, if the SMTC *duration* is set to 5 subframes and the subcarrier spacing is 15 kHz then the bit string will have a length of 5 bits because there are 5 slots in 5 subframes. In contrast, if the SMTC *duration* is set to 5 subframes and the subcarrier spacing is 240 kHz then the bit string will have a length of 80 bits because there are 80 slots in 5 subframes. The UE measures the RSSI during slots which correspond to a '1' within the bit string. *endSymbol* defines the symbols within the measurement slots which can be used to measure the RSSI. The value of *endSymbol* is a pointer to a row within a 3GPP standardised look-up table (presented in Table 155)

endSymbol	Symbol Indices
0	{0, 1}
1	{0, 1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11}
2	{0, 1, 2, 3, 4, 5}
3	{0, 1, 2, 3, 4, 5, 6, 7}

Table 155 – Symbols to be used for RSSI measurements within Measurement Slots

★ *ssb-ToMeasure* specifies the set of SS/PBCH Blocks to be measured within the SMTC measurement duration. A short, medium or long bitmap is broadcast according to the frequency range. A short bitmap is broadcast for carriers below 3 GHz (up to 4 SS/PBCH), a medium bitmap is broadcast for carriers between 3 GHz and 6 GHz (up to 8 SS/PBCH), and a long bitmap is broadcast for carriers greater than 6 GHz (up to 64 SS/PBCH). The UE measures SS/PBCH Blocks which correspond to a '1' within the bit string. The UE measures all SS/PBCH Blocks if *ssb-ToMeasure* is excluded from the SIB

★ *deriveSSB-IndexFromCell* indicates whether or not the UE can use the timing of the serving cell to derive the indices of the SS/PBCH Blocks transmitted by neighbouring cells. The UE assumes radio frame alignment across cells on the serving frequency if this field is set to 'True'

6.4 SYSTEM INFORMATION BLOCK 3

★ SIB3 provides cell specific information for intra-frequency cell reselection. Cell specific information can be provided for up to 16 intra-frequency cells. In addition, up to 16 PCI ranges can be specified for blacklisting. The content of SIB3 is presented in Table 156

SIB3			
intraFreqNeighCellList	SEQUENCE {1 to 16 instances}		
	physCellId	0 to 1007	
	q-OffsetCell	-24, -22, -20, -18, -16, -14, -12, -10, -8, -6, -5, -4, -3, -2, -1, 0, 1, 2, 3, 4, 5, 6, 8, 10, 12, 14, 16, 18, 20, 22, 24 dB	
	q-RxLevMinOffsetCell	1 to 8 (actual value = signalled value × 2)	
	q-RxLevMinOffsetCellSUL	1 to 8 (actual value = signalled value × 2)	
	q-QualMinOffsetCell	1 to 8	
intraFreqBlackCellList	SEQUENCE {1 to 16 instances}		
	PCI-Range	start	0 to 1007
		range	4, 8, 12, 16, 24, 32, 48, 64, 84, 96, 128, 168, 252, 504, 1008

Table 156 – Content of System Information Block 3 (SIB3)

★ *physCellId* specifies the Physical layer Cell Identity (PCI) for the intra-frequency cell

★ *q-OffsetCell* corresponds to the value of '$Qoffset_{s,n}$' which is used during the ranking of intra-frequency cells. A positive value makes the neighbouring cell appear less attractive, so cell reselection is less likely to occur

★ *q-RxLevMinOffsetCell* defines a cell specific offset which is added to the value of *q-RxLevMin* when evaluating the criteria for cell selection. The value of *q-RxLevMin* is broadcast within SIB2. Only positive values are defined so the offset always makes the cell selection criteria more stringent

★ *q-RxLevMinOffsetCellSUL* defines a cell specific offset which is added to the value of *q-RxLevMinSUL* when evaluating the criteria for cell selection. These parameters are applicable when the UE supports a Supplemental Uplink (SUL) for the target neighbouring cell

★ *q-QualMinOffsetCell* defines a cell specific offset which is added to the value of *q-QualMin* when evaluating the criteria for cell selection. The value of *q-QualMin* is broadcast within SIB2. Only positive values are defined so the offset always makes the cell selection criteria more stringent

★ *intraFreqBlackCellList* allows the specification of up to 16 PCI ranges to be blacklisted. Each PCI range can include 1 or more consecutive PCI. A single PCI is specified by including the '*start*' value but excluding the '*range*' value

6.5 SYSTEM INFORMATION BLOCK 4

★ SIB4 provides information regarding inter-frequency cell reselection. Frequency specific information can be provided for up to 8 carriers. Cell specific information can be provided for up to 16 cells on each carrier. In addition, up to 16 PCI ranges can be specified for blacklisting on each carrier. The first part of the content belonging to SIB4 is presented in Table 157

SIB4							
interFreqCarrierFreqList	SEQUENCE {1 to 8 instances}						
	dl-CarrierFreq	0 to 3279165					
	frequencyBandList	SEQUENCE {1 to 8 instances}					
		freqBandIndicatorNR	1 to 1024				
		nr-NS-PmaxList	SEQUENCE {1 to 8 instances}				
			additionalPmax	-30 to 33 dBm			
			additionalSpectrumEmission	0 to 7			
	frequencyBandListSUL	SEQUENCE {1 to 8 instances}					
		freqBandIndicatorNR	1 to 1024				
		nr-NS-PmaxList	SEQUENCE {1 to 8 instances}				
			additionalPmax	-30 to 33 dBm			
			additionalSpectrumEmission	0 to 7			
	nrofSS-BlocksToAverage	2 to 16					
	absThreshSS-BlocksConsolidation	thresholdRSRP	0 to 127				
		thresholdRSRQ	0 to 127				
		thresholdSINR	0 to 127				
	smtc	periodicityAndOffset	CHOICE				
			5 subframes	0 to 4	40 subframes	0 to 39	
			10 subframes	0 to 9	80 subframes	0 to 79	
			20 subframes	0 to 19	160 subframes	0 to 159	
		duration	1, 2, 3, 4, 5 subframes				
	ssbSubcarrierSpacing	15, 30, 120, 240 kHz					
	ssb-ToMeasure	CHOICE					
		Short Bitmap	BIT STRING {4 bits}	Medium Bitmap	BIT STRING {8 bits}	Long Bitmap	BIT STRING {64 bits}
	deriveSSB-IndexFromCell	BOOLEAN					
	ss-RSSI-Measurement	measurementSlots	BIT STRING {1 to 80 bits}				
		endSymbol	0 to 3				

Table 157 – Content of System Information Block 4 (SIB4) – Part 1

★ *dl-CarrierFreq* specifies the Absolute Radio Frequency Channel Number (ARFCN) for the SS/PBCH belonging to the inter-frequency carrier, i.e. it specifies the frequency domain location of the SS/PBCH

★ *frequencyBandList* and *frequencyBandListSUL* are used within the context of 'Multiple Frequency Bands', which refers to operating bands which overlap, i.e. a specific carrier frequency can belong to multiple operating bands. The configuration of 'Multiple Frequency Bands' allows a UE to use an operating band which is not normally supported by the UE. For example, a UE used within its home country may support operating band 'Home'. That UE may roam into a different country which offers services using operating band 'Roam'. The UE may not normally support operating band 'Roam'. However, if operating band 'Roam' overlaps with operating band 'Home', the UE is physically capable of using at least some of the carriers belonging to operating band 'Roam'

★ *frequencyBandList* and *frequencyBandListSUL* allow up to 8 compatible operating bands to be listed. In each case, it is possible to specify up to 8 pairs of {*additionalPmax*, *additionalSpectrumEmission*}, i.e. for a specific maximum transmit power, the UE must achieve a specific additional spectrum emission requirement

★ Cell reselection is based upon cell level measurements rather than beam level measurements. When the Base Station transmits multiple beams, a UE is required to generate a cell level measurement from one or more beam level measurements

★ A UE derives a cell level measurement by calculating the linear average of the measurements belonging to a maximum of *nrofSS-BlocksToAverage* beams, where each beam has a measurement which exceeds *absThreshSS-BlocksConsolidation*. If SIB2 excludes either of these parameters, the UE generates the cell level measurement using only the strongest beam level measurement. The UE also generates the cell level measurement using only the strongest beam level measurement if the strongest beam has a measurement below the value of *absThreshSS-BlocksConsolidation*

★ *smtc* defines the SS/PBCH Block Measurement Timing Configuration (SMTC). The SMTC specifies the time window during which the UE measures the SS/PBCH Blocks belonging to neighbouring cells. The *periodicityAndOffset* is used to calculate the SFN and subframe associated with the start of each measurement window. The System Frame Numbers (SFN) which include the start of a measurement window satisfy the following condition: $SFN \bmod T = \mathrm{FLOOR}(Offset / 10)$, where $T = \mathrm{CEIL}(Periodicity / 10)$. The starting subframe is defined by $Offset \bmod 10$, if *Periodicity* is greater than 5 subframes. Otherwise, the starting subframes are defined by *Offset* and *Offset* + 5 (there are 2 windows per radio frame when the period is 5 ms). *duration* defines the length of the measurement window

★ *ssbSubcarrierSpacing* defines the subcarrier spacing of the SS/PBCH Blocks to be measured

★ *ssb-ToMeasure* specifies the set of SS/PBCH Blocks to be measured within the SMTC measurement duration. A short, medium or long bitmap is broadcast according to the frequency range. A short bitmap is broadcast for carriers below 3 GHz (up to 4 SS/PBCH), a medium bitmap is broadcast for carriers between 3 GHz and 6 GHz (up to 8 SS/PBCH), and a long bitmap is broadcast for carriers greater than 6 GHz (up to 64 SS/PBCH). The UE measures SS/PBCH Blocks which correspond to a '1' within the bit string. The UE measures all SS/PBCH Blocks if *ssb-ToMeasure* is excluded from the SIB

★ *deriveSSB-IndexFromCell* indicates whether or not the UE can use the timing of the serving cell to derive the indices of the SS/PBCH Blocks transmitted by neighbouring cells. The UE assumes radio frame alignment across cells if this field is set to 'True'. Deriving the indices of neighbouring SS/PBCH Blocks from the timing of the serving cell helps to reduce measurement delays because it avoids the requirement to decode the PBCH belonging to neighbouring cells

★ *ss-RSSI-Measurement* is used to configure the RSSI measurements which are required to calculate RSRQ, i.e. RSRQ = SS-RSRP / (RSSI / N), where 'N' is the number of Resource Blocks used for the RSSI measurement

★ *measurementSlots* provides a bit string where each bit corresponds to a slot within the SMTC *duration*. For example, if the SMTC *duration* is set to 5 subframes and the subcarrier spacing is 15 kHz then the bit string will have a length of 5 bits because there are 5 slots in 5 subframes. In contrast, if the SMTC *duration* is set to 5 subframes and the subcarrier spacing is 240 kHz then the bit string will have a length of 80 bits because there are 80 slots in 5 subframes. The UE measures the RSSI during slots which correspond to a '1' within the bit string. *endSymbol* defines the symbols within the measurement slots which can be used to measure the RSSI. The value of *endSymbol* is a pointer to a row within a 3GPP standardised look-up table (presented in Table 155, section 6.3)

★ The second part of the content belonging to SIB4 is presented in Table 158

★ *q-RxLevMin* defines the minimum RSRP requirement for the target inter-frequency cell. *q-RxLevMinSUL* is used when the Base Station and UE support a Supplemental Uplink (SUL) for the target carrier. The link budget belonging to a Supplemental Uplink may differ from the link budget for the Normal Uplink. If coverage is uplink limited then *q-RxLevMinSUL* can be adjusted relative to *q-RxLevMin* to reflect the difference in link budgets

★ *q-QualMin* defines the minimum RSRQ requirement for the target inter-frequency cell. The UE assumes a value of minus infinity if this information element is not broadcast, i.e. the UE always passes the RSRQ check

★ *p-Max* defines the maximum UE transmit power permitted within inter-frequency neighbouring cells. *p-Max* impacts the cell selection criteria if the UE transmit power capability is below the value of *p-Max*. It is assumed that the coverage of the inter-frequency cell has been planned based upon the value of *p-Max*. This means that the Base Station would not be able to receive a cell edge UE with a lower transmit power capability. In this case, Qrxlevmin is increased to ensure that the UE can only camp on the cell when the UE is closer to the Base Station. This corresponds to the value of 'Pcompensation' within the cell selection equation for Srxlev

★ *t-ReselectionNR* defines the time-to-trigger for inter-frequency cell reselection. *sf-Medium* and *sf-High* define scaling factors for medium and high mobility conditions. *t-ReselectionNR* is multiplied by the appropriate scaling factor when medium or high mobility is detected

SIB4 continued				
interFreqCarrierFreqList (continued)	q-RxLevMin	-70 to -22 dBm (actual value = signalled value × 2)		
	q-RxLevMinSUL	-70 to -22 dBm (actual value = signalled value × 2)		
	q-QualMin	-43 to -12 dB		
	p-Max	-30 to 33 dBm		
	t-ReselectionNR	0 to 7 s		
	t-ReselectionNR-SF	sf-Medium	0.25, 0.5, 0.75, 1.0	
		sf-High	0.25, 0.5, 0.75, 1.0	
	threshX-HighP	0 to 31 (actual value = signalled value × 2)		
	threshX-LowP	0 to 31 (actual value = signalled value × 2)		
	threshX-Q	threshX-HighQ	0 to 31	
		threshX-LowQ	0 to 31	
	cellReselectionPriority	0 to 7		
	cellReselectionSubPriority	0.2, 0.4, 0.6, 0.8		
	q-OffsetFreq	-24, -22, -20, -18, -16, -14, -12, -10, -8, -6, -5, -4, -3, -2, -1, 0, 1, 2, 3, 4, 5, 6, 8, 10, 12, 14, 16, 18, 20, 22, 24 dB		
	interFreqNeighCellList	SEQUENCE {1 to 16 instances}		
		physCellId	0 to 1007	
		q-OffsetCell	-24, -22, -20, -18, -16, -14, -12, -10, -8, -6, -5, -4, -3, -2, -1, 0, 1, 2, 3, 4, 5, 6, 8, 10, 12, 14, 16, 18, 20, 22, 24 dB	
		q-RxLevMinOffsetCell	1 to 8	
		q-RxLevMinOffsetCellSUL	1 to 8	
		q-QualMinOffsetCell	1 to 8	
	interFreqBlackCellList	SEQUENCE {1 to 16 instances}		
		PCI-Range	start	0 to 503
			range	4, 8, 12, 16, 24, 32, 48, 64, 84, 96, 128, 168, 252, 504, 1008

Table 158 – Content of System Information Block 4 (SIB4) – Part 2

★ *threshX-HighP* is applicable when the target carrier has a higher Absolute Priority than the serving carrier. Cell reselection towards a higher priority carrier is permitted if Srxlev for the candidate cell is greater than the value of *threshX-HighP*

★ *threshX-LowP* is applicable when the target carrier has a lower Absolute Priority than the serving carrier. Cell reselection towards a lower priority carrier is permitted if Srxlev for the candidate cell is greater than the value of *threshX-LowP*, while Srxlev for the serving cell is less than the value of *threshServingLowP* broadcast within SIB2

★ *threshX-HighQ* is applicable when the target carrier has a higher Absolute Priority than the serving carrier. Cell reselection towards a higher priority carrier is permitted if Squal for the candidate cell is greater than the value of *threshX-HighQ*. Squal is used for cell reselection instead of Srxlev if SIB2 broadcasts a value for *threshServingLowQ*

★ *threshX-LowQ* is applicable when the target carrier has a lower Absolute Priority than the serving carrier. Cell reselection towards a lower priority carrier is permitted if Squal for the candidate cell is greater than the value of *threshX-LowQ*, while Squal for the serving cell is less than the value of *threshServingLowQ* broadcast within SIB2

★ *cellReselectionPriority* and *cellReselectionSubPriority* are summed to generate the Absolute Priority for the inter-frequency carrier

★ *q-OffsetFreq* corresponds to the value of '$\text{Qoffset}_{\text{frequency}}$' (frequency specific offset) which is used during the ranking of equal priority inter-frequency cells. A positive value makes the inter-frequency cell appear less attractive, so cell reselection is less likely to occur

★ *interFreqNeighCellList* provides a set of cell specific parameters for cells belonging to the carrier defined by *dl-CarrierFreq*

★ *physCellId* specifies the Physical layer Cell Identity (PCI) for the inter-frequency cell

★ *q-OffsetCell* corresponds to the value of '$\text{Qoffset}_{\text{s,n}}$' (cell specific offset) which is used during the ranking of inter-frequency cells. A positive value makes the neighbouring cell appear less attractive, so cell reselection is less likely to occur

★ *q-RxLevMinOffsetCell* defines a cell specific offset which is added to the value of *q-RxLevMin* when evaluating the criteria for cell selection. Only positive values are defined so the offset always makes the criteria more stringent. *q-RxLevMinOffsetCellSUL* defines a cell specific offset which is added to the value of *q-RxLevMinSUL* when evaluating the criteria for cell selection

★ *q-QualMinOffsetCell* defines a cell specific offset which is added to the value of *q-QualMin* when evaluating the criteria for cell selection. Only positive values are defined so the offset always makes the cell selection criteria more stringent

★ *intraFreqBlackCellList* allows the specification of up to 16 PCI ranges to be blacklisted. Each PCI range can include 1 or more consecutive PCI. A single PCI is specified by including the '*start*' value but excluding the '*range*' value

6.6 SYSTEM INFORMATION BLOCK 5

★ SIB5 provides information regarding inter-system cell reselection towards 4G (LTE). Information can be included for up to 8 LTE carriers. The content of SIB5 is presented in Table 159

SIB5				
carrierFreqListEUTRA	SEQUENCE {1 to 8 instances}			
	carrierFreq	0 to 262143		
	eutra-multiBandInfoList	SEQUENCE {1 to 8 instances}		
		eutra-FreqBandIndicator	1 to 256	
		eutra-NS-PmaxList	SEQUENCE {1 to 8 instances}	
			additionalPmax	-30 to 33
			additionalSpectrumEmission	1 to 288
	eutra-FreqNeighCellList	SEQUENCE {1 to 8 instances}		
		physCellId	0 to 503	
		q-OffsetCell	-24, -22, -20, -18, -16, -14, -12, -10, -8, -6, -5, -4, -3, -2, -1, 0, 1, 2, 3, 4, 5, 6, 8, 10, 12, 14, 16, 18, 20, 22, 24	
		q-RxLevMinOffsetCell	1 to 8 (actual value = signalled value × 2)	
		q-QualMinOffsetCell	1 to 8	
	eutra-BlackCellList	SEQUENCE {1 to 16 instances}		
		EUTRA-PhysCellIdRange	start	0 to 503
			range	4, 8, 12, 16, 24, 32, 48, 64, 84, 96, 128, 168, 252, 504
	allowedMeasBandwidth	6, 15, 25, 50, 75, 100 Resource Blocks		
	presenceAntennaPort1	BOOLEAN		
	cellReselectionPriority	0 to 7		
	cellReselectionSubPriority	0.2, 0.4, 0.6, 0.8		
	threshX-High	0 to 31 (actual value = signalled value × 2)		
	threshX-Low	0 to 31 (actual value = signalled value × 2)		
	q-RxLevMin	-70 to -22 (actual value = signalled value × 2)		
	q-QualMin	-34 to -3		
	p-MaxEUTRA	-30 to 33		
	threshX-Q	threshX-HighQ	0 to 31	
		threshX-LowQ	0 to 31	
t-ReselectionEUTRA	0 to 7 seconds			
t-ReselectionEUTRA-SF	sf-Medium	0.25, 0.5, 0.75, 1.0		
	sf-High	0.25, 0.5, 0.75, 1.0		

Table 159 – Content of System Information Block 5 (SIB5)

★ *carrierFreq* specifies the Absolute Radio Frequency Channel Number (ARFCN) belonging to the LTE carrier

★ *eutra-multiBandInfoList* can be used within the context of multi-band scenarios, i.e. allowing a UE to use an operating band which is not normally supported by the UE. This type of scenario occurs when operating bands overlap. For example, a UE used within its home country may support operating band 18. That UE may roam into a different country which offers services using operating band 26. The UE may not normally support operating band 26. However, operating band 18 is a subset of operating band 26 so the UE is physically capable of using at least some of the carriers belonging to operating band 26

★ The ARFCN specified by *carrierFreq* identifies the operating band within the local country (LTE ARFCN values are unique across operating bands, even when those operating bands overlap). *eutra-FreqBandIndicator* specifies an operating band which is compatible with the operating band specified by *carrierFreq*. This means that a UE which supports an operating band specified by *eutra-FreqBandIndicator* can make use of the ARFCN specified by *carrierFreq*, even when it does not support the operating band normally associated with the ARFCN

★ *eutra-multiBandInfoList* allows up to 8 compatible operating bands to be listed. In each case, it is possible to specify up to 8 pairs of {*additionalPmax*, *additionalSpectrumEmission*}, i.e. for a specific maximum transmit power, the UE must achieve a specific additional spectrum emission requirement

- *eutra-FreqNeighCellList* allows the specification of up to 8 PCI. Each PCI can be made more or less attractive for cell reselection by configuring positive or negative values for *q-OffsetCell*. In addition, the Qrxlevmin and Qqualmin requirements for the target LTE cell can be made more stringent by specifying values for *q-RxLevMinOffsetCell* and *q-QualMinOffsetCell*
- *eutra-BlackCellList* allows the specification of up to 16 PCI ranges to be blacklisted. Each PCI range can include 1 or more consecutive PCI. A single PCI is specified by including the '*start*' value but excluding the '*range*' value
- *allowedMeasBandwidth* specifies the maximum allowed measurement bandwidth for the target cell. The bandwidth is specified in terms of Resource Blocks. 6, 15, 25, 25, 50, 75, and 100 Resource Blocks correspond to the 1.4, 3, 5, 10, 15, 20 MHz channel bandwidths
- *presenceAntennaPort1* indicates whether or not neighbouring LTE cells use antenna port 1. If the value 'True' is broadcast, the UE can assume that at least 2 cell specific antenna ports are used in all neighbouring cells, i.e. at least ports 0 and 1. RSRP and RSRQ measurements can be based upon Cell specific Reference Signal transmissions from both antenna ports when available
- *cellReselectionPriority* and *cellReselectionSubPriority* are summed to generate the Absolute Priority for the target LTE carrier
- *threshX-High* is applicable when the target LTE carrier has a higher Absolute Priority than the serving NR carrier. Cell reselection towards a higher priority carrier is permitted if Srxlev for the candidate cell is greater than the value of *threshX-High*
- *threshX-Low* is applicable when the target LTE carrier has a lower Absolute Priority than the serving NR carrier. Cell reselection towards a lower priority carrier is permitted if Srxlev for the candidate cell is greater than the value of *threshX-Low*, while Srxlev for the serving cell is less than the value of *threshServingLowP* broadcast within SIB2
- *q-RxLevMin* defines the minimum RSRP requirement for the target LTE cell. This value can be modified by *q-RxLevMinOffsetCell* if a value has been broadcast for the relevant PCI. Similarly, *q-QualMin* defines the minimum RSRQ requirement for the target LTE cell, and can be modified by *q-QualMinOffsetCell* if a value has been broadcast for the relevant PCI
- *p-MaxEUTRA* defines the maximum UE transmit power permitted in the LTE cell. *p-MaxEUTRA* impacts the cell selection criteria if the UE transmit power capability is less than the value of *p-MaxEUTRA*. It is assumed that the coverage of the LTE cell has been planned based upon the value of *p-MaxEUTRA*. This means that the Base Station would not be able to receive a cell edge UE with a lower transmit power capability. In this case, Qrxlevmin is increased to ensure that the UE can only camp on the cell when the UE is closer to the Base Station. This corresponds to the value of 'Pcompensation' within the cell selection equation for Srxlev
- *threshX-HighQ* is applicable when the target LTE carrier has a higher Absolute Priority than the serving NR carrier. Cell reselection towards a higher priority carrier is permitted if Squal for the candidate cell is greater than the value of *threshX-HighQ*. Squal is used for cell reselection instead of Srxlev if SIB2 broadcasts a value for *threshServingLowQ*
- *threshX-LowQ* is applicable when the target LTE carrier has a lower Absolute Priority than the serving NR carrier. Cell reselection towards a lower priority carrier is permitted if Squal for the candidate cell is greater than the value of *threshX-LowQ*, while Squal for the serving cell is less than the value of *threshServingLowQ* broadcast within SIB2
- *t-ReselectionEUTRA* defines the time-to-trigger for cell reselection towards LTE. *sf-Medium* and *sf-High* define scaling factors for medium and high mobility conditions. *t-ReselectionEUTRA* is multiplied by the appropriate scaling factor when medium or high mobility is detected. The parameters used to detect medium and high mobility are broadcast in SIB2

6.7 SYSTEM INFORMATION BLOCK 6

- SIB6 provides support for the Earthquake and Tsunami Warning System (ETWS). ETWS is an example of a Public Warning System (PWS). ETWS warning notifications can be either primary (short notifications delivered within 4 seconds) or secondary (more detailed information). SIB6 broadcasts primary notifications whereas SIB7 broadcasts secondary notifications
- The 5G radio access network performs scheduling and broadcasting of the warning message content received from the Cell Broadcast Center (CBC). This content is received from the CBC via the AMF
- The content of SIB6 is presented in Table 160

SIB6	
messageIdentifier	BIT STRING (16 bits)
serialNumber	BIT STRING (16 bits)
warningType	OCTET STRING

Table 160 – Content of System Information Block 6 (SIB6)

- The Message Identifier is a string of 16 bits which defines the type of ETWS notification. These are specified within 3GPP TS 23.041. Examples include earthquake warning, tsunami warning, earthquake and tsunami warning, other emergency, or test message
- The Serial Number is a string of 16 bits used to track any changes in the ETWS notification. It includes:

- 1 bit emergency user alert flag to instruct the UE to alert the end-user, e.g. by playing a tone or vibrating
- 1 bit pop-up flag to instruct the UE to display a message on its screen
- 8 bit message code used to further specify the type of ETWS notification
- 2 bit geographical scope to indicate the area over which the message is applicable, i.e. cell, location area, or PLMN. It also indicates the display mode, i.e. whether or not the warning is to be displayed at all times
- 4 bit update number used to indicate a change in the message content. The update number differentiates between older and newer versions of the same message

★ The Warning Type specifies whether the warning is for a tsunami, earthquake or tsunami and earthquake. It also includes user alert and pop-up information

6.8 SYSTEM INFORMATION BLOCK 7

★ SIB7 also provides support for the Earthquake and Tsunami Warning System (ETWS). ETWS warning notifications can be either primary (short notifications delivered within 4 seconds) or secondary (more detailed information). SIB6 broadcasts primary notifications whereas SIB7 broadcasts secondary notifications

★ The content of SIB7 is presented in Table 161

SIB7	
messageIdentifier	BIT STRING (16 bits)
serialNumber	BIT STRING (16 bits)
warningMessageSegmentType	notLastSegment, lastSegment
warningMessageSegmentNumber	0 to 63
warningMessageSegment	OCTET STRING
dataCodingScheme	OCTET STRING

Table 161 – Content of System Information Block 7 (SIB7)

★ The Message Identifier is a string of 16 bits which defines the type of ETWS notification as specified within 3GPP TS 23.041. Examples include earthquake warning, tsunami warning, earthquake and tsunami warning, other emergency, or test message

★ The Serial Number string includes the same fields as the Serial Number string within SIB6

★ The Warning Message Segment Type indicates whether or not the message segment is the last segment of the complete message

★ The Warning Message Segment Number represents the number of the subsequent Message Segment. This number is used when reconstructing the complete message

★ The Warning Message Segment provides a segment of the message

★ The Data Coding Scheme identifies the alphabet/coding and language used for the ETWS message. The allowed values are specified within 3GPP TS 23.038

★ 3GPP References: TS 38.331, TS 23.041

6.9 SYSTEM INFORMATION BLOCK 8

★ SIB8 is used to provide a Commercial Mobile Alert Service (CMAS) notification. CMAS is an example of a Public Warning System (PWS) which is able to deliver multiple, concurrent warning text messages. The Federal Communications Commission (FCC) established CMAS to allow service providers to send emergency alerts as text messages to their users who have CMAS capable UE

★ The content of SIB8 is presented in Table 162

★ *messageIdentifier* is a string of 16 bits which defines the type of CMAS message broadcast by SIB8. These are specified within 3GPP TS 23.041. Examples include 'Presidential Alerts', 'Extreme Alerts with Severity of Extreme, Urgency of Immediate, and Certainty of Observed' and 'Severe Alerts with Severity of Severe, Urgency of Expected, and Certainty of Likely'

★ *serialNumber* is a string of 16 bits used to track any changes in the CMAS notification. The serial number is updated every time a CMAS message with a specific Message Identifier is updated

★ *warningMessageSegmentType* is used to indicate whether or not the Message Segment is the last segment belonging to the message

SIB8	
messageIdentifier	BIT STRING (16 bits)
serialNumber	BIT STRING (16 bits)
warningMessageSegmentType	notLastSegment, lastSegment
warningMessageSegmentNumber	0 to 63
warningMessageSegment	OCTET STRING
dataCodingScheme	OCTET STRING
warningAreaCoordinatesSegment	OCTET STRING

Table 162 – Content of System Information Block 8 (SIB8)

★ *warningMessageSegmentNumber* represents the number of the Message Segment. This number is used when reconstructing the complete message. It can be allocated values between 0 and 63

★ *warningMessageSegment* is a section of the CMAS message

★ *dataCodingScheme* identifies the alphabet/coding and language used for the CMAS message. The allowed values are specified within 3GPP TS 23.038

★ *warningAreaCoordinatesSegment* provides information regarding the area across which the CMAS warning message is valid. The UE uses this information to determine whether or not the warning message is displayed

★ 3GPP References: TS 38.331, TS 23.041

6.10 SYSTEM INFORMATION BLOCK 9

★ SIB9 provides timing information for Coordinated Universal Time (UTC), GPS time and local time. This timing information can be used by the higher layers of the UE, e.g. to synchronise the UE clock or to assist with GPS initialisation. The timing information may also be used by specific services, e.g. multimedia broadcast multicast services

★ Alternatively, a UE can acquire timing information from a Network Time Protocol (NTP) server, or from the Core Network. The AMF can provide timing information using the NAS: 'Configuration Update Command' message. However, SIB9 is capable of providing greater accuracy than these alternative solutions. The content of SIB9 is presented in Table 163

SIB9		
timeInfo	timeInfoUTC	0 to 549755813887
	dayLightSavingTime	BIT STRING { SIZE 2 }
	leapSeconds	-127 to 128
	localTimeOffset	-63 to 64

Table 163 – Content of System Information Block 9 (SIB9)

★ *timeInfoUTC* specifies the Coordinated Universal Time (UTC) at the radio frame boundary which occurs at, or immediately after the end of the System Information (SI) window within which SIB9 is transmitted. The value specifies the number of 10 ms units since 00:00:00 on Gregorian calendar date 1st January 1900

★ *dayLightSavingTime* specifies whether or not Daylight Saving Time (DST) should be applied when deriving the local time. A value of '00' indicates that DST should not be applied; a value of '01' indicates that +1 hour of DST should be applied; a value of '10' indicates that +2 hours of DST should be applied. The value of '11' is currently reserved

★ DST advances the local time during the summer period. In the northern hemisphere, this corresponds to months between March/April and September/November, whereas in the southern hemisphere, this corresponds to months between September/November and March/April

★ *leapSeconds* allows the GPS time to be derived from the UTC time, i.e. GPS time = UTC Time + *leapSeconds*. UTC time includes the impact of leap seconds to account for changes in the rate of rotation of the earth. Within the context of UTC time, a minute can sometimes have a duration or 61 seconds or 59 seconds. GPS time is simply based upon atomic clocks and does not include the impact of leap seconds

★ *localTimeOffset* specifies the difference between UTC time and the local time in units of 15 minutes, i.e. local time = UTC time + *localTimeOffset* × 15 minutes. This time offset accounts for the wide range of time zones used around the world

★ 3GPP References: TS 38.331, TS 24.501, TS 24.008

7 UPLINK SIGNALS AND CHANNELS

7.1 UPLINK CHANNEL MAPPINGS

★ Logical channels transfer data (RLC PDU) between the RLC and MAC layers. Transport channels transfer data (MAC PDU) between the MAC and Physical layers. Physical channels transfer data across the air-interface. MAC PDU are also known as Transport Blocks

★ Physical signals are used for various physical layer measurements. These measurements can be used for uplink channel estimation during demodulation, downlink channel estimation when channel reciprocity exists, uplink beam management, selection of uplink precoding weights, phase error estimation, channel aware scheduling and link adaptation

★ The mappings between the various channel types are illustrated in Figure 238. This figure also illustrates the set of uplink signals

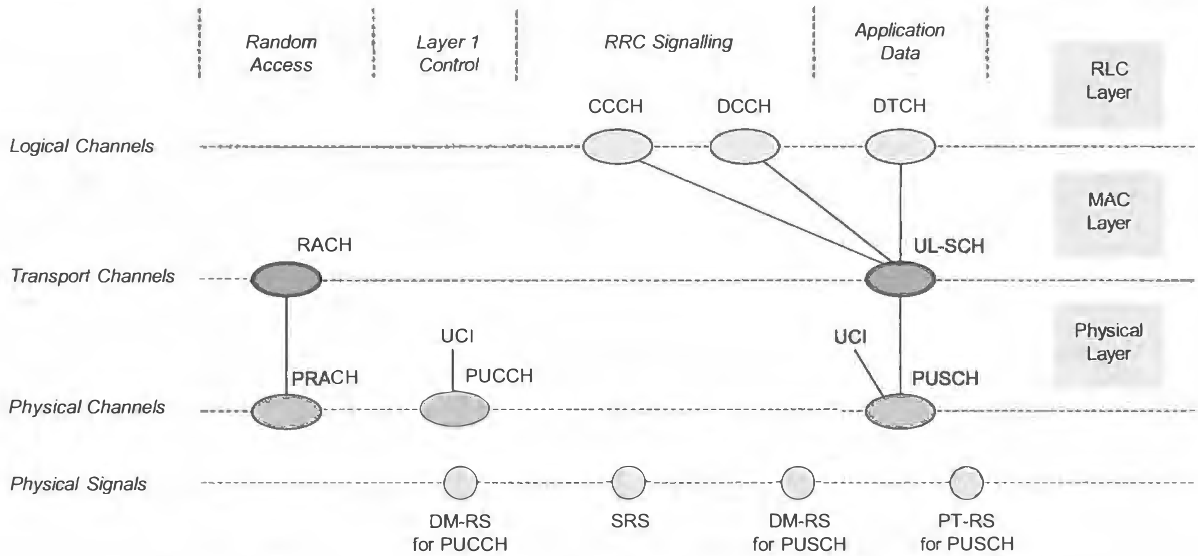


Figure 238 – Mapping of uplink logical channels onto transport channels and physical channels

★ The Common Control Channel (CCCH) and Dedicated Control Channel (DCCH) are used to transfer RRC signalling messages, i.e. data belonging to the set of Signalling Radio Bearers (SRB). The Dedicated Traffic Channel (DTCH) is used to transfer application data. All SRB data and all application data is mapped onto the UL-SCH and PUSCH

★ The PUCCH physical channel is not used to transfer higher layer information, so does not have associated logical nor transport channels. The PUCCH transfers Uplink Control Information (UCI). Uplink Control Information includes Scheduling Requests, HARQ Acknowledgements and Channel State Information (CSI). A CSI report can include various combinations of the following: Rank Indicator (RI), Layer Indicator (LI), Precoding Matrix Indicator (PMI), Channel Quality Indicator (CQI), CSI Reference Signal Indicator (CRI), SS/PBCH Block Resource Indicator (SSBRI) and Layer 1 RSRP

★ The Random Access Channel (RACH) is used to transfer the index of the preamble sequence which has been selected for the PRACH, i.e. the MAC layer completes the preamble selection procedure and subsequently passes the result to the Physical layer

★ There are Demodulation Reference Signals (DMRS) for the PUCCH and PUSCH. These Reference Signals are sequences which are known to the Base Station. The Base Station compares the received version of the sequence with the known reference to estimate the impact of the propagation channel. The UE can then apply an inverse of the propagation channel before demodulation

★ The Sounding Reference Signal (SRS) can be used by the Base Station for channel aware packet scheduling and link adaptation. When channel reciprocity exists, the SRS can be used for downlink channel estimation. When channel reciprocity does not exist, the SRS can be used for uplink beam management. The SRS can also be used to support the selection of uplink precoding weights for both non-codebook based transmission and codebook based transmission

★ The Phase Tracking Reference Signal (PTRS) can be used to help compensate for phase noise generated by the local oscillators at both the transmitter and receiver. Phase noise is not a significant issue for the lower operating bands but becomes more significant for the higher operating bands. The PTRS may also be used to support channel estimation during demodulation, i.e. to complement the Demodulation Reference Signal (DMRS). The PTRS occupies less Resource Elements than the DMRS so channel estimation is likely to be less accurate but it creates a smaller overhead towards the PUSCH

7.2 PHYSICAL RANDOM ACCESS CHANNEL

7.2.1 BACKGROUND

★ The Physical Random Access Channel (PRACH) is used to transmit Random Access preambles, i.e. MSG1 belonging to the Random Access procedure. MSG2 uses the PDSCH whereas MSG3 uses the PUSCH. The Random Access procedure is described in section 13.1

★ The PRACH is always transmitted using antenna port 4000

★ The general structure of a PRACH transmission is illustrated in Figure 239. The PRACH transmission includes a cyclic prefix and one or more repetitions of a sequence. 3GPP has specified a range of PRACH formats with up to 12 repetitions of the PRACH sequence. The guard period allows for differences in the propagation delay, i.e. the PRACH is transmitted before uplink synchronisation is achieved so UE transmitting from cell edge are received later than UE transmitting close to the Base Station

★ The example illustrated in Figure 239 has a guard band between the edges of the PRACH and the adjacent PUSCH Resource Blocks. The existence and size of this guard band depends upon the combination of PRACH and PUSCH subcarrier spacings

★ Figure 239 illustrates a single PRACH resource surrounded by PUSCH Resource Blocks. PRACH resources can be time multiplexed and frequency multiplexed. The time multiplexing configuration distributes the set of PRACH resources over time. A high density configuration can lead to a burst of continuous PRACH resources in the time domain. The frequency multiplexing configuration allows up to 8 PRACH resources to be stacked in a contiguous section of bandwidth

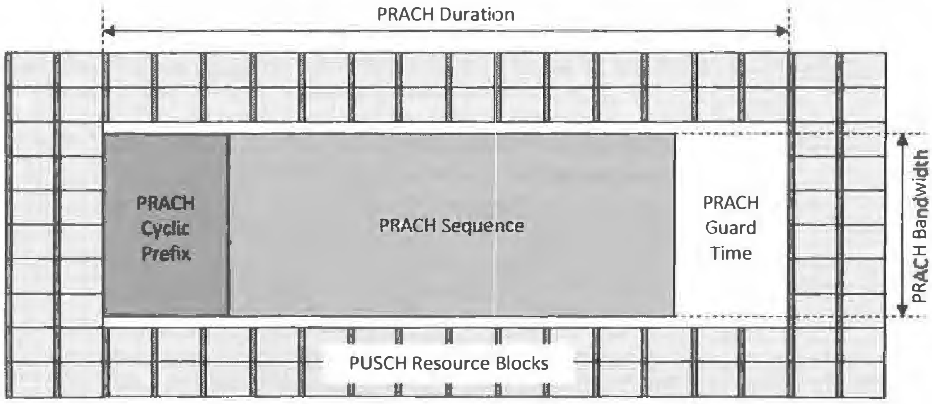


Figure 239 – General structure of a PRACH transmission
(example based upon Long Sequence PRACH with 1 ms duration and 15 kHz subcarrier spacing for the PUSCH)

★ The PRACH (the Random Access preamble) is generated from a Zadoff-Chu (ZC) sequence:

  o a ZC sequence is a sequence of complex numbers which has some important mathematical properties. These properties make ZC sequences particularly useful for mobile telecommunications. An example ZC sequence is illustrated in Figure 240

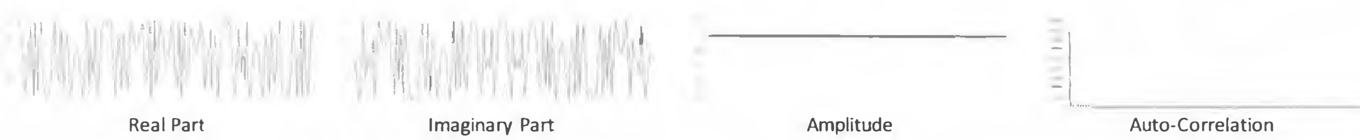


Figure 240 – Example Zadoff-Chu sequence with its Amplitude and Auto-Correlation

  o Property 1: of a ZC sequence is its constant amplitude which helps to minimise the Peak-to-Average Power Ratio (PAPR) of the transmitted signal. This allows the power amplifier to operate at a higher average power and also more efficiently

  o Property 2: of a ZC sequence is the result of its auto-correlation which generates a very large output spike when the time shift is zero, i.e. correlating a ZC sequence with a duplicate ZC sequence generates a large result when the two sequences are time synchronised. The output from the auto-correlation is very low for all non-zero time shifts. This property helps the Base Station receiver to synchronise with the transmitted sequence

  o the combination of these first two properties leads to a ZC sequence being categorised as a Constant Amplitude Zero Auto-Correlation (CAZAC) sequence

  o Property 3: of a ZC sequence is the result of the cross-correlation between one ZC sequence and another ZC sequence. This correlation generates a very low result for all time shifts. This property helps the receiver to avoid confusing one ZC sequence for another, i.e. the receiver will only obtain a spike from the output of its correlator when using the correct reference ZC sequence

- Property 4: of a ZC sequence is the ability to generate 'x-1' ZC sequences of length 'x'. These sequences are known as Root Sequences. In the case of 5G, 3GPP has specified sequence lengths of 839 and 139 for the PRACH, so there are 838 and 138 Root Sequences respectively

- Property 5: of a ZC sequence is the ability to generate additional sequences by applying cyclic shifts to each Root Sequence. These additional sequences also have the same constant amplitude, auto-correlation and cross correlation properties. Figure 241 illustrates the concept of generating additional sequences by applying a cyclic shift

Figure 241 – Generating sequences from a Root Sequence using Cyclic Shifts

- The total number of sequences available for the PRACH depends upon the sequence length and the size of the cyclic shift. For example, when using a sequence length of 839 and a cyclic shift size of 119, then it is possible to generate ROUND DOWN (839/119) = 7 sequences from each root sequence. There are 838 root sequences so in this example there is a total capacity of 7 × 838 = 5866 sequences

- The duration of a ZC sequence transmitted on the PRACH is equal to 1/subcarrier spacing. For example, the sequence occupies 1/1250 = 800 μs when using a subcarrier spacing of 1.25 kHz, or 1/5000 = 200 μs when using a subcarrier spacing of 5 kHz. Some PRACH formats include repetitions of the ZC sequence so the body of the PRACH can be a multiple of these durations

★ The PRACH may experience frequency offsets:

- the local oscillators at the UE transmitter and Base Station receiver can generate frequency offsets if their output frequencies do not precisely match, i.e. the step-up from baseband to RF at the transmitter does not equal the step-down from RF to baseband at the receiver. A UE local oscillator may have an accuracy of 0.1 parts per million (ppm). This leads to a frequency offset of up to 600 Hz when assuming a 6 GHz carrier frequency. A Base Station local oscillator may have an accuracy of 0.05 parts per million (ppm) which leads to a frequency offset of up to 300 Hz when assuming a 6 GHz carrier frequency

- UE mobility can also generate frequency offsets. A UE moving at 500 km/hr while using a carrier frequency of 6 GHz, generates a round trip Doppler frequency offset of 5.6 kHz. The Doppler frequency offset is calculated as (Carrier Frequency × UE speed / speed of light). The round trip Doppler frequency is double this result because offsets can accumulate from both the downlink and uplink transmissions. The UE uses the downlink signal as a reference so Doppler offsets in the uplink are added to those in the downlink

- these local oscillator and Doppler frequency offsets sum to 6.5 kHz when assuming a speed of 500 km/hr and a carrier frequency of 6 GHz. This represents a worst case scenario for Frequency Range 1 (450 MHz to 6 GHz). Channels belonging to Frequency Range 2 (24.25 GHz to 52.60 GHz) are less likely to be used for high speed scenarios due to their limited cell range, i.e. there would be a requirement for very frequent handovers

★ Frequency offsets have a negative impact upon PRACH performance by generating additional peaks in the auto-correlation function:

- the Base Station may synchronise with one of these additional peaks. In this case, the Base Station would generate an inaccurate estimate of the propagation delay between the UE and Base Station. This would lead to an inaccurate Timing Advance command within the Random Access Response (MSG2), which could then cause a failure when the Base Station attempts to receive MSG3

- larger frequency offsets generate additional auto-correlation peaks which are further from the ideal original peak. As the frequency offset increases, there is a point at which the Base Station will incorrectly identify the PRACH cyclic shift transmitted by the UE. This will generate a false detection at the Base Station, i.e. the UE transmits preamble 'A', while the Base Station detects preamble 'B'. When using the 1.25 kHz subcarrier spacing for the PRACH, false detections are likely to occur if the frequency offset exceeds 625 Hz. The probability of incorrectly identifying the PRACH cyclic shift becomes very high if the frequency offset reaches 1.25 kHz

★ Figure 242 illustrates an example of the additional cyclic shifts generated by positive and negative frequencies offsets. This example is based upon a ZC sequence length of 839 and a Cyclic Shift size of 55, i.e. in the absence of frequency offsets there are ROUND DOWN (839 / 55) = 15 Cyclic Shifts. These 15 cyclic shifts are normally available for selection by the UE when transmitting the PRACH. Figure 242 illustrates the 10 additional cyclic shifts which are generated when the first 5 normal cyclic shifts experience positive and negative frequency offsets. In this example it is assumed that the magnitude of each frequency offset is equal to the subcarrier spacing of the PRACH. Each additional cyclic shift is positioned close to one of the remaining normal cyclic shifts. This means that if a UE transmits one of the first 5 normal cyclic shifts, and the transmission experiences a frequency offset equal to the subcarrier spacing, then the Base Station will incorrectly identify the transmission as one of the 10 remaining normal cyclic shifts

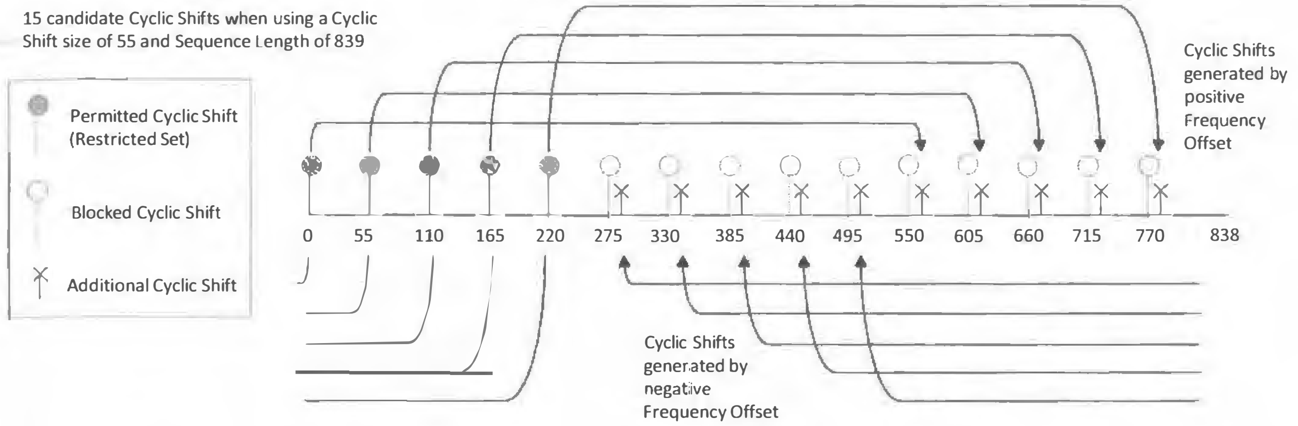


Figure 242 – PRACH Cyclic Shifts generated by positive and negative frequency offsets

★ 3GPP has introduced the concept of 'Restricted Sets' to mitigate the impact of relatively large frequency offsets. This solution reduces the number of cyclic shifts which can be applied to each Root Sequence to ensure that there is no ambiguity as long as the frequency offset remains below a specific upper limit. The 'Restricted Set' in Figure 242 corresponds to the first 5 cyclic shifts (labelled as permitted cyclic shifts). The remaining 10 cyclic shifts are blocked from use to avoid any ambiguity

★ Figure 242 illustrates one example of a Restricted Set of permitted cyclic shifts. Different Root Sequences exhibit different patterns of additional cyclic shifts after experiencing frequency offsets. Thus, the number of permitted cyclic shifts and their position depends upon the Root Sequence

★ 3GPP TS 38.211 specifies Unrestricted Sets of cyclic shifts for low to medium mobility. 'Type A' Restricted Sets are specified for high mobility, whereas 'Type B' Restricted Sets are specified for very high mobility. These categories of cyclic shifts are summarised in Figure 243. The Unrestricted Sets are intended for use with frequency offsets which do not exceed half of the subcarrier spacing. 'Type A' Restricted Sets are intended for use with frequency offsets which do not exceed the subcarrier spacing, whereas 'Type B' Restricted Sets are intended for use with frequency offsets which do not exceed twice the subcarrier spacing

	Unrestricted Set PRACH Preambles	Type A Restricted Set PRACH Preambles	Type B Restricted Set PRACH Preambles
	Low to Medium mobility	High mobility	Very High mobility
1.25 kHz PRACH subcarrier spacing	Frequency Offset up to 625 Hz	Frequency Offset up to 1.25 kHz	Frequency Offset up to 2.5 kHz
5 kHz PRACH subcarrier spacing	Frequency Offset up to 2.5 kHz	Frequency Offset up to 5 kHz	Frequency Offset up to 10 kHz

Figure 243 – Sets of PRACH Cyclic Shifts for low, medium, high and very high mobility

★ Increasing the PRACH subcarrier spacing increases robustness against frequency offsets (the duration of the PRACH transmission becomes shorter when using a higher subcarrier spacing so the frequency offset has less time to rotate the transmitted sequence)

★ Identifying the UE speed associated with each frequency offset requires assumptions regarding the operating band and the accuracy of the UE and Base Station local oscillators. If worst case assumptions are made regarding the accuracy of the local oscillators then the maximum UE speed associated with each set of PRACH preambles is relatively low. Figure 244 illustrates the UE speeds which correspond to a range of Doppler frequency offsets when assuming 100 % accurate local oscillators, i.e. the best case scenario

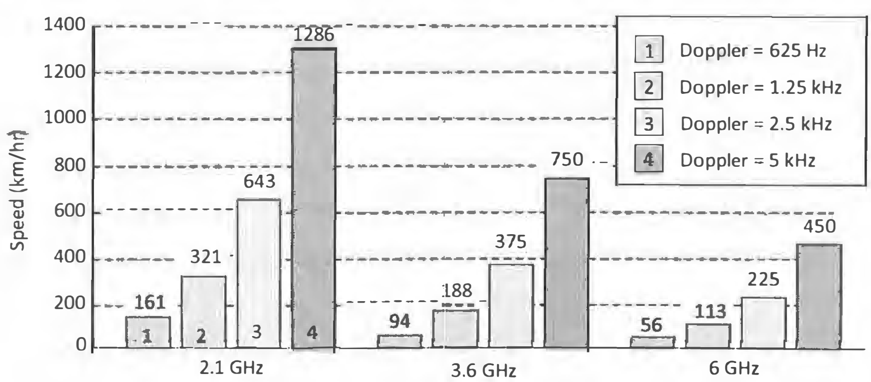


Figure 244 – Speeds associated with Doppler round trip Frequency Offsets

★ 3GPP has specified two main categories of PRACH to cope with the requirements of each Frequency Range (and their corresponding symbol and slot durations). These two categories are illustrated in Figure 245:

- long sequence PRACH preambles can only be used by cells belonging to Frequency Range 1 (450 MHz to 6 GHz). These preambles use Root Sequences which have a length of 839 (meaning that there are 838 Root Sequences). Long preambles are designed to support relatively large cell ranges (up to 100 km). Their cyclic prefix and guard period durations are long to support the round-trip propagation delays associated with large cell ranges. Long preambles use relatively small subcarrier spacings (1.25 kHz and 5 kHz). This makes them more vulnerable to frequency offsets. In addition, they may be used to provide coverage for high mobility scenarios with high Doppler frequency offsets. For this reason, the Type A and Type B Restricted Sets are specified for use with long PRACH preambles. Long preambles are intended for cells which are able to accommodate relatively long periods of uplink transmission, e.g. FDD cells, TDD cells with a 15 kHz subcarrier spacing, or TDD cells with multiple consecutive uplink slots. Long PRACH preambles are described in greater detail in section 7.2.3

- short sequence PRACH preambles can be used by cells belonging to either Frequency Range 1 (450 MHz to 6 GHz) or Frequency Range 2 (24.25 GHz to 52.6 GHz). These preambles use Root Sequences which have a length of 139 (meaning there are 138 Root Sequences). Short preambles are designed to support relatively small cell ranges (up to about 9 km, but with many configurations having a significantly smaller cell range). Short preambles use relatively large subcarrier spacings (15, 30, 60 and 120 kHz). This makes them less vulnerable to frequency offsets generated by either non-ideal oscillators or high mobility (Doppler frequency offsets). This means that it has not been necessary to specify Restricted Sets to protect short preambles from frequency offsets. Short preambles are intended for cells which are unable to accommodate relatively long periods of uplink transmission. In the case of Frequency Range 2 with analogue beamforming, only a single beam can be active at any point in time so it is not possible to share PRACH occasions across beams nor frequency multiplex the PRACH occasions associated with each beam. Short preambles allow the set of PRACH occasions to be time multiplexed with minimal latency, i.e. the time taken to cycle through the set of PRACH occasions belonging to the set of beams is relatively short. Short PRACH preambles are described in section 7.2.4

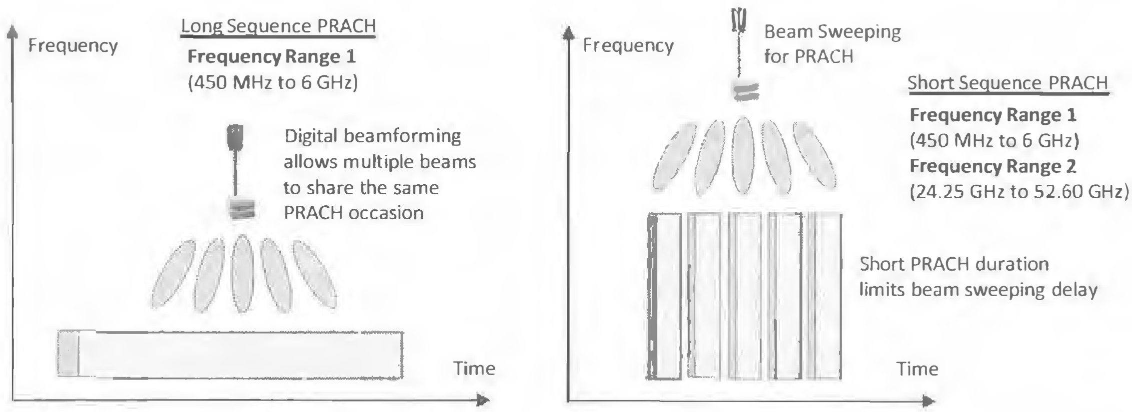


Figure 245 – Long and Short PRACH transmissions for Low and High operating bands

★ Short preambles have a reduced sequence capacity when compared to long preambles. Earlier in this section it was stated that the total number of sequences available depends upon the sequence length and size of the cyclic shift

- long preambles have a length of 839 and assuming a cyclic shift size of 119 (as an example), then it is possible to generate ROUND DOWN (839/119) = 7 sequences from each Root Sequence. There are 838 Root Sequences so there is a total capacity of 7 × 838 = 5866 sequences. A Random Access occasion normally uses 64 preambles which require ROUND UP (64 / 7) = 10 Root Sequences. This leads to a Root Sequence re-use pattern size of ROUND DOWN (838/10) = 83

- short sequences have a length of 139 and assuming a cyclic shift size of 23 (as an example), then it is possible to generate ROUND DOWN (139/23) = 6 sequences from each Root Sequence. There are 138 Root Sequences so there is a total capacity of 6 × 138 = 828 sequences. A Random Access occasion normally uses 64 preambles which require ROUND UP (64 / 6) = 11 Root Sequences. This leads to a Root Sequence re-use pattern size of ROUND DOWN (138/11) = 12

★ The small Root Sequence re-use pattern size associated with short preambles is expected to be manageable. Short preambles are intended to be used by cells with a small cell range. This tends to mean that cells have fewer neighbours and so Root Sequences can be re-used with a smaller pattern size. The Root Sequence re-use pattern size can be increased if less than 64 PRACH preambles are allocated to each Random Access occasion. This reduces PRACH capacity but helps to simplify the Root Sequence planning procedure

★ Table 164 summarises the subcarrier spacings used by the long and short PRACH preambles

	Frequency Range	Subcarrier Spacings
Long PRACH preambles	1	1.25, 5 kHz
Short PRACH preambles	1	15, 30 kHz
	2	60, 120 kHz

Table 164 – PRACH Subcarrier Spacings associated with each Frequency Range for Long and Short Preambles

7.2.2 PRACH GENERATION

★ Once the UE has identified the PRACH preamble to be transmitted (the Root Sequence and cyclic shift), the UE generates the corresponding Zadoff-Chu (ZC) sequence according to the following equations:

$$x_u(i) = e^{-j\frac{\pi u i (i+1)}{L_{RA}}}, \qquad i = 0, 1, \ldots L_{RA} - 1$$

$$x_{u,v}(n) = x_u((n + C_v) mod\, L_{RA})$$

★ The first equation generates the Zadoff-Chu sequence which corresponds to the u^{th} Root Sequence of length L_{RA}, where L_{RA} is 839 for a long preamble and 139 for a short preamble

★ The second equation applies the appropriate cyclic shift to the Root Sequence. C_v is the size of the cyclic shift. x_u is indexed using modular arithmetic to provide the wrap-around characteristic of the cyclic shift

★ The resultant sequence $x_{u,v}(n)$ is used as a time domain sequence. This means that it must be converted into the frequency domain prior to mapping onto the set of PRACH subcarriers. 3GPP TS 38.211 specifies the following Discrete Fourier Transform (DFT) to generate the frequency domain representation of the Zadoff-Chu sequence:

$$y_{u,v}(n) = \sum_{m=0}^{L_{RA}-1} x_{u,v}(m) \times e^{-j\frac{2\pi m n}{L_{RA}}}$$

★ The DFT result has a length equal to the length of the original Zadoff-Chu sequence. This result is mapped directly onto the set of 839 PRACH subcarriers when using a long preamble, or onto the set of 139 PRACH subcarriers when using a short preamble

★ Once the DFT result is mapped onto the set of PRACH subcarriers, an Inverse DFT is used to generate the time domain waveform to be transmitted across the air-interface. The inverse DFT does not simply reverse the preceding DFT because different sets of frequencies are used in each calculation. The DFT equation presented above illustrates that frequencies start from 0, i.e. 'm' = 0. In the case of the Inverse DFT, frequencies start from the position of the PRACH within the channel bandwidth. This general principle is illustrated in Figure 246

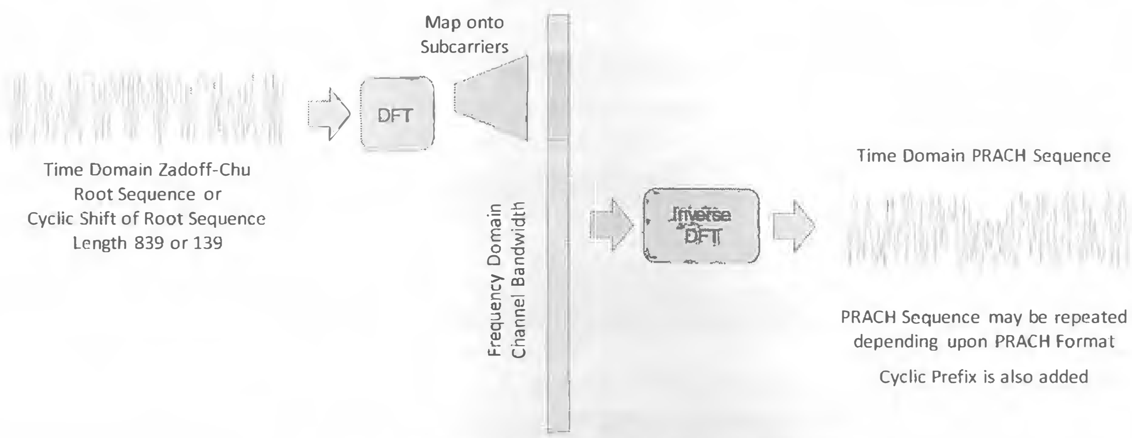


Figure 246 – Generation of PRACH from Zadoff-Chu Sequence

★ 3GPP TS 38.211 specifies the following equation for the Inverse DFT to generate the time domain waveform:

$$s_l^{(p,\mu)}(t) = \sum_{k=0}^{L_{RA}-1} a_k^{(p,RA)} \times e^{j2\pi(k+Kk_1+\bar{k})\Delta f_{RA}(t-N_{CP,l}^{RA}T_c-t_{start}^{RA})}$$

★ The summation is across the set of L_{RA} subcarriers. $a_k^{(p,RA)}$ corresponds to the k^{th} output from the DFT which is mapped onto the k^{th} subcarrier and is transmitted using antenna port 'p'. The exponential is in the form of $e^{j\omega t}$, where $\omega = 2\pi f = 2\pi\,(k + Kk_1 + \bar{k})\,\Delta f_{RA}$, i.e. the frequency is expressed as a multiple of the PRACH subcarrier spacing (Δf_{RA}). The section within the parenthesis defines the frequency domain position within the channel bandwidth

★ 'k' corresponds to the PRACH subcarrier number incremented according to the summation. 'K' is the ratio of the subcarrier spacing of the uplink Bandwidth Part, to the subcarrier spacing of the PRACH, i.e. $K = \Delta f \,/\, \Delta f_{RA}$. This ratio is required because k_1 has units of the subcarrier spacing of the uplink Bandwidth Part rather than units of the subcarrier spacing of the PRACH, i.e. 'K' is used to convert the units of k_1 to units of the subcarrier spacing of the PRACH. 'k_1' is defined using the following expression:

$$k_1 = 12N_{BWP,i}^{start} + 12n_{RA}^{start} + 12n_{RA}N_{RB}^{RA} - 12N_{grid}^{size,\mu}/2 + k_o^{\mu}$$

★ This expression for k_1 determines the frequency domain position of the PRACH in five steps. The first three of these steps are illustrated in Figure 247

- the first step uses $N_{BWP,i}^{start}$ to determine the position of the relevant Bandwidth Part within the channel bandwidth. This variable uses Common Resource Block numbering to specify the first Resource Block belonging to the Bandwidth Part. The factor of 12 converts the Resource Block Index to a subcarrier index
- the second step uses n_{RA}^{start} to determine the position of the PRACH resource allocations within the Bandwidth Part. This variable uses Resource Block numbering from within the Bandwidth Part. The factor of 12 converts the Resource Block Index to a subcarrier index
- the third step uses a combination of n_{RA} and N_{RB}^{RA} to determine the position of the specific PRACH resource allocation within the set of PRACH resource allocations. This step is relevant when multiple PRACH resource allocations have been configured in the frequency domain, i.e. PRACH resources are frequency multiplexed. If there is only a single PRACH resource allocation then $n_{RA} = 0$ and this step has no impact. n_{RA} represents the index of the PRACH resource allocation, whereas N_{RB}^{RA} represents the number of Resource Blocks used by each PRACH resource allocation
- the fourth step adjusts the subcarrier numbering to position subcarrier 0 at the center of the channel bandwidth. This means that k_1 can be either positive or negative. $N_{grid}^{size,\mu}$ defines the overall number of Resource Blocks belonging to the channel bandwidth
- the fifth step adjusts the result by k_0^{μ}. This step aligns the frequency domain position with the Resource Block grid for the largest configured subcarrier spacing. This step is necessary because the centers of the Resource Block grids for each subcarrier spacing are not always aligned

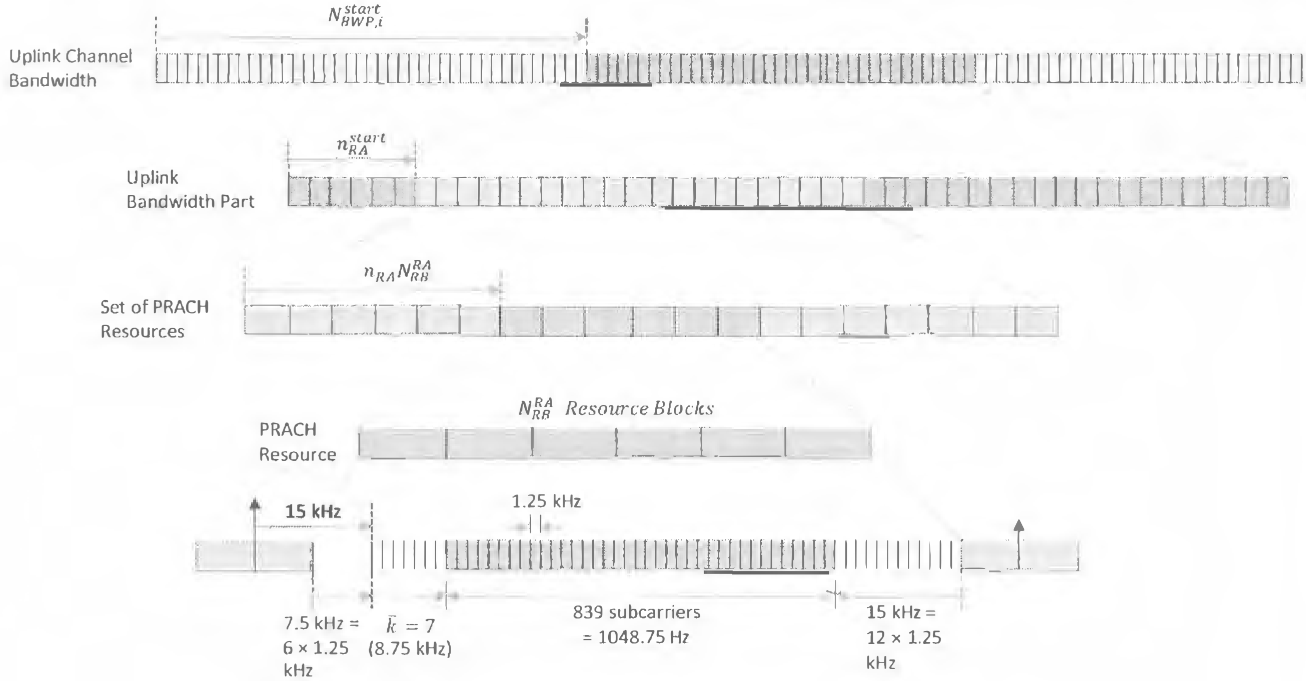


Figure 247 – Frequency domain position of the PRACH
(example assumes 1.25 kHz subcarrier spacing for the PRACH and 15 kHz subcarrier spacing for the PUSCH)

★ Figure 247 also illustrates the use of the $\bar{k}$ variable from within the frequency domain term of the Inverse DFT exponential, i.e. $2\pi\ (k + Kk_1 + \bar{k})\ \Delta f_{RA}$. This variable has units of the subcarrier spacing of the PRACH. It is used to position the PRACH transmission within the center of the Resource Blocks allocated to the PRACH. 3GPP TS 38.211 specifies a fixed look-up table for the value of $\bar{k}$ based upon the preamble length, subcarrier spacing for the PRACH and subcarrier spacing for the PUSCH. This look-up table is presented as Table 165. The table also specifies the number of Resource Blocks allocated to the PRACH (N_{RB}^{RA})

★ The values of $\bar{k}$ are not immediately obvious because the starting position is based upon the subcarrier spacing of the PUSCH, i.e. k_1 is based upon the subcarrier spacing of the PUSCH. The example shown in Figure 247 is based upon a PUSCH subcarrier spacing of 15 kHz so the starting position is 15 kHz from the adjacent PUSCH subcarrier. This places the starting position 7.5 kHz into the PRACH

Resource Allocation. The example is based upon a long PRACH with a subcarrier spacing of 1.25 kHz so the PRACH transmission occupies 1048.75 kHz. 6 PUSCH Resource Blocks are allocated for the PRACH which corresponds to 6 × 12 × 15 = 1080 kHz, i.e. there is 1080 – 1048.75 = 31.25 kHz of guard band to allocate. This corresponds to 25 subcarriers of 1.25 kHz. 13 subcarriers are allocated below the PRACH transmission and 12 subcarriers are allocated above the PRACH transmission. The 7.5 kHz of guard band provided by the starting position corresponds to 6 subcarriers and so $\bar{k}$ = 7 to provide the total of 13 subcarriers

L_{RA}	Δf^{RA} for PRACH	Δf for PUSCH	N_{RB}^{RA}	$\bar{k}$
839	1.25	15	6	7
		30	3	1
		60	2	133
	5	15	24	12
		30	12	10
		60	6	7
139	15	15	12	2
		30	6	
		60	3	
	30	15	24	
		30	12	
		60	6	
	60	60	12	
		120	6	
	120	60	24	
		120	12	

Table 165 – Values of $\bar{k}$ as a function of PRACH length, PRACH subcarrier spacing and PUSCH subcarrier spacing

★ Returning to the equation for the Inverse DFT, the time component of $s_l^{(p,\mu)}(t)$ is given by $(t - N_{CP,l}^{RA} T_c - t_{start}^{RA})$, where the range of time is given by $t_{start}^{RA} \le t < t_{start}^{RA} + (N_u + N_{CP,l}^{RA})T_c$

★ This indicates that $(N_u + N_{CP,l}^{RA})T_c$ defines the duration of the PRACH transmission. $N_u\ T_c$ corresponds to the duration of the PRACH sequence. This duration may include a single PRACH sequence or repetitions of the PRACH sequence. $N_{CP,l}^{RA}\ T_c$ corresponds to the duration of the PRACH cyclic prefix

★ The starting time of the transmission is specified using t_{start}^{RA}

- o in the case of the long PRACH formats, the starting time is defined by the 'Starting Symbol' specified by the PRACH Configuration Index. The vast majority of Configuration Indices have a 'Starting Symbol' of 0 meaning that the PRACH occasion starts at the beginning of the relevant subframe. A relatively small number of Configuration indices have a 'Starting Symbol' of 7 meaning that the PRACH occasion starts during symbol 7 of the relevant subframe (symbol numbering is based upon the 15 kHz numerology, i.e. 14 symbols per subframe)
- o in the case of the short PRACH formats and Frequency Range 1, the starting time is a symbol within a 1 ms subframe. There are 14 symbols within the subframe when using the 15 kHz subcarrier spacing, whereas there are 28 symbols within the subframe when using the 30 kHz subcarrier spacing. The PRACH Configuration Index provides the parameters which allow the UE to calculate the appropriate symbol within the relevant subframe
- o in the case of the short PRACH formats and Frequency Range 2, the starting time is a symbol within a slot belonging to the 60 kHz numerology. There are 14 symbols within the slot when using the 60 kHz subcarrier spacing, whereas there are 28 symbols within the slot when using the 120 kHz subcarrier spacing. The PRACH Configuration Index provides the parameters which allow the UE to calculate the appropriate symbol within the relevant slot

★ Table 166 summarises the way in which the starting time is specified for both the long and short PRACH formats. Examples of calculating the starting position for the short PRACH formats are provided in Section 7.2.4

	Frequency Range	Starting Position	Subcarrier Spacing	Number of Potential Starting Symbols
Long PRACH preambles	1	within a Subframe	1.25, 5 kHz	14 symbols
Short PRACH preambles	1	within a Subframe	15 kHz	14 symbols
			30 kHz	28 symbols
	2	within a Slot belonging to the 60 kHz numerology	60 kHz	14 symbols
			120 kHz	28 symbols

Table 166 – Potential starting symbols for Long and Short PRACH formats

7.2.3 LONG SEQUENCE PRACH FORMATS

★ 3GPP TS 38.211 specifies 4 PRACH formats which use long Zadoff-Chu (ZC) sequences. The key characteristics of these PRACH formats are:

- o sequence length of 839, leading to 838 Root Sequences
- o subcarrier spacings of 1.25 kHz and 5 kHz, leading to sequence durations of 800 μs and 200 μs respectively
- o applicable to operating bands belonging to Frequency Range 1 (450 MHz to 6 GHz)
- o applicable to FDD and TDD configurations which allow relatively long periods of continuous uplink transmission

★ Table 167 presents the 4 PRACH formats using the long Zadoff-Chu sequence:

- o Format 0 is copied from 4G format 0. It provides a maximum cell range of 14.5 km and is intended for scenarios where 4G spectrum has been re-farmed for 5G, i.e. the existing 4G site density is re-used for 5G. It creates a relatively low overhead in the time domain (total duration of 1 ms)
- o Format 1 is copied from 4G format 3. It provides a maximum cell range of 100 km so is intended for long range deployment scenarios. The large cell range is visible from the longer cyclic prefix which must accommodate the cell edge round trip propagation delay. The ZC sequence is transmitted twice to increase the signal to noise ratio at the Base Station receiver. Format 1 creates a relatively large overhead in the time domain (total duration of 3 ms)
- o Format 2 is intended for scenarios which require coverage enhancement. The ZC sequence is transmitted 4 times to increase the signal to noise ratio at the Base Station receiver, i.e. 6 dB gain relative to format 0. Within this context, coverage enhancement refers to improving coverage within the normal cell range, i.e. providing deeper indoor coverage. It does not refer to an extended cell range because the cyclic prefix is relatively short and supports a maximum cell range of 22.1 km. This format creates the largest overhead in the time domain (total duration of 4 ms)
- o Format 3 is intended for high speed scenarios. The higher subcarrier spacing means that it is less vulnerable to Doppler shifts. This PRACH format is intended to cope with Doppler shifts generated by speeds of 500 km/hr while using a 6 GHz RF carrier. The larger subcarrier spacing leads to an increased bandwidth so format 4 generates a larger overhead than format 0. The larger subcarrier spacing also leads to a shorter sequence duration so the sequence is transmitted 4 times while keeping the total duration equal to 1 ms

Format	Subcarrier Spacing	Sequence Length	Bandwidth	Cyclic Prefix Duration	Sequence Duration	Guard Period Duration	Total Duration	Assumed Delay Spread	Typical Maximum Cell Range
0	1.25 kHz	839	1048.75 kHz	103.13 μs	1 × 800 μs	96.88 μs	1 ms	5.2 μs	14.5 km
1				684.38 μs	2 × 800 μs	715.63 μs	3 ms	16.7 μs	100.2 km
2				152.60 μs	4 × 800 μs	647.40 μs	4 ms	5.2 μs	22.1 km
3	5 kHz		4195 kHz	103.13 μs	4 × 200 μs	96.88 μs	1 ms	5.2 μs	14.5 km

Table 167 – PRACH Formats using a Long Sequence (applicable to operating bands < 6 GHz)

★ The cell range figures provided in Table 167 are calculated from the durations of the cyclic prefix and guard period. The resultant cell range is the minimum of the two calculations:

- o the cyclic prefix must accommodate the propagation channel delay spread and the round trip propagation delay. In general, delay spread is assumed to increase with cell range so a larger delay spread is assumed for format 1

  Cell Range from Cyclic Prefix = [(Cyclic Prefix Duration – Delay Spread) × speed of light] / 2

- o the guard period must accommodate the round trip propagation delay

  Cell Range from Guard Period = [Guard Period Duration × speed of light] / 2

★ These calculations ensure that the PRACH does not generate inter-symbol interference. They also ensure that the Base Station receives a complete version of the PRACH preamble. Figure 248 illustrates the consequence of exceeding the calculated maximum cell range. The Base Station may successfully detect the PRACH preamble when a UE exceeds the calculated maximum cell range and so the Random Access procedure can still succeed. However, the additional delay means that the Base Station will not receive the complete transmission and the tail end of the transmission may generate inter-symbol interference

★ Cell range may be further limited by the cyclic shift used to generate multiple sequences from each Root Sequence. Selection of the appropriate cyclic shift size is typically a Radio Network Planning task

★ The bandwidths presented in Table 167 are calculated as the sequence length × subcarrier spacing, i.e. the bandwidth occupied by the PRACH transmission. These bandwidths do not occupy an integer number of PUSCH Resource Blocks so there is margin to allow a guard band between the PRACH and the adjacent Resource Blocks. Table 168 presents the guard band size for each combination of PRACH subcarrier spacing and PUSCH subcarrier spacing. With the exception of one case, the guard band size is 31.25 kHz. The PRACH subcarrier spacing of 1.25 kHz with the PUSCH subcarrier spacing of 60 kHz generates a guard band size of 391.25 kHz

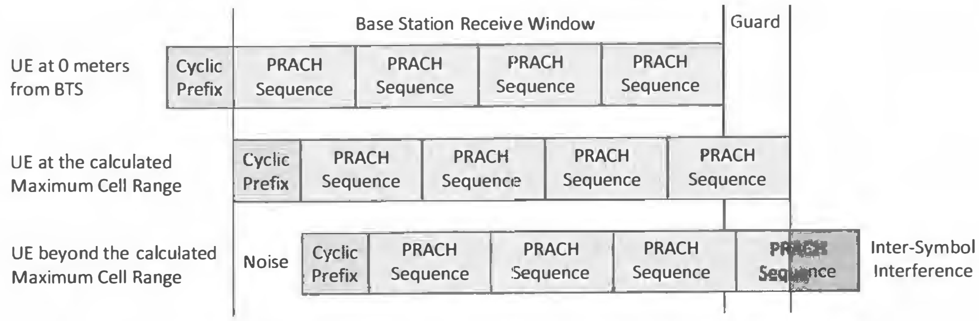


Figure 248 – PRACH transmissions delayed by increasing propagation distance

PRACH Subcarrier Spacing	Sequence Length	PRACH Bandwidth	PUSCH Subcarrier Spacing					
			15 kHz		30 kHz		60 kHz	
			RB Occupied by PRACH	Guard Band	RB Occupied by PRACH	Guard Band	RB Occupied by PRACH	Guard Band
1.25 kHz	839	1048.75 kHz	6 PRB 1080 kHz	25 subcarriers 31.25 kHz	3 PRB 1080 kHz	25 subcarriers 31.25 kHz	2 PRB 1440 kHz	313 subcarriers 391.25 kHz
5 kHz		4195 kHz	24 PRB 4320 kHz	25 subcarriers 31.25 kHz	12 PRB 4320 kHz	25 subcarriers 31.25 kHz	6 PRB 4320 kHz	25 subcarriers 31.25 kHz

Table 168 –Resource Blocks (RB) occupied by the PRACH and the resultant Guard Bands

★ Table 169 presents the set of unrestricted cyclic shifts for the 1.25 kHz subcarrier spacing. Unrestricted cyclic shifts are applicable to deployment scenarios with low to medium mobility. These cyclic shifts are the same as those used for 4G PRACH preamble formats 0 to 3. The 'Sequences per Root Sequence' column is calculated as ROUND DOWN (839 / Cyclic Shift). The 'Root Sequences required per Cell' column is calculated as ROUND UP (64 / Sequences per Root Sequence). The 'Root Sequence Re-use Pattern' column is calculated as ROUND DOWN (838 / Root Sequences required per Cell)

★ The Cell Range figures in Table 169 are calculated as 300 × [(Cyclic Shift – 1) × (800 /839) – Delay Spread] / (2 × 1000), where 300 corresponds to the speed of light in meters per µs, 800 corresponds to the long sequence duration in µs, 2 accounts for the round trip distance and 1000 provides the conversion from meters to km. Table 169 presents cell range figures for two assumed delay spreads. 5.2 µs is consistent with the assumed delay spread in Table 167, while 6.4 µs is another common assumption. Table 167 also uses a delay spread assumption of 16.7 µs for the 100 km cell range calculation. If this delay spread is applied to the cyclic shift of 0 then the resultant cell range is 117.35 km, i.e. achieving a 100 km cell range requires PRACH format 1 in combination with a cyclic shift of 0

Zero Correlation Zone Configuration	Sequence Length	Cyclic Shift	Sequences per Root Sequence	Root Sequences required per Cell	Root Sequence Re-use Pattern	Cell Range (5.2 µs Delay Spread)	Cell Range (6.4 µs Delay Spread)
1	839	13	64	1	838	0.94 km	0.76 km
2		15	55	2	419	1.22 km	1.04 km
3		18	46			1.65 km	1.47 km
4		22	38			2.22 km	2.04 km
5		26	32			2.80 km	2.62 km
6		32	26	3	279	3.65 km	3.47 km
7		38	22			4.51 km	4.33 km
8		46	18	4	209	5.66 km	5.48 km
9		59	14	5	167	7.52 km	7.34 km
10		76	11	6	139	9.95 km	9.77 km
11		93	9	8	104	12.38 km	12.20 km
12		119	7	10	83	16.10 km	15.92 km
13		167	5	13	64	22.96 km	22.78 km
14		279	3	22	38	38.98 km	38.80 km
15		419	2	32	26	59.01	58.83 km
0		0	1	64	13	119.08 km	118.90 km

Table 169 – Root Sequence Re-Use Pattern and Cell Range for Subcarrier Spacing of 1.25 kHz (Unrestricted Cyclic Shift)

★ Table 169 illustrates that larger cyclic shifts are able to support larger cell ranges but lead to smaller Root Sequence re-use pattern sizes. It is important to select a cyclic shift which provides a cell range which is greater than or equal to the actual cell range. The Random Access procedure will fail if coverage extends beyond the cell range associated with the cyclic shift. This is caused by the Base Station incorrectly detecting the cyclic shift transmitted by the UE. In the case of the contention based Random Access procedure, the Base Station will proceed to transmit the Random Access Response message (MSG2) but it will address an incorrect cyclic shift. This means that the UE will not receive MSG2. From a UE perspective, the MSG1 to MSG2 success rate will be poor, while from a Base Station perspective, the MSG1 to MSG3 success rate will be poor

★ Table 170 presents the set of unrestricted cyclic shifts for the 5 kHz subcarrier spacing. The key point regarding this table is the trade-off between resilience to Doppler frequency offsets and cell range. The 5 kHz subcarrier spacing has been specified for high mobility scenarios because it provides increased resilience against Doppler frequency offsets. However, increasing the subcarrier spacing by a factor of 4 causes the sequence duration to decrease by a factor of 4. This leads to significantly smaller cell ranges (if the delay spread is assumed to be 0 μs in both cases, and an equal cyclic shift is considered then the cell range also decreases by a factor of 4)

★ Table 170 presents cell range figures for delay spreads of 5.2 μs and 6.4 μs to allow a comparison with Table 169. These delay spreads are too large for the smaller cyclic shifts so a set of cell range figures are also presented for 0 μs delay spread

Zero Correlation Zone Configuration	Sequence Length	Cyclic Shift	Sequences per Root Sequence	Root Sequences required per Cell	Root Sequence Re-use Pattern	Cell Range (0 μs Delay Spread)	Cell Range (5.2 μs Delay Spread)	Cell Range (6.4 μs Delay Spread)
1	839	13	64	1	838	0.43 km	-	-
2		26	32	2	419	0.89 km	0.11 km	-
3		33	25	3	279	1.14 km	0.36 km	0.18 km
4		38	22			1.32 km	0.54 km	0.36 km
5		41	20	4	209	1.43 km	0.65 km	0.47 km
6		49	17			1.72 km	0.94 km	0.76 km
7		55	15	5	167	1.93 km	1.15 km	0.97 km
8		64	13			2.25 km	1.47 km	1.29 km
9		76	11	6	139	2.68 km	1.90 km	1.72 km
10		93	9	8	104	3.29 km	2.51 km	2.33 km
11		119	7	10	83	4.22 km	3.44 km	3.26 km
12		139	6	11	76	4.93 km	4.15 km	3.97 km
13		209	4	16	52	7.4 km	6.66 km	6.48 km
14		279	3	22	38	9.94 km	9.16 km	8.98 km
15		419	2	32	26	14.95 km	14.17 km	13.99 km
0		0	1	64	13	29.96 km	29.18 km	29.00 km

Table 170 – Root Sequence Re-Use Pattern and Cell Range for Subcarrier Spacing of 5 kHz (Unrestricted Cyclic Shift)

★ The 'PRACH Configuration Index' defines the time domain position of the PRACH. 3GPP TS 38.211 specifies 2 sets of Configuration Indices for the long PRACH preambles. The first set is applicable to Paired and Supplemental Uplink spectrum within Frequency Range 1. This set is presented in Table 171. The second set is applicable to Unpaired spectrum within Frequency Range 1. This set is presented in Table 172

★ The radio frames which include PRACH opportunities are specified using the '$n_{SFN}\ mod\ x = y$' rule. For example, when 'x = 16' and 'y = 1' then there are PRACH opportunities within radio frames 1, 17, 33, 49, 65, ... When 'x = 1' and 'y = 0' there are PRACH opportunities within every radio frame. The Configuration Index tables also define the subframe(s) within which the PRACH opportunities start (recall that there are always 10 × 1 ms subframes within a 10 ms radio frame irrespective of the numerology). Some Configuration Indices specify only a single subframe per radio frame. Other Configuration Indices specify all 10 subframes

★ The Configuration Index tables include a PRACH Duration column. This column is not used for long PRACH preambles so it is set to 0 to ensure that it does not impact the time domain calculations which are based upon a common set of equations for both long and short PRACH preambles

★ The Total Duration of the PRACH, as presented in Table 167 sets the upper limit for the number of PRACH starting subframes. PRACH formats 0 and 3 have durations of 1 ms so all 10 subframes can be specified as starting subframes, e.g. PRACH Configuration Index 27 within Table 171. PRACH format 1 has a duration of 3 ms so there can be a maximum of 3 time domain allocations per radio frame, e.g. PRACH Configuration Index 52 within Table 171. PRACH format 2 has a duration of 4 ms so in principle there can be a maximum of 2 time domain allocations per radio frame although 3GPP has specified only a single time domain allocation

★ The combination of radio frames and subframes defines the time domain capacity of the PRACH. Up to 8 PRACH resource allocations can be frequency multiplexed within each of the allocated subframes. This leads to a minimum PRACH capacity of 1 resource allocation per 16 radio frames, and a maximum PRACH capacity of 1280 resource allocations per 16 radio frames (assuming 8 PRACH resource allocations in every subframe)

★ Selecting a PRACH Configuration Index with a high time domain capacity provides a benefit in terms of latency, i.e. the average waiting time for a PRACH occasion decreases. The drawback of an increased PRACH capacity is an increased overhead from the perspective of the PUSCH

★ 5G allows the configuration of lower PRACH densities relative to 4G. Both Table 171 and Table 172 have minimum densities of 1 PRACH occasion every 160 ms. In the case of 4G, the minimum PRACH density is 1 PRACH occasion every 20 ms. The 5G minimum PRACH density is within the range of densities used by the 4G NPRACH (applicable to NB-IoT)

PRACH PREAMBLE FORMAT 0					
PRACH Configuration Index	n_{SFN} mod x = y		Subframe Number	Starting Symbol	PRACH Duration
	x	y			
0	16	1	1	0	0
1	16	1	4	0	0
2	16	1	7	0	0
3	16	1	9	0	0
4	8	1	1	0	0
5	8	1	4	0	0
6	8	1	7	0	0
7	8	1	9	0	0
8	4	1	1	0	0
9	4	1	4	0	0
10	4	1	7	0	0
11	4	1	9	0	0
12	2	1	1	0	0
13	2	1	4	0	0
14	2	1	7	0	0
15	2	1	9	0	0
16	1	0	1	0	0
17	1	0	4	0	0
18	1	0	7	0	0
19	1	0	1, 6	0	0
20	1	0	2, 7	0	0
21	1	0	3, 8	0	0
22	1	0	1, 4, 7	0	0
23	1	0	2, 5, 8	0	0
24	1	0	3, 6, 9	0	0
25	1	0	0, 2, 4, 6, 8	0	0
26	1	0	1, 3, 5, 7, 9	0	0
27	1	0	0, 1, 2, 3, 4, 5, 6, 7, 8, 9	0	0

PRACH PREAMBLE FORMAT 1					
PRACH Configuration Index	n_{SFN} mod x = y		Subframe Number	Starting Symbol	PRACH Duration
	x	y			
28	16	1	1	0	0
29	16	1	4	0	0
30	16	1	7	0	0
31	16	1	9	0	0
32	8	1	1	0	0
33	8	1	4	0	0
34	8	1	7	0	0
35	8	1	9	0	0
36	4	1	1	0	0
37	4	1	4	0	0
38	4	1	7	0	0
39	4	1	9	0	0
40	2	1	1	0	0
41	2	1	4	0	0
42	2	1	7	0	0
43	2	1	9	0	0
44	1	0	1	0	0
45	1	0	4	0	0
46	1	0	7	0	0
47	1	0	1, 6	0	0
48	1	0	2, 7	0	0
49	1	0	3, 8	0	0
50	1	0	1, 4, 7	0	0
51	1	0	2, 5, 8	0	0
52	1	0	3, 6, 9	0	0

PRACH PREAMBLE FORMAT 2					
PRACH Configuration Index	n_{SFN} mod x = y		Subframe Number	Starting Symbol	PRACH Duration
	x	y			
53	16	1	1	0	0
54	8	1	1	0	0
55	4	0	1	0	0
56	2	0	1	0	0
57	2	0	5	0	0
58	1	0	1	0	0
59	1	0	5	0	0

PRACH PREAMBLE FORMAT 3					
PRACH Configuration Index	n_{SFN} mod x = y		Subframe Number	Starting Symbol	PRACH Duration
	x	y			
60	16	1	1	0	0
61	16	1	4	0	0
62	16	1	7	0	0
63	16	1	9	0	0
64	8	1	1	0	0
65	8	1	4	0	0
66	8	1	7	0	0
67	4	1	1	0	0
68	4	1	4	0	0
69	4	1	7	0	0
70	4	1	9	0	0
71	2	1	1	0	0
72	2	1	4	0	0
73	2	1	7	0	0
74	2	1	9	0	0
75	1	0	1	0	0
76	1	0	4	0	0
77	1	0	7	0	0
78	1	0	1, 6	0	0
79	1	0	2, 7	0	0
80	1	0	3, 8	0	0
81	1	0	1, 4, 7	0	0
82	1	0	2, 5, 8	0	0
83	1	0	3, 6, 9	0	0
84	1	0	0, 2, 4, 6, 8	0	0
85	1	0	1, 3, 5, 7, 9	0	0
86	1	0	0, 1, 2, 3, 4, 5, 6, 7, 8, 9	0	0

Table 171 – PRACH Configuration Indices for PRACH Formats 0 to 3 (Frequency Range 1 Paired and Supplemental Uplink Spectrum)

PRACH PREAMBLE FORMAT 0					
PRACH Configuration Index	n_{SFN} mod x = y		Subframe Number	Starting Symbol	PRACH Duration
	x	y			
0	16	1	9	0	0
1	8	1	9	0	0
2	4	1	9	0	0
3	2	0	9	0	0
4	2	1	9	0	0
5	2	0	4	0	0
6	2	1	4	0	0
7	1	0	9	0	0
8	1	0	8	0	0
9	1	0	7	0	0
10	1	0	6	0	0
11	1	0	5	0	0
12	1	0	4	0	0
13	1	0	3	0	0
14	1	0	2	0	0
15	1	0	1, 6	0	0
16	1	0	1, 6	7	0
17	1	0	4, 9	0	0
18	1	0	3, 8	0	0
19	1	0	2, 7	0	0
20	1	0	8, 9	0	0
21	1	0	4, 8, 9	0	0
22	1	0	3, 4, 9	0	0
23	1	0	7, 8, 9	0	0
24	1	0	3, 4, 8, 9	0	0
25	1	0	6, 7, 8, 9	0	0
26	1	0	1, 4, 6, 9	0	0
27	1	0	1, 3, 5, 7, 9	0	0

PRACH PREAMBLE FORMAT 1					
PRACH Configuration Index	n_{SFN} mod x = y		Subframe Number	Starting Symbol	PRACH Duration
	x	y			
28	16	1	7	0	0
29	8	1	7	0	0
30	4	1	7	0	0
31	2	0	7	0	0
32	2	1	7	0	0
33	1	0	7	0	0

PRACH PREAMBLE FORMAT 2					
PRACH Configuration Index	n_{SFN} mod x = y		Subframe Number	Starting Symbol	PRACH Duration
	x	y			
34	16	1	6	0	0
35	8	1	6	0	0
36	4	1	6	0	0
37	2	0	6	7	0
38	2	1	6	7	0
39	1	0	6	7	0

PRACH PREAMBLE FORMAT 3					
PRACH Configuration Index	n_{SFN} mod x = y		Subframe Number	Starting Symbol	PRACH Duration
	x	y			
40	16	1	9	0	0
41	8	1	9	0	0
42	4	1	9	0	0
43	2	0	9	0	0
44	2	1	9	0	0
45	2	0	4	0	0
46	2	1	4	0	0
47	1	0	9	0	0
48	1	0	8	0	0
49	1	0	7	0	0
50	1	0	6	0	0
51	1	0	5	0	0
52	1	0	4	0	0
53	1	0	3	0	0
54	1	0	2	0	0
55	1	0	1, 6	0	0
56	1	0	1, 6	7	0
57	1	0	4, 9	0	0
58	1	0	3, 8	0	0
59	1	0	2, 7	0	0
60	1	0	8, 9	0	0
61	1	0	4, 8, 9	0	0
62	1	0	3, 4, 9	0	0
63	1	0	7, 8, 9	0	0
64	1	0	3, 4, 8, 9	0	0
65	1	0	1, 4, 6, 9	0	0
66	1	0	1, 3, 5, 7, 9	0	0

Table 172 – PRACH Configuration Indices for PRACH Formats 0 to 3 (Frequency Range 1 Unpaired Spectrum)

★ In the case of TDD (unpaired spectrum), PRACH occasions are only permitted during uplink symbols. In general, radio frames start with downlink symbols and finish with uplink symbols. The use of flexible symbols means that the boundary between the downlink and uplink can be changed dynamically. The PRACH time domain allocations within Table 172 are generally placed at the end of a radio frame to help ensure that they occupy uplink symbols. PRACH formats 0 and 3 have durations of 1 ms so placing the PRACH occasion within subframe 9 corresponds to the end of the radio frame. PRACH format 1 has a duration of 3 ms so starting the PRACH occasion during subframe 7 corresponds to the end of the radio frame (PRACH occupies subframes 7, 8 and 9). PRACH format 2 has a duration of 4 ms so starting the PRACH occasion during subframe 6 corresponds to the end of the radio frame (PRACH occupies subframes 6, 7, 8 and 9).

★ In the case of TDD, there are some PRACH Configuration Indices which have a Starting Symbol of 7 rather than 0. This means that the PRACH occasion starts half-way through a subframe. These configurations are intended to support different uplink/downlink patterns. For example, Configuration Indices 16 and 56 define PRACH occasions which start during symbol 7 of subframes 1 and 6. These configurations are intended to support 2.5 ms uplink/downlink switching patterns, as illustrated in upper part of Figure 249. The lower part of Figure 249 illustrates that a 2.5 ms uplink/downlink switching pattern can also be supported by starting the PRACH during symbol 0 of subframes 4 and 9 (corresponds to PRACH Configuration Indices 17 and 57)

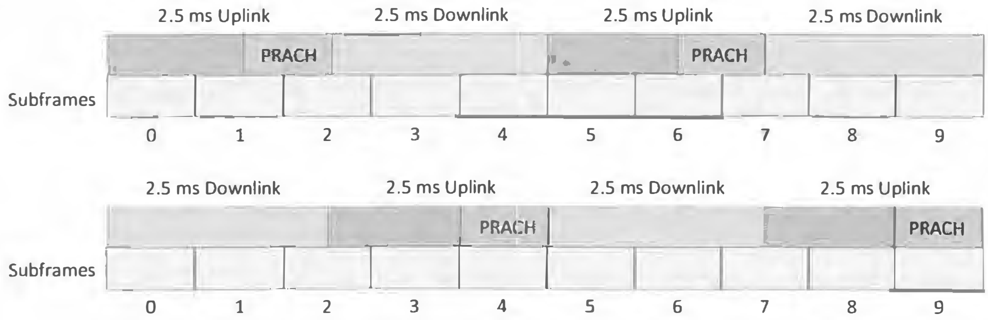


Figure 249 – PRACH positions when using 2.5 ms uplink/downlink switching pattern

7.2.4 SHORT SEQUENCE PRACH FORMATS

★ 3GPP TS 38.211 specifies 9 PRACH formats which use short Zadoff-Chu (ZC) sequences. The key characteristics of these PRACH formats are:

- o sequence length of 139, leading to 138 Root Sequences
- o applicable to Frequency Range 1 (450 MHz to 6 GHz) when using subcarrier spacings of 15 kHz or 30 kHz, with corresponding sequence durations of 66.67 μs and 33.33 μs respectively
- o applicable to Frequency Range 2 (24.25 GHz to 52.6 GHz) when using subcarrier spacings of 60 kHz or 120 kHz, with corresponding sequence durations of 16.67 μs and 8.33 μs respectively
- o suitable for cells with small to medium cell range
- o applicable to TDD configurations which are restricted to relatively short periods of continuous uplink transmission

★ The short PRACH formats are named A1, A2, A3, B1, B2, B3, B4, C0 and C2. These PRACH formats are illustrated in Figure 250, and are specified in Table 173. Figure 250 illustrates a specific number of repetitions for each PRACH format, e.g. PRACH format A1 is illustrated with 6 repetitions. In practice, the number of repetitions depends upon the PRACH Configuration Index presented later in this section

★ Formats A1, A2 and A3 have cyclic prefix/sequence combinations which occupy an integer number of symbols. This means that there is no explicit guard period between consecutive PRACH occasions. For these PRACH formats, the start of one PRACH occasion acts as a guard period for the previous PRACH occasion. The final PRACH occasion in the sequence relies upon having a guard period at the end of the sequence transmission

★ Formats A1, A2 and A3 have durations of 2, 4 and 6 symbols respectively. Format A1 includes 2 repetitions of the PRACH sequence, while Format A2 includes 4 repetitions and Format A3 includes 6 repetitions. Each repetition has a duration equal to the payload of the PUSCH, i.e. $2048 \times T_S \times 2^{\mu}$, where $T_S = 1 / (15\,000 \times 2048)$ seconds and μ is the subcarrier spacing index. This means that the cyclic prefix durations are multiples of the normal cyclic prefix duration

★ The maximum cell ranges associated with formats A1, A2 and A3 are calculated as [(Cyclic Prefix Duration – Delay Spread) × speed of light] / 2. Cell range calculations usually account for the guard period. In this case, the guard period does not limit the cell range because it is either an empty symbol or the start of another PRACH occasion. The Delay Spread for formats A2 and A3 is assumed to equal the duration of the normal cyclic prefix, i.e. $144 \times T_S \times 2^{\mu}$. This corresponds to the maximum delay spread which can be tolerated by the PUSCH without experiencing inter-symbol interference. This assumption means that the assumed delay spread decreases as the subcarrier spacing increases. Format A1 is intended for small cell deployment so the assumed delay spread is reduced to $96 \times T_S \times 2^{\mu}$

★ Format A1 has a maximum cell range of 938 m when using Frequency Range 1 and a maximum cell range of 234 m when using Frequency Range 2. The maximum cell range figures increase for formats A2 and A3 due to the larger cyclic prefix durations. Format A3 has a maximum cell range of 3.5 km when using Frequency Range 1 and a maximum cell range of 879 m when using Frequency Range 2

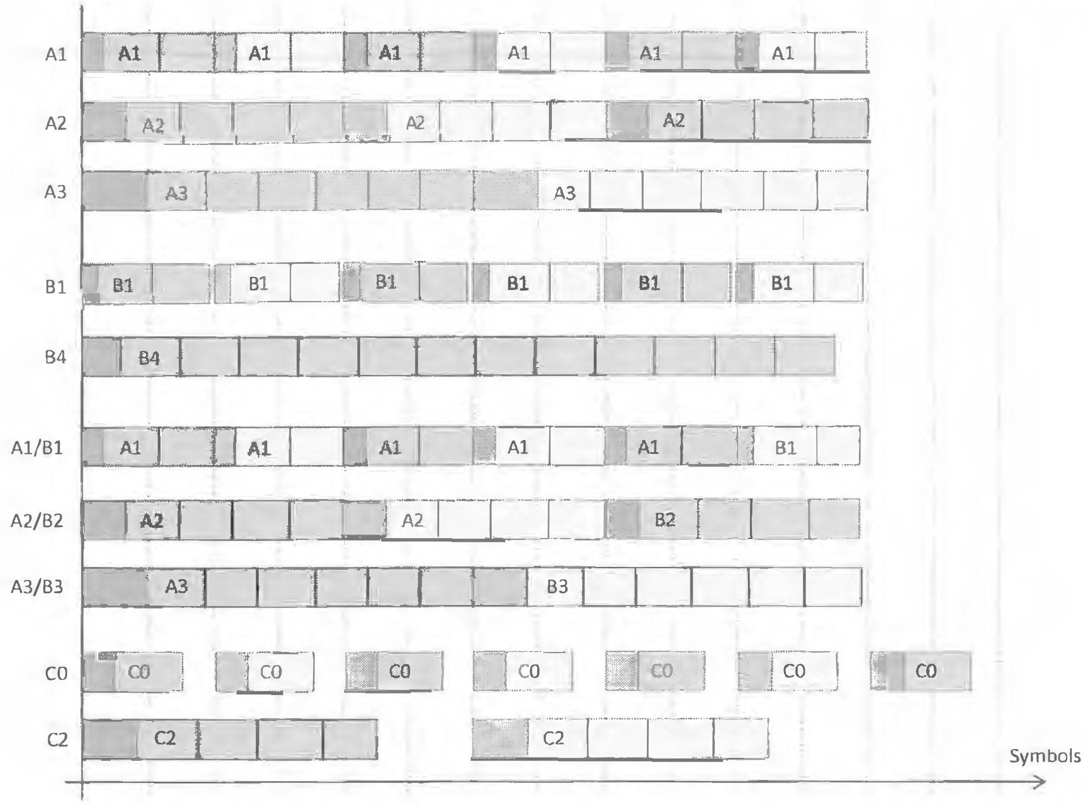


Figure 250 – Short PRACH formats

- Format B1 can be used alone, or in combination with format A1. When used in combination with format A1, there is a series of format A1 PRACH occasions followed by a single format B1 PRACH occasion. Format B4 can only be used alone, whereas formats B2 and B3 can only be used in combination with formats A2 and A3 respectively
- Formats B1, B2, B3 and B4 have cyclic prefix/sequence combinations which occupy a non-integer number of symbols. This means that there is an explicit guard period between the end of a PRACH occasion and the start of the next symbol. When using format combinations, there is no explicit guard period between the series of format A1/A2/A3 but the final PRACH occasion using format B1/B2/B3 provides a guard period before data transmission within the next symbol
- Formats B1, B2, B3 and B4 include 2, 4, 6 and 12 repetitions of the PRACH sequence respectively. The duration of each sequence is the same as that belonging to formats A1, A2 and A3, i.e. i.e. $2048 \times T_s \times 2^{\mu}$. The cyclic prefix durations are reduced relative to formats A1, A2 and A3. This creates the guard period at the end of the PRACH occasion but reduces the maximum cell range
- The maximum cell ranges associated with formats B1, B2, B3 and B4 are calculated as the minimum of the cell ranges defined by the cyclic prefix duration and the guard period duration. Cell range calculated from the cyclic prefix duration is given by [(Cyclic Prefix Duration – Delay Spread) × speed of light] / 2. Cell range calculated from the guard period duration is given by [Guard Period Duration × speed of light] / 2
- The Delay Spread for formats B2, B3 and B4 is assumed to equal the duration of the normal cyclic prefix, i.e. $144 \times T_s \times 2^{\mu}$. This corresponds to the maximum delay spread which can be tolerated by the PUSCH without experiencing inter-symbol interference. This assumption means that the assumed delay spread decreases as the subcarrier spacing increases. Format B1 is intended for small cell deployment so the assumed delay spread is reduced to $96 \times T_s \times 2^{\mu}$
- Format B1 has a maximum cell range of 352 m when using Frequency Range 1 and a maximum cell range of 88 m when using Frequency Range 2. Format B4 has a maximum cell range of 3.9 km when using Frequency Range 1 and a maximum cell range of 967 m when using Frequency Range 2. When using format B1 in combination with format A1, the maximum cell range is defined by the minimum of the two individual cell ranges. This means that the cell range will be defined by format B1. Similarly, the cell range is defined by format B2 when format B2 is used in combination with format A2
- Formats C0 and C2 were introduced to support larger cell ranges with the short PRACH preamble. The cyclic prefix and guard period belonging to these formats have longer durations than the other formats. Format C2 has a maximum cell range of 9.3 km when using Frequency Range 1 and a maximum cell range of 2.3 km when using Frequency Range 2. These cell ranges remain smaller than those supported by the long PRACH preambles. This indicates that it is mandatory to use the long PRACH preambles to deploy macro cells with ranges greater than 10 km
- The principle illustrated in Figure 248 also applies to short PRACH preambles, i.e. the Random Access procedure may be successful at distances greater than the maximum cell range calculated for a specific PRACH Format. However, the additional delay means that the Base Station will not receive the complete transmission and the tail end of the transmission may generate inter-symbol interference. Cell range may be further limited by the cyclic shift used to generate the PRACH preambles from the Root Sequences

Format	Cyclic Prefix Duration	Sequence Duration	Guard Period Duration	Total Duration (symbols)	Assumed Delay Spread	Subcarrier Spacing	CP + Seq. Duration (μs)	Assumed Delay Spread	Maximum Cell Range
A1	$288 \times T_s \times 2^{-\mu}$	$2 \times 2048 \times T_s \times 2^{-\mu}$	0	2 symbols	$96 \times T_s \times 2^{-\mu}$	15 kHz	142.71	3.13 μs	938 m
						30 kHz	71.35	1.56 μs	469 m
						60 kHz	35.68	0.78 μs	234 m
						120 kHz	17.84	0.39 μs	117 m
A2	$576 \times T_s \times 2^{-\mu}$	$4 \times 2048 \times T_s \times 2^{-\mu}$	0	4 symbols	$144 \times T_s \times 2^{-\mu}$	15 kHz	285.42	4.69 μs	2109 m
						30 kHz	142.71	2.34 μs	1055 m
						60 kHz	71.35	1.17 μs	527 m
						120 kHz	35.68	0.59 μs	264 m
A3	$864 \times T_s \times 2^{-\mu}$	$6 \times 2048 \times T_s \times 2^{-\mu}$	0	6 symbols	$144 \times T_s \times 2^{-\mu}$	15 kHz	428.13	4.69 μs	3516 m
						30 kHz	214.06	2.34 μs	1758 m
						60 kHz	107.03	1.17 μs	879 m
						120 kHz	53.52	0.59 μs	439 m
B1	$216 \times T_s \times 2^{-\mu}$	$2 \times 2048 \times T_s \times 2^{-\mu}$	$72 \times T_s \times 2^{-\mu}$	2 symbols	$96 \times T_s \times 2^{-\mu}$	15 kHz	140.36	3.13 μs	352 m
						30 kHz	70.18	1.56 μs	176 m
						60 kHz	35.09	0.78 μs	88 m
						120 kHz	17.55	0.39 μs	44 m
B2	$360 \times T_s \times 2^{-\mu}$	$4 \times 2048 \times T_s \times 2^{-\mu}$	$216 \times T_s \times 2^{-\mu}$	4 symbols	$144 \times T_s \times 2^{-\mu}$	15 kHz	278.39	4.69 μs	1055 m
						30 kHz	139.19	2.34 μs	527 m
						60 kHz	69.60	1.17 μs	264 m
						120 kHz	34.80	0.59 μs	132 m
B3	$504 \times T_s \times 2^{-\mu}$	$6 \times 2048 \times T_s \times 2^{-\mu}$	$360 \times T_s \times 2^{-\mu}$	6 symbols	$144 \times T_s \times 2^{-\mu}$	15 kHz	416.41	4.69 μs	1758 m
						30 kHz	208.20	2.34 μs	879 m
						60 kHz	104.10	1.17 μs	439 m
						120 kHz	52.05	0.59 μs	220 m
B4	$936 \times T_s \times 2^{-\mu}$	$12 \times 2048 \times T_s \times 2^{-\mu}$	$792 \times T_s \times 2^{-\mu}$	12 symbols	$144 \times T_s \times 2^{-\mu}$	15 kHz	830.47	4.69 μs	3867 m
						30 kHz	415.23	2.34 μs	1934 m
						60 kHz	207.62	1.17 μs	967 m
						120 kHz	103.81	0.59 μs	483 m
C0	$1240 \times T_s \times 2^{-\mu}$	$1 \times 2048 \times T_s \times 2^{-\mu}$	$1096 \times T_s \times 2^{-\mu}$	2 symbols	$144 \times T_s \times 2^{-\mu}$	15 kHz	107.03	4.69 μs	5352 m
						30 kHz	53.52	2.34 μs	2676 m
						60 kHz	26.76	1.17 μs	1338 m
						120 kHz	13.38	0.59 μs	669 m
C2	$2048 \times T_s \times 2^{-\mu}$	$4 \times 2048 \times T_s \times 2^{-\mu}$	$2912 \times T_s \times 2^{-\mu}$	6 symbols	$144 \times T_s \times 2^{-\mu}$	15 kHz	333.33	4.69 μs	9297 m
						30 kHz	166.67	2.34 μs	4648 m
						60 kHz	83.33	1.17 μs	2324 m
						120 kHz	41.67	0.59 μs	1162 m

Table 173 – PRACH Formats using a Short Sequence
(15 kHz and 30 kHz subcarrier spacings applicable to FR1, 60 kHz and 120 kHz subcarrier spacings applicable to FR2)

★ The repetition of the sequence within short PRACH preambles can be used to either improve SINR, or provide transmission across multiple positions of a beam sweep. These concepts are illustrated in Figure 251

★ If a single beam receives multiple repetitions then the repetitions can be combined to increase the signal to noise ratio. This helps to improve the quality of the output from the correlator used to detect the received preamble

★ When using beam sweeping, the UE identifies the best downlink beam by measuring the SS/PBCH Block transmitted by each beam. In the case of TDD, channel reciprocity allows the best uplink beam to be deduced from the best downlink beam. This means that the UE only needs to transmit its PRACH preamble to a single beam. In the case of FDD, the UE may not be able to identify the best uplink beam from the best downlink beam. The UE can transmit its PRACH preamble across multiple beams to allow the Base Station to identify the best uplink beam

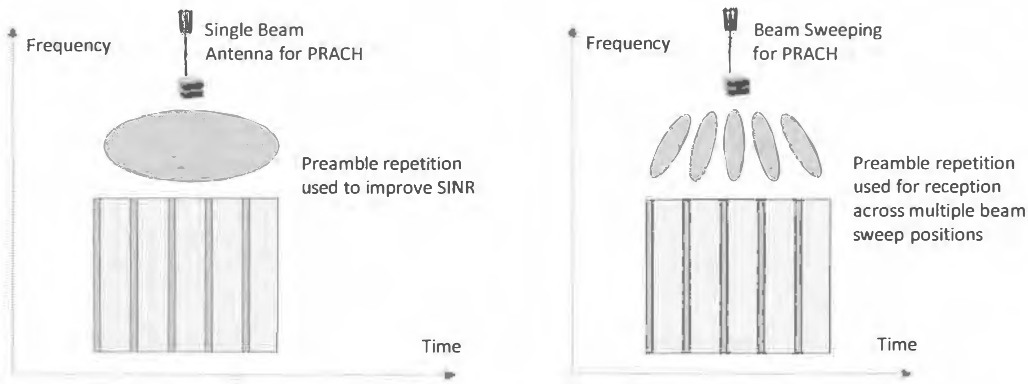


Figure 251 – Using the repetitions within short PRACH preambles

★ As indicated by Figure 245, short PRACH preambles occupy a wider bandwidth than long PRACH preambles. Table 174 presents the bandwidth occupied by the short PRACH preambles as a function of the subcarrier spacing. The maximum preamble bandwidth within Frequency Range 1 is less than 5 MHz. This means that a UE which has a relatively low bandwidth capability can transmit the PRACH preambles to access the network. The maximum preamble bandwidth within Frequency Range 2 is less than 20 MHz. This means that UE which support Frequency Range 2 must have a higher bandwidth capability

★ Table 174 also presents the number of Resource Blocks allocated to each PRACH occasion and the corresponding bandwidth allocation. The sequence length of 139 is not a multiple of 12 so the PRACH does not occupy an integer number of Resource Blocks. In all cases there are 5 additional PRACH subcarriers which can act as a guard band. For example, the 15 kHz PRACH occupies 2.085 MHz and is allocated 2.16 MHz so there is 75 kHz of guard band which corresponds to 5 × 15 kHz

		Frequency Range 1		Frequency Range 2	
		15 kHz PRACH	30 kHz PRACH	60 kHz PRACH	120 kHz PRACH
Bandwidth Occupied by PRACH Subcarriers		2.085 MHz	4.17 MHz	8.34 MHz	16.68 MHz
Resource Block and Bandwidth Allocations	15 kHz PUSCH	12 PRB 2.16 MHz	24 PRB 4.32 MHz	-	-
	30 kHz PUSCH	6 PRB 2.16 MHz	12 PRB 4.32 MHz	-	-
	60 kHz PUSCH	3 PRB 2.16 MHz	6 PRB 4.32 MHz	12 PRB 8.64 MHz	24 PRB 17.28 MHz
	120 kHz PUSCH	-	-	6 PRB 8.64 MHz	12 PRB 17.28 MHz

Table 174 – Bandwidth occupied by the short PRACH preamble as a function of the subcarrier spacing

★ Long PRACH preambles can use both Unrestricted cyclic shifts and Restricted cyclic shifts. In contrast, 3GPP has only specified Unrestricted cyclic shifts for short PRACH preambles. Restricted cyclic shifts are used to provide resilience against frequency offsets. Short PRACH preambles are inherently resilient to frequency offsets due to their larger subcarrier spacing. This means that it has not been necessary to specify Restricted cyclic shifts

★ Table 175 presents the set of Unrestricted cyclic shifts for the short PRACH preambles. These cyclic shifts are applicable to all short PRACH preamble formats and all subcarrier spacings. The 'Sequences per Root Sequence' column is calculated as ROUND DOWN (139 / Cyclic Shift). The 'Root Sequences required per Cell' column is calculated as ROUND UP (64 / Sequences per Root Sequence). The 'Root Sequence Re-use Pattern' column is calculated as ROUND DOWN (138 / Root Sequences required per Cell)

★ The Root Sequence re-use pattern sizes for short PRACH preambles (presented in Table 175) are significantly smaller than those for the long PRACH preambles (presented in Table 169 and Table 170). For example, a cyclic shift of 15 leads to a re-use pattern size of 17 when using a short PRACH preamble, whereas a cyclic shift of 15 leads to a re-use pattern size of 419 when using a long PRACH preamble with a 1.25 kHz subcarrier spacing. This smaller Root Sequence re-use pattern size results from the smaller set of Root Sequences, i.e. 138 root sequences compared to 838 Root Sequences. The smaller re-use pattern size makes Radio Network Planning more challenging

★ In some cases, it may be necessary to allocate less than 64 PRACH preambles to each PRACH occasion. This reduces the number of Root Sequences used by each PRACH occasion and so increases the re-use pattern size. For example, allocating 32 PRACH preambles to each PRACH occasion can reduce the Root Sequence requirement per cell by a factor of 2

Zero Correlation Zone Configuration	Sequence Length	Cyclic Shift	Sequences per Root Sequence	Root Sequences required per Cell	Root Sequence Re-use Pattern
1	139	2	69	1	138
2		4	34	2	69
3		6	23	3	46
4		8	17	4	34
5		10	13	5	27
6		12	11	6	23
7		13	10	7	19
8		15	9	8	17
9		17	8		
10		19	7	10	13
11		23	6	11	12
12		27	5	13	10
13		34	4	16	8
14		46	3	22	6
15		69	2	32	4
0		0	1	64	2

Table 175 – Root Sequence Re-Use Pattern for Short PRACH Preambles (Unrestricted Cyclic Shift)

★ The maximum cell range associated with each cyclic shift and each subcarrier spacing is presented in Table 176. These figures are calculated as 300 × [(Cyclic Shift – 1) × (1000 /(subcarrier spacing × 139)) – Delay Spread] / (2 × 1000), where 300 corresponds to the speed of light in meters per μs, the subcarrier spacing has units of kHz and 2 accounts for the round trip distance.

★ Table 176 presents cell range figures for two assumed delays spreads per subcarrier spacing. The first assumed delay spread for each subcarrier spacing is 0 μs, i.e. no delay spread. This generates the largest possible cell range. The second assumed delay spread for each subcarrier spacing has been set to the duration of the normal cyclic prefix, i.e. $144 \times T_s \times 2^{-\mu}$. This represents the worst case delay spread which can be tolerated by data transmission without experiencing inter-symbol interference. This assumption is consistent with the assumed delay spreads within Table 173 (with the exception of formats A1 and B1 which target small cell deployment scenarios with shorter delay spreads)

	15 kHz Subcarrier Spacing		30 kHz Subcarrier Spacing		60 kHz Subcarrier Spacing		120 kHz Subcarrier Spacing	
Zero Correlation Zone Configuration	0 μs Delay Spread	4.69 μs Delay Spread	0 μs Delay Spread	2.34 μs Delay Spread	0 μs Delay Spread	1.17 μs Delay Spread	0 μs Delay Spread	0.59 μs Delay Spread
1	72 m	-	36 m	-	18 m	-	9 m	-
2	216 m	-	108 m	-	54 m	-	27 m	-
3	360 m	-	180 m	-	90 m	-	45 m	-
4	504 m	-	252 m	-	126 m	-	63 m	-
5	647 m	-	324 m	-	162 m	-	81 m	-
6	791 m	88 m	396 m	45 m	198 m	22 m	99 m	10 m
7	863 m	160 m	432 m	81 m	216 m	40 m	108 m	19 m
8	1007 m	304 m	504 m	153 m	252 m	76 m	126 m	37 m
9	1151 m	448 m	576 m	225 m	288 m	112 m	144 m	55 m
10	1295 m	591 m	647 m	296 m	324 m	148 m	162 m	73 m
11	1583 m	879 m	791 m	440 m	396 m	220 m	198 m	109 m
12	1871 m	1167 m	935 m	584 m	468 m	292 m	234 m	145 m
13	2374 m	1671 m	1187 m	836 m	594 m	418 m	297 m	208 m
14	3237 m	2534 m	1619 m	1268 m	809 m	634 m	405 m	316 m
15	4892 m	4189 m	2446 m	2095 m	1223 m	1048 m	612 m	523 m
0	9928 m	9225 m	4964 m	4613 m	2482 m	2307 m	1241 m	1153 m

Table 176 – Short PRACH Preamble Cell Range for each Cyclic Shift and Subcarrier Spacing (Unrestricted Cyclic Shift)

★ The non-zero delay spread assumptions are too large for the smaller cyclic shifts (zero correlation zone values 1 to 5). In these cases, the delay spread itself leads to sequence detection ambiguity, even without any propagation delay

★ The cell range figures in Table 176 should be used in combination with those within Table 173, i.e. the smaller cell range dominates. Achieving a cell range greater than 9 km requires a combination of the 15 kHz subcarrier spacing, 64 Root Sequences per cell and PRACH format C2. Allocating 64 Root Sequences per cell leads to a re-use pattern size of only 2. In practice, it will be challenging to plan a network using a re-use pattern size of 2 unless the PRACH occasions in neighbouring cells are isolated in the time and/or frequency domains. In this case, it may be necessary to reduce the number of PRACH preambles allocated to each PRACH occasion. This will reduce the Root Sequence requirement per cell and increase the re-use pattern size

★ Similar to the long PRACH preambles, it is important to select a cyclic shift which provides a cell range which is greater than or equal to the actual cell range. The random access procedure will fail if coverage extends beyond the cell range associated with the cyclic shift. This is caused by the Base Station incorrectly detecting the cyclic shift transmitted by the UE

★ The 'PRACH Configuration Index' defines the time domain position of the PRACH. 3GPP TS 38.211 specifies 3 sets of Configuration Indices for the short PRACH preambles. The first set is applicable to Paired and Supplemental Uplink spectrum within Frequency Range 1. The second set is applicable to Unpaired spectrum within Frequency Range 1. The third set is applicable to Unpaired spectrum within Frequency Range 2

★ Table 177 and Table 178 provide a comparison of PRACH Configuration Indices for Frequency Range 1 Unpaired Spectrum and Frequency Range 2 Unpaired Spectrum. Only a subset of Configuration Indices are presented for the purposes of the comparison

★ Similar to the long PRACH preambles, the radio frames which include short PRACH opportunities are specified using the '$n_{SFN}\ mod\ x = y$' rule. For example, when 'x = 16' and 'y = 1' then there are PRACH opportunities within radio frames 1, 17, 33, 49, 65, ... When 'x = 1' and 'y = 0' there are PRACH opportunities within every radio frame

PRACH PREAMBLE FORMAT A1							
PRACH Configuration Index	n_{SFN} mod x = y		Subframe Number	Starting Symbol	Number of PRACH Slots within a Subframe	Number of Time Domain PRACH within a Slot	PRACH Duration
	x	y					
67	16	1	9	0	2	6	2
68	8	1	9	0	2	6	2
69	4	1	9	0	1	6	2
70	2	1	9	0	1	6	2
71	2	1	4, 9	7	1	3	2
72	2	1	7, 9	7	1	3	2
73	2	1	7, 9	0	1	6	2
74	2	1	8, 9	0	2	6	2
75	2	1	4, 9	0	2	6	2
76	2	1	2, 3, 4, 7, 8, 9	0	1	6	2
77	1	0	9	0	2	6	2
78	1	0	9	7	1	3	2

Table 177 – Subset of PRACH Configuration Indices for PRACH Format A1 (Frequency Range 1 Unpaired Spectrum)

PRACH PREAMBLE FORMAT A1							
PRACH Configuration Index	n_{SFN} mod x = y		Slot Number	Starting Symbol	Number of PRACH Slots within a 60 kHz Slot	Number of Time Domain PRACH within a Slot	PRACH Duration
	x	y					
0	16	1	4,9,14,19,24,29,34,39	0	2	6	2
1	16	1	3,7,11,15,19,23,27,31,35,39	0	1	6	2
2	8	1,2	9,19,29,39	0	2	6	2
3	8	1	4,9,14,19,24,29,34,39	0	2	6	2
4	8	1	3,7,11,15,19,23,27,31,35,39	0	1	6	2
5	4	1	4,9,14,19,24,29,34,39	0	1	6	2
6	4	1	4,9,14,19,24,29,34,39	0	2	6	2
7	4	1	3,7,11,15,19,23,27,31,35,39	0	1	6	2
8	2	1	7,15,23,31,39	0	2	6	2
9	2	1	4,9,14,19,24,29,34,39	0	1	6	2
10	2	1	4,9,14,19,24,29,34,39	0	2	6	2
11	2	1	3,7,11,15,19,23,27,31,35,39	0	1	6	2

Table 178 – Subset of PRACH Configuration Indices for PRACH Format A1 (Frequency Range 2 Unpaired Spectrum)

★ The Configuration Index tables for Frequency Range 1 (15 kHz and 30 kHz subcarrier spacings) specify the subframe(s) within which the PRACH occasions start. There are 10 subframes within a radio frame so the values range from 0 to 9. In contrast, the Configuration Index tables for Frequency Range 2 (60 kHz and 120 kHz subcarrier spacings) specify the slot(s) within which the PRACH occasions start. Slot timing is based upon the 60 kHz subcarrier spacing. There are 40 slots within a radio frame when using the 60 kHz subcarrier spacing so the values range from 0 to 39

★ 3GPP has specified a larger number of starting slot numbers for Frequency Range 2 than starting subframe numbers for Frequency Range 1. For example, Configuration Index 67 for Frequency Range 1 includes only a single subframe, whereas Configuration Index 0 for Frequency Range 2 includes 8 slots. This trend results from Frequency Range 2 requiring an increased number of beams to provide coverage across the cell. Frequency Range 1 supports up to 8 SS/PBCH Blocks which can be transmitted using up to 8 beams. Frequency Range 2 supports up to 64 SS/PBCH Blocks which can be transmitted using up to 64 beams. This means that Frequency Range 2 must support at least 64 PRACH occasions multiplexed in the time domain

★ Configuration Index 0 for Frequency Range 2 specifies 8 starting slots and 6 PRACH occasions within each slot. In addition, it specifies 2 slots within each 60 kHz slot. The latter is applicable to the 120 kHz subcarrier spacing which has 2 slots within each 60 kHz slot. This means that there are 48 PRACH occasions within the radio frame when using the 60 kHz subcarrier spacing and 96 PRACH occasions within the radio frame when using the 120 kHz subcarrier spacing

★ Configuration Index 11 for Frequency Range 2 specifies 10 starting slots and 6 PRACH occasions within each slot. In this case, it specifies only 1 slot within each 60 kHz slot so both the 60 kHz and 120 kHz subcarrier spacings have 60 PRACH occasions within the radio frame

★ Table 179 presents an example Configuration Index for each short PRACH format. The PRACH durations reflect the durations illustrated in Figure 250. This table illustrates the combination of PRACH formats A1 with B1, A2 with B2 and A3 with B3. When PRACH formats are combined, the first format is used for all PRACH occasions within a slot, except the final occasion. The second format is used for the final PRACH occasion within the slot. For example, Configuration Index 202 specifies the A1/B1 combination with 6 PRACH occasions within a slot. This means that each slot includes 5 PRACH occasions using format A1 and 1 PRACH occasion using format B1

★ Table 179 illustrates that some Configuration Indices have a Starting Symbol of 2. This allows the PDCCH to provide control plane signalling before the start of the PRACH occasions

PRACH Preamble Format	PRACH Configuration Index	n_{SFN} mod x = y		Slot Number	Starting Symbol	Number of PRACH Slots within a 60 kHz Slot	Number of Time Domain PRACH within a Slot	PRACH Duration
		x	y					
A1	0	16	1	4,9,14,19,24,29,34,39	0	2	6	2
A2	29	16	1	4,9,14,19,24,29,34,39	0	2	3	4
A3	59	16	1	4,9,14,19,24,29,34,39	0	2	2	6
B1	89	16	1	4,9,14,19,24,29,34,39	2	2	6	2
B4	112	16	1,2	4,9,14,19,24,29,34,39	0	2	1	12
C0	144	16	1	4,9,14,19,24,29,34,39	0	2	7	2
C2	173	16	1	4,9,14,19,24,29,34,39	0	2	2	6
A1/B1	202	16	1	4,9,14,19,24,29,34,39	2	1	6	2
B2/B2	220	16	1	4,9,14,19,24,29,34,39	2	1	3	4
A3/B3	238	16	1	4,9,14,19,24,29,34,39	2	1	2	6

Table 179 – Example PRACH Configuration Index for each short PRACH Format (Frequency Range 2 Unpaired Spectrum)

★ The PRACH is described further within the context of the Random Access procedure within section 13.1, and within the context of Radio Network Planning within section 16.10

★ 3GPP References: TS 38.211

7.3 PHYSICAL UPLINK CONTROL CHANNEL

★ The PUCCH is used to transfer Uplink Control Information (UCI). This includes:

- o HARQ acknowledgements
- o Scheduling Requests (SR)
- o periodic and semi-persistent Channel State Information (CSI) reports

★ 3GPP TS 38.211 specifies the five PUCCH formats presented in Table 180. These are categorised according to their capacity and their duration:

- o Formats 0 and 1 are designed to transfer small payloads. These PUCCH Formats are able to transfer 1 or 2 HARQ acknowledgements plus a Scheduling Request. They are not able to transfer CSI reports. Formats 2, 3 and 4 are designed to accommodate larger payloads which can include CSI reports
- o Formats 0 and 2 have short durations of only 1 or 2 symbols. These PUCCH Formats can be used for low latency applications which require the UCI to be transferred with minimal delay. Formats 1, 3 and 4 have long durations of up to 14 symbols. These longer durations help to improve both coverage and capacity

Format	Payload	Payload Size	Duration	Duration in Symbols	Resource Blocks	Waveform	Modulation	DMRS	Code Multiplexing Capability
0	SR, HARQ ACK	1 or 2 bits	Short	1 or 2	1	CP-OFDM	-	No	12 cyclic shifts
1			Long	4 to 14			BPSK or QPSK	Yes	12 cyclic shifts & 1 to 7 OCC
2	SR, HARQ ACK, CSI	> 2 bits	Short	1 or 2	1 to 16		QPSK		None
3			Long	4 to 14	1 to 16 [1]	DFT-S-OFDM	$\pi/2$ BPSK or QPSK		
4			Long	4 to 14	1				2 or 4 OCC

[1] restricted to {1, 2, 3, 4, 5, 6, 8, 9, 10, 12, 15, 16} Resource Blocks to help simplify DFT-S-OFDM implementation

Table 180 – The set of PUCCH Formats

★ Formats 0 and 1 which have low capacities occupy only a single Resource Block in the frequency domain. Format 4 which has a moderate capacity also occupies only a single Resource Block. Formats 2 and 3 occupy up to 16 Resource Blocks. In the case of Format 3 there is a restriction placed upon the specific Resource Block numbers which can be used. This restriction is imposed because Format 3 uses the DFT-S-OFDM waveform. The implementation of the Transform Precoding used to generate the DFT-S-OFDM waveform is simplified by adopting this restriction. PUCCH Format 3 has the largest capacity because it can occupy a large number of symbols and a large number of Resource Blocks

★ Format 0 does not require a modulation scheme because it is based upon the transmission of specific sequences. The remaining formats use either BPSK, QPSK of $\pi/2$ BPSK. $\pi/2$ BPSK is intended to provide an option for improving coverage, i.e. a low order modulation scheme with reduced Peak to Average Power Ratio (PAPR). QPSK has a higher capacity than $\pi/2$ BPSK so is able to accommodate increased levels of channel coding redundancy. This helps to improve the coverage of QPSK

★ With the exception of Format 0, all of the PUCCH Formats use a Demodulation Reference Signal (DMRS). The DMRS represents an overhead from the perspective of the PUCCH payload because it occupies some of the PUCCH Resource Elements. However, it allows the Base Station receiver to use coherent demodulation, i.e. the Base Station can use the DMRS to estimate the impact of the propagation channel and then use that information when decoding the payload

★ All PUCCH Formats allow frequency domain and time domain multiplexing of UE. Formats 0, 1 and 4 also allow code multiplexing of UE within shared time/frequency resources. Code multiplexing increases the capacity of the PUCCH

- o PUCCH Format 0: a total of 12 cyclic shifts are available. The multiplexing capacity depends upon the type of payload being transferred. For example, UE transferring a single HARQ acknowledgement require 2 cyclic shifts so up to 6 UE can be multiplexed. UE transferring two HARQ acknowledgements and a Scheduling Request require 8 cyclic shifts so only a single UE with this type of payload can use a specific time/frequency resource
- o PUCCH Format 1: a total of 12 cyclic shifts and up to 7 Orthogonal Cover Codes (OCC) are available. The multiplexing capacity depends upon the PUCCH duration. A PUCCH duration of 14 symbols allows the payload to occupy 7 symbols and allows the use of 7 OCC (when frequency hopping is disabled). This provides a total multiplexing capacity of $12 \times 7 = 84$. A PUCCH duration of 4 symbols allows the payload to occupy 2 symbols and allows the use of 2 OCC (when frequency hopping is disabled). This provides a total multiplexing capacity of $12 \times 2 = 24$
- o PUCCH Format 4: OCC spreading factors of 2 and 4 are supported. The spreading factor of 4 provides the higher multiplexing capacity and allows up to 4 UE to share the same time/frequency resource but reduces the physical layer capacity of the PUCCH, i.e. it reduces the number of modulation symbols which can be presented to the spreading function. This reduces the quantity of redundancy and the associated channel coding gain

★ The UE transmits both the PUCCH and the Demodulation Reference Signal (DMRS) for the PUCCH using antenna port 2000. Sharing the same antenna port means that both the PUCCH and the DMRS experience the same propagation channel

★ A UE can transmit 1 or 2 PUCCH within a slot for a specific serving cell. When transmitting 2 PUCCH within a slot, the 2 PUCCH must occupy different symbols and at least 1 PUCCH must use Format 0 or Format 2, i.e. a short duration PUCCH

★ When establishing an RRC Connection from Idle mode, the UE is required to acknowledge the reception of MSG4 by sending a single HARQ acknowledgement on the PUCCH. This acknowledgement is sent before the UE has received any dedicated UE configuration information, i.e. the UE has not been allocated any dedicated PUCCH resources

★ The UE extracts cell specific configuration information from SIB1. This information includes the *PUCCH-ConfigCommon* parameter structure presented in Table 181. This structure provides the *pucch-ResourceCommon* information element which defines a pointer towards a cell specific PUCCH resource. The value of *pucch-ResourceCommon* ranges from 0 to 15 indicating that there are 16 cell specific PUCCH resources. These 16 resources are presented in Table 182

PUCCH-ConfigCommon	
pucch-ResourceCommon	0 to 15
pucch-groupHopping	neither, enable, disable
hoppingId	0 to 1024
p0-nominal	-202 to 24

Table 181 – PUCCH-ConfigCommon parameter structure from SIB1

<table>
<tr><th>Index</th><th>PUCCH Format</th><th>First Symbol</th><th>Number of Symbols</th><th>PRB Offset</th><th>Set of Initial CS Indices</th><th>PRB Allocation</th></tr>
<tr><td>0</td><td rowspan="3">0</td><td rowspan="3">12</td><td rowspan="3">2</td><td rowspan="2">0</td><td>{0, 3}</td><td>8</td></tr>
<tr><td>1</td><td rowspan="2">{0, 4, 8}</td><td rowspan="2">6</td></tr>
<tr><td>2</td><td>3</td></tr>
<tr><td>3</td><td rowspan="13">1</td><td rowspan="4">10</td><td rowspan="4">4</td><td rowspan="2">0</td><td>{0, 6}</td><td>8</td></tr>
<tr><td>4</td><td rowspan="3">{0, 3, 6, 9}</td><td rowspan="3">4</td></tr>
<tr><td>5</td><td>2</td></tr>
<tr><td>6</td><td>4</td></tr>
<tr><td>7</td><td rowspan="4">4</td><td rowspan="4">10</td><td rowspan="2">0</td><td>{0, 6}</td><td>8</td></tr>
<tr><td>8</td><td rowspan="3">{0, 3, 6, 9}</td><td rowspan="3">4</td></tr>
<tr><td>9</td><td>2</td></tr>
<tr><td>10</td><td>4</td></tr>
<tr><td>11</td><td rowspan="5">0</td><td rowspan="5">14</td><td rowspan="2">0</td><td>{0, 6}</td><td>8</td></tr>
<tr><td>12</td><td rowspan="4">{0, 3, 6, 9}</td><td rowspan="4">4</td></tr>
<tr><td>13</td><td>2</td></tr>
<tr><td>14</td><td>4</td></tr>
<tr><td>15</td><td>$\lfloor N_{BWP}^{size}/4 \rfloor$</td></tr>
</table>

Table 182 – Cell specific PUCCH resources identified by the *pucch-ResourceCommon* information element

★ The first 3 cell specific PUCCH resources are based upon the transmission of PUCCH Format 0 across 2 symbols. These resources are likely to be used for small cell scenarios with relatively good coverage. The remaining 13 cell specific PUCCH resources are based upon the transmission of PUCCH Format 1 across 4, 10 or 14 symbols. These resources are more likely to be used for cells which have larger cell ranges and more demanding coverage requirements (both Formats 0 and 1 occupy a single Resource Block)

★ In the case of Format 1 cell specific PUCCH resources, there are 3 or 4 PRB Offsets associated with each value of First Symbol. This allows a different PRB Offset to be allocated to each sector of a 3 or 4 sector Base Station

★ The UE always applies frequency hopping when transmitting the PUCCH prior to receiving any dedicated UE configuration information

★ Each cell specific PUCCH resource is associated with a set of 16 UE specific PUCCH resources. An individual UE identifies its PUCCH resource using a combination of the PUCCH Resource Indicator and the allocated Control Channel Element (CCE). The PUCCH Resource Indicator is a 3 bit field from within the PDCCH Downlink Control Information (DCI) used to allocate the PDSCH. In general, this could be either DCI Format 1_0 or Format 1_1 but DCI Format 1_0 is used when allocating PDSCH resources for MSG4. The index of the allocated CCE is used to calculate a single bit of information. The combined set of 4 bits is used to identify 1 out of 16 UE specific PUCCH resources. The calculation used to identify the allocated UE specific PUCCH resource is shown below:

$n_{CCE,0}$ ranges from 0 to ($N_{CCE,0}$ - 1)

Δ_{PRI} ranges from 0 to 7

$$r_{PUCCH} = \underbrace{\left\lfloor \frac{2 \times n_{CCE,0}}{N_{CCE,0}} \right\rfloor}_{0,1} + \underbrace{2 \times \Delta_{PRI}}_{0,2,4,6,8,10,12,14}$$

Δ_{PRI} is the PUCCH Resource Indicator from within the DCI

$n_{CCE,0}$ is the index of the first CCE used to provide the PDSCH resource allocation

$N_{CCE,0}$ is the total number of CCE within the Control Resource Set (CORESET)

★ The UE specific PUCCH resource is used to identify a PUCCH Resource Block allocation and a PUCCH Cyclic Shift allocation. The calculation used to identify the PUCCH Resource Blocks is presented in Figure 252. If $r_{PUCCH} < 8$ then the calculation on the left is used. In this case, the first frequency hop is towards the lower edge of the Bandwidth Part, whereas the second frequency hop is towards the upper edge of the Bandwidth Part. Each hop accommodates half of the number of symbols presented in Table 182. If $r_{PUCCH} \geq 8$ then the calculation on the right is used. In this case, the position of the frequency hops is reversed to allow UE to be multiplexed in the frequency domain. The value of N_{BWP}^{size} is given by the number of Resource Blocks within the initial uplink Bandwidth Part. The value of RB_{BWP}^{offset} corresponds to the 'PRB Offset' within Table 182. The value of N_{CS} is set equal to the number of Initial Cyclic Shift Indices within Table 182

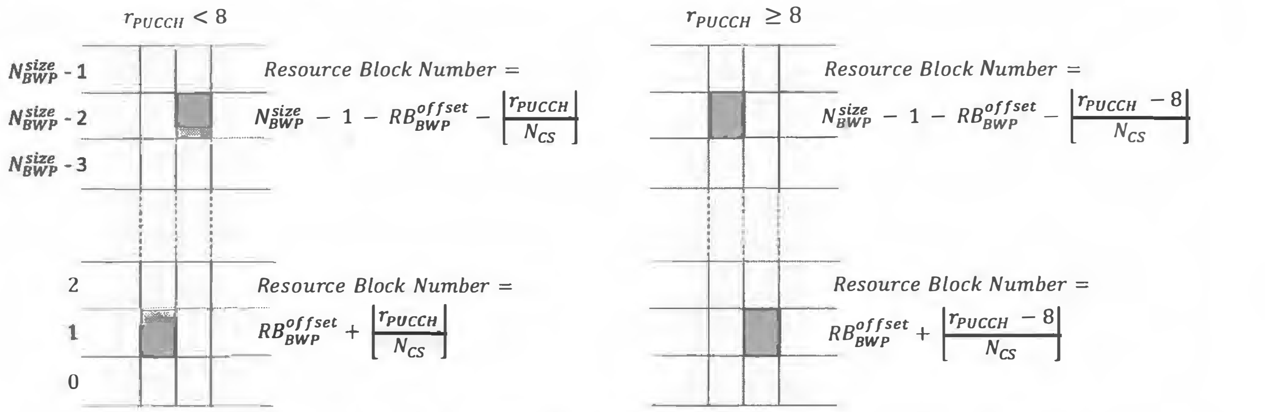


Figure 252 – PUCCH Resource Block calculation for common PUCCH configuration within SIB1

★ The total number of Resource Blocks allocated to the common PUCCH configuration is given by ROUND UP (8 / N_{CS}). The result from this calculation is presented within the final column of Table 182. The total number of UE specific resources is 16 so the Resource Block allocation decreases as the number of initial cyclic shifts increases

★ When $r_{PUCCH} < 8$, the initial cyclic shift is selected from the set of initial cyclic shifts by calculating the index as $r_{PUCCH}\ mod\ N_{CS}$. For example, if r_{PUCCH} = 4 and the number of initial cyclic shifts according to Table 182 is 3 then $r_{PUCCH}\ mod\ N_{CS} = 1$ so the second initial cyclic shift is selected. When $r_{PUCCH} \geq 8$, the calculation becomes $(r_{PUCCH} - 8)\ mod\ N_{CS}$

★ Table 183 presents an example set of UE specific PUCCH resources for *pucch-ResourceCommon* = 0, i.e. PUCCH Format 0 with a PRB Offset = 0 and cyclic shifts of 0 and 3. This example assumes that the Bandwidth Part includes 100 Resource Blocks

	UE 1	UE 2	UE 3	UE 4	UE 5	UE 6	UE 7	UE 8	UE 9	UE 10	UE 11	UE 12	UE 13	UE 14	UE 15	UE 16
r_{PUCCH}	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
$PRB_{FIRST\ HOP}$	0		1		2		3		99		98		97		96	
$PRB_{SECOND\ HOP}$	99		98		97		96		0		1		2		3	
Initial Cyclic Shift	0	3	0	3	0	3	0	3	0	3	0	3	0	3	0	3
First Symbol	12															
Second Symbol	13															

Table 183 – Example set of UE specific PUCCH resources for pucch-ResourceCommon = 0

★ Dedicated UE signalling can be used to configure up to 4 PUCCH Resource Sets. Each Resource Set includes one or more PUCCH Resources and a specification of the maximum PUCCH payload. This concept of PUCCH Resource Sets is illustrated in Figure 253

★ The first Resource Set (*Pucch-ResourceSetId* = 0), can include up to 32 instances of PUCCH Formats 0 and 1. This Resource Set can transfer a maximum payload of 2 bits plus a positive or negative Scheduling Request

★ The remaining Resource Sets (*Pucch-ResourceSetId* = 1, 2, 3), can include up to 8 instances of PUCCH Formats 2, 3 and 4. These Resource Sets can transfer larger payloads. PUCCH Resource Set 3 can transfer payloads up to 1706 bits. PUCCH Resource Sets 1 and 2 have configurable maximum payloads which can range from 4 to 256 bits

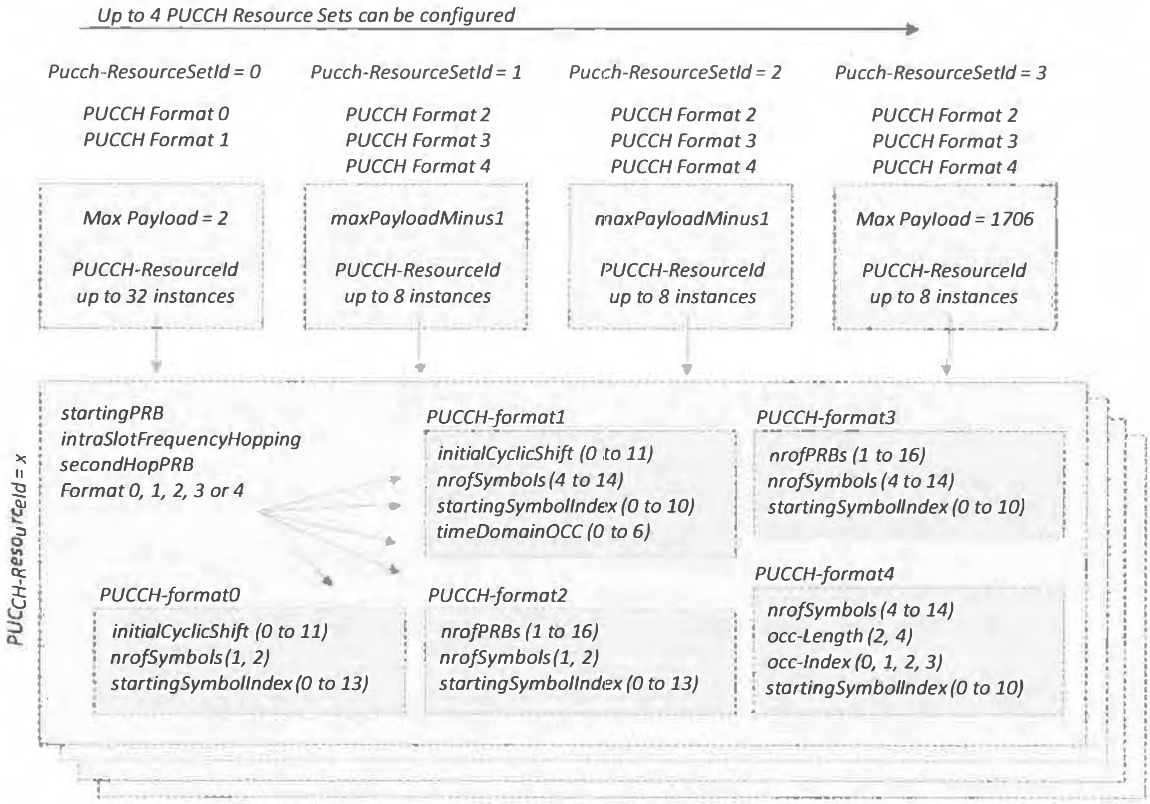


Figure 253 – PUCCH Resource Sets allocated to UE using dedicated signalling

★ Each PUCCH Resource within a PUCCH Resource Set defines a *startingPRB* value which defines the frequency domain position at which the PUCCH transmission starts. There is also a flag to indicate whether or not intra-slot frequency hopping is enabled. Inclusion of this flag indicates that frequency hopping is enabled and then it is also necessary to specify the *secondHopPRB* information element to specify the frequency domain position of the second hop. The remaining parameters belonging to a PUCCH Resource are dependent upon the PUCCH Format. In all cases, it is necessary to configure the PUCCH duration (*nrofSymbols*) and the starting symbol (*startingSymbolIndex*). PUCCH Formats 2 and 3 also require a PRB allocation (*nrofPRBs*)

★ Prior to transmitting the PUCCH, the UE has to identify the appropriate PUCCH Resource. There are two general solutions for identifying the appropriate PUCCH Resource:

- the UE applies a set of pre-defined rules to select a PUCCH Resource Set, and then selects a PUCCH Resource from within that set, i.e. a two step procedure. This approach is adopted when HARQ acknowledgements are transferred
- the UE uses configuration information to select a PUCCH Resource directly based upon its identity. All PUCCH Resources across all sets have a unique identity within the range 0 to 127. This allows specific PUCCH resources to be configured for specific purposes. This approach is adopted when Scheduling Requests or Channel State Information reports are transferred

★ If the Uplink Control Information (UCI) to be transferred on the PUCCH includes only HARQ acknowledgements then selection of the PUCCH Resource Set is based upon the number of bits to be transferred (N_{UCI})

- 1st Resource Set (*Pucch-ResourceSetId* = 0) is selected if $N_{UCI} \leq 2$
- 2nd Resource Set (*Pucch-ResourceSetId* = 1) is selected if configured, and if $2 < N_{UCI} \leq N_2$, where N_2 is given by the corresponding instance of *maxPayloadMinus1*
- 3rd Resource Set (*Pucch-ResourceSetId* = 2) is selected if configured, and if $N_2 < N_{UCI} \leq N_3$, where N_3 is given by the corresponding instance of *maxPayloadMinus1*
- 4th Resource Set (*Pucch-ResourceSetId* = 3) is selected if configured, and if $N_3 < N_{UCI} \leq 1706$

★ If the selected PUCCH Resource Set includes up to 8 resources then the PUCCH Resource Indicator (3 bits) within the PDCCH DCI Format 1_0 or 1_1 is used to select the PUCCH Resource. If the selected PUCCH Resource Set includes more than 8 resources then the following equations are used to select the PUCCH Resource

★ The basic principle of these equations is as follows: the PUCCH Resource Set is divided into 8 groups, the PUCCH Resource Indicator (Δ_{PRI}) is used to select a specific group and then the first CCE associated with the PDCCH DCI ($n_{CCE,p}$) is used to select a PUCCH Resource from within the group. The equations are relatively complex because the groups are not always equally sized. For example, if there are 9 resources within the PUCCH Resource Set then the first group has 2 entries while the remaining 7 groups have 1 entry. If there are 10 resources within the PUCCH Resource Set then the first 2 groups have 2 entries while the remaining 6 groups have 1 entry. This pattern is followed until all groups have 2 entries. If there are 17 resources within the PUCCH Resource Set then the first group has 3 entries while the remaining 7 groups have 2 entries. The maximum number of resources within a PUCCH Resource Set is 32 in which case all groups have 4 entries

This part selects a resource from within a group of resources

This part selects 1 group out of 8 groups based upon the PUCCH Resource indicator (Δ_{PRI})

$$r_{PUCCH} = \left\lfloor \frac{n_{CCE,p} \times \lceil R_{PUCCH}/8 \rceil}{N_{CCE,p}} \right\rfloor + \Delta_{PRI} \times \lceil R_{PUCCH}/8 \rceil \qquad \text{If } \Delta_{PRI} < R_{PUCCH} \bmod 8$$

$$r_{PUCCH} = \left\lfloor \frac{n_{CCE,p} \times \lfloor R_{PUCCH}/8 \rfloor}{N_{CCE,p}} \right\rfloor + \Delta_{PRI} \times \lfloor R_{PUCCH}/8 \rfloor + R_{PUCCH} \bmod 8 \qquad \text{If } \Delta_{PRI} \geq R_{PUCCH} \bmod 8$$

★ If a UE transmits only a Scheduling Request, the PUCCH Resource is selected based upon the logical channel which is triggering the Scheduling Request. Figure 254 illustrates that the logical channel configuration includes a Scheduling Request Identity which points towards a specific Scheduling Request Resource Configuration. The Scheduling Request Resource Configuration includes a pointer towards a specific PUCCH Resource, i.e. separate Scheduling Request PUCCH resources can be configured for each logical channel allowing the UE to identify the logical channel which has triggering the Scheduling Request

Figure 254 – PUCCH Resource Identity associated with a Scheduling Request Resource

★ If a UE transmits only a Channel State Information (CSI) report, the PUCCH Resource is selected based upon the corresponding CSI report configuration. Figure 255 illustrates that the CSI Report Configuration parameter set includes a *reportConfigType* information element. This information element specifies the report configuration type as either periodic, semi-persistent on the PUCCH, semi-persistent on the PUSCH or aperiodic. The first two options lead to CSI reporting on the PUCCH. In these cases, a PUCCH Resource Identity is specified for each uplink Bandwidth Part. This instructs the UE to use a specific PUCCH resource when transmitting a specific CSI report

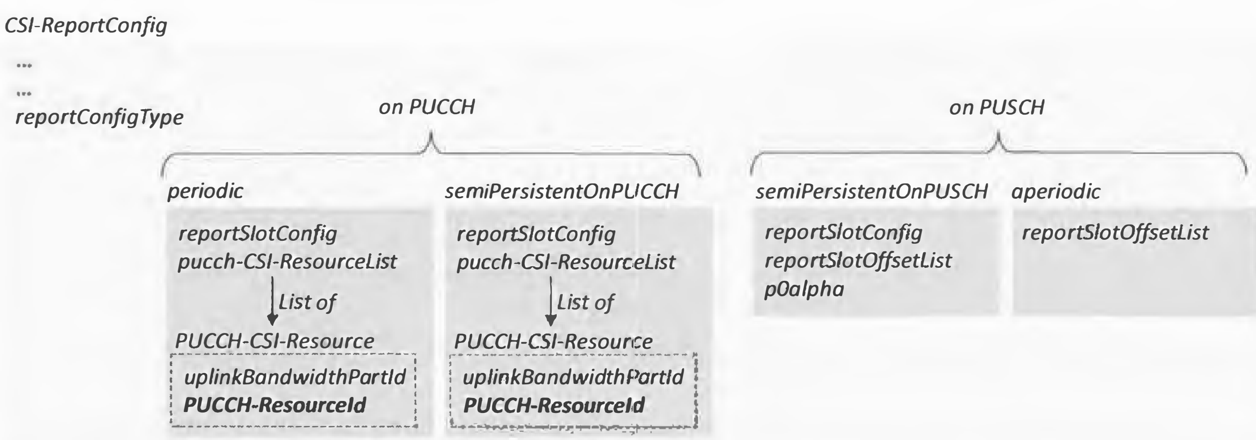


Figure 255 – PUCCH Resource Identity associated with a CSI Report Configuration

★ The transmission of HARQ acknowledgements in combination with a Scheduling Request using PUCCH Formats 0 and 1 is described within sections 7.3.1 and 7.3.2 respectively. When using PUCCH Formats 2, 3 or 4 to transfer HARQ Acknowledgements, Scheduling Request bits can be appended to the HARQ acknowledgements prior to Physical layer processing. Similarly, when using PUCCH Formats 2, 3 or 4 to transfer a CSI report, Scheduling Request bits can be appended to the CSI report prior to Physical layer processing

★ 3GPP References: TS 38.213, TS 38.211

7.3.1 PUCCH FORMAT 0

★ PUCCH Format 0 is used to transfer 1 or 2 HARQ acknowledgements and/or a Scheduling Request (SR)

★ It occupies 1 Resource Block in the frequency domain and either 1 or 2 symbols in the time domain. This means that PUCCH Format 0 occupies either 12 or 24 Resource Elements. Transmission across 2 symbols can be used to improve coverage

★ Frequency hopping is possible when PUCCH Format 0 occupies 2 symbols, i.e. the first symbol is transmitted using one part of the channel bandwidth while the second symbol is transmitted using another part of the channel bandwidth. Frequency hopping is always applied when PUCCH Format 0 is used prior to the allocation of dedicated PUCCH resources, i.e. when using the common PUCCH resource configuration provided in SIB 1. Otherwise, Frequency hopping can be enabled/disabled by the Base Station

★ PUCCH Format 0 does not have a Demodulation Reference Signal (DMRS) so the Base Station receiver uses non-coherent detection

★ The UE is allocated a specific sequence to transmit as PUCCH Format 0. This sequence has length 12 so there is a single entry for each subcarrier. The sequence is repeated when the transmission occupies 2 symbols. The UE transfers information by applying a specific cyclic shift to the sequence. The Base Station identifies the cyclic shift and subsequently deduces the corresponding information content

★ Figure 256 illustrates the cyclic shifts used to signal 1 or 2 HARQ acknowledgements and/or a Scheduling Request (SR)

- o a single HARQ acknowledgement is signalled using cyclic shifts of 0 and 6. A cyclic shift of 0 is interpreted as a negative acknowledgement, whereas a cyclic shift of 6 is interpreted as a positive acknowledgement
- o two HARQ acknowledgements are signalled using cyclic shifts of 0, 3, 6 and 9. These cyclic shifts are mapped onto the four combinations of positive and negative acknowledgements
- o a Scheduling Request is signalled using a single cyclic shift of 0. This corresponds to a positive Scheduling Request, i.e. indicating that the UE would like to receive an uplink resource allocation. A negative Scheduling Request corresponds to the UE not requiring an uplink resource allocation and in this case, the UE does not transmit on the PUCCH
- o the combination of a single HARQ acknowledgement and a Scheduling Request is signalled using cyclic shifts of 0, 3, 6 and 9, i.e. the same set of cyclic shifts as used to signal two HARQ acknowledgements. The UE and Base Station differentiate between these two scenarios based upon timing and the number of downlink packets which require acknowledgement. The transmission of a single HARQ acknowledgement and Scheduling Request is applicable when a single downlink packet requires acknowledgement, and the timing of that acknowledgement coincides with the timing of a periodic Scheduling Request opportunity
- o the combination of two HARQ acknowledgements and a Scheduling Request is signalled using cyclic shifts of 0, 1, 3, 4, 6, 7, 9 and 10. This scenario is applicable when two downlink packets require acknowledgement, and the timing of those acknowledgements coincides with the timing of a periodic Scheduling Request opportunity. The use of 8 cyclic shifts increases the probability of incorrect cyclic shift detection at the Base Station. However, the mapping has been defined such that adjacent cyclic shifts transfer the same HARQ acknowledgement information. If the Base Station incorrectly detects an adjacent cyclic shift then the HARQ acknowledgement information is still received correctly and only the Scheduling Request information is received incorrectly

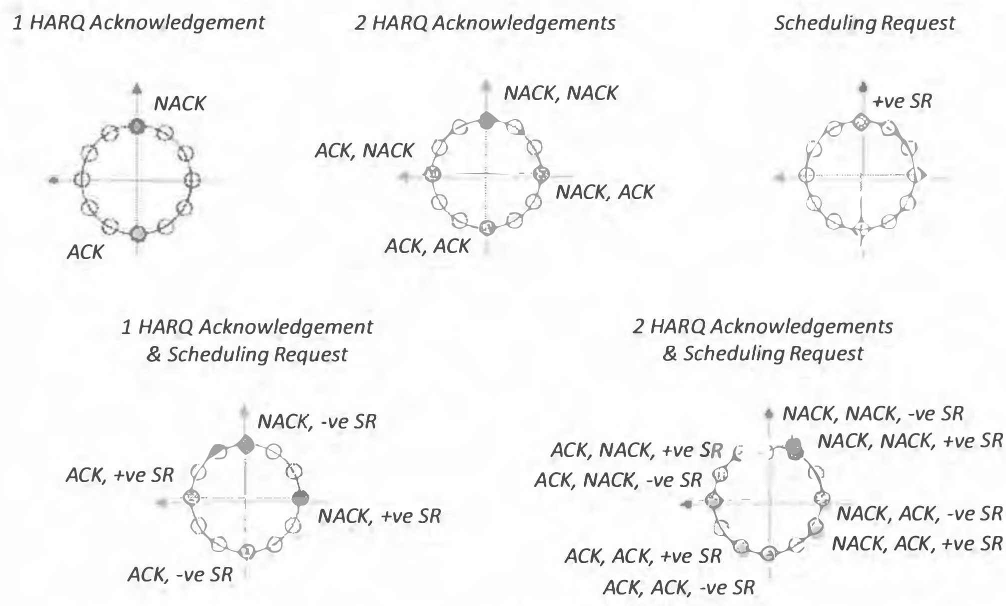


Figure 256 – Cyclic shifts applied to signal HARQ acknowledgements and Scheduling Requests

★ 3GPP TS 38.211 uses the equation below to apply the cyclic shift, where α represents the cyclic shift and $\bar{r}_{u,v}(n)$ represents the sequence of length 12. It is not immediately obvious that α is generating a cyclic shift. However, a cyclic shift in the time domain corresponds to a series of phase shifts in the frequency domain. The sequence is mapped directly onto the set of subcarriers so corresponds to a frequency domain sequence. The combination of α and n provides the series of frequency domain phase shifts which generate the cyclic shift in the time domain

$$r_{u,v}^{(\alpha,\delta)}(n) = e^{j\alpha n} \times \bar{r}_{u,v}(n) \qquad 0 \le n < 12$$

★ The cyclic shifts illustrated in Figure 256 provide a simplistic view of the cyclic shifts which are used in reality. 3GPP TS 38.211 specifies the cyclic shift (phase shift) using the equation shown below:

Initial cyclic shift — Function based upon pseudo random sequence

$$\alpha = \frac{2\pi}{12} \times \left[\left(m_0 + m_{cs} + n_{cs}(n_{s,f}^{\mu}, l + l')\right) \bmod 12\right]$$

Cyclic shift offset based upon information content

★ This equation generates values within the set: {0, 1, 2, … 9, 10, 11} × 2π/12. The value of m_{cs} transfers the information content and corresponds to the values illustrated in Figure 256. For example, when sending a NACK, ACK without a Scheduling Request then m_{cs} = 3. The value of m_0 represents the initial cyclic shift. Figure 256 assumes that the initial cyclic shift is zero. A non-zero initial cyclic shift rotates all of the images within Figure 256. Allocating different initial cyclic shifts to different UE allows those UE to share the same PUCCH Format 0 Resource Blocks and symbols. For example, allocating 3 UE with initial cyclic shifts of 0, 1 and 2 allows those UE to share the same resources when transmitting 2 HARQ acknowledgements without a Scheduling Request

★ If PUCCH Format 0 is used prior to the allocation of dedicated PUCCH resources, i.e. when using the common PUCCH resource configuration provided in SIB 1, then the initial cyclic shift is selected from the set shown in Table 182 based upon the rules described below that table. If PUCCH Format 0 is used after the allocation of dedicated PUCCH resources then the initial cyclic shift is signalled as part of the PUCCH Resource configuration illustrated in Figure 253. The relevant information from this figure is repeated below within Table 184

PUCCH-Resource		
pucch-ResourceId	0 to 127	
startingPRB	0 to 274	
intraSlotFrequencyHopping	enabled	
secondHopPRB	0 to 274	
format	PUCCH-format0	
	initialCyclicShift	0 to 11
	nrofSymbols	1, 2
	startingSymbolIndex	0 to 13

Table 184 – PUCCH Format 0 information within PUCCH Resource configuration

★ Returning to the equation above, $n_{CS}(n_{s,f}^{\mu}, l + l')$ is a function which provides 'cyclic shift hopping'. This function is based upon a pseudo random sequence which is initialised by the cell level *hoppingId* information element signalled as part of the common PUCCH configuration presented in Table 181. Configuring *hoppingId* at a cell level means that all UE within the cell generate the same pseudo random sequence and follow the same cyclic shift hopping pattern

★ The sequence to which the cyclic shift is applied ($\bar{r}_{u,v}(n)$ in the equation above) is selected in two steps. The first step selects a group of sequences. There are 30 groups of sequences and these groups are indexed using the variable '*u*'. The second step selects a sequence from within the group. There is only a single sequence within each group with length 12. So in the case of PUCCH Format 0, the same sequence is always selected from each group. This sequence is indexed using the variable '*v*' = 0

★ The selection of 'u' depends upon the use of group hopping which is configured using the *pucch-GroupHopping* information element signalled as part of the common PUCCH configuration presented in Table 181. This information element can be configured with values of 'neither', 'enable' or 'disable'. The value of 'disable' is used to disable group hopping and enable sequence hopping from within the group. In the case of PUCCH Format 0, there is only a single sequence within each group so sequence hopping is not applicable. The index of the group 'u' is calculated as:

$$u = (f_{gh} + f_{ss}) \bmod 30$$

- In all cases, $f_{ss} = n_{ID}$ mod 30, where n_{ID} is the *hoppingId* signalled within the common PUCCH configuration presented in Table 181
- If *pucch-GroupHopping* is set to 'neither' then $f_{gh} = 0$. This means that neither the group nor the sequence change over time
- If *pucch-GroupHopping* is set to 'enable' then f_{gh} is based upon a pseudo random sequence which is initialised at the start of each radio frame using the result of ROUND DOWN (n_{ID} / 30), where n_{ID} is the *hoppingId*. This means that the group changes over time. All UE within the cell use the same pseudo random sequence so all UE follow the same hopping pattern
- If PUCCH Format 0 is used prior to the allocation of dedicated PUCCH resources, i.e. when using the common PUCCH resource configuration provided by SIB 1, then the transmission always has a duration of 2 symbols and frequency hopping is always enabled between the 2 symbols. The hopping pattern is described in section 7.3 and is illustrated in Figure 252
- If PUCCH Format 0 is used after the allocation of dedicated PUCCH resources, then frequency hopping can be enabled or disabled according to the configuration of the PUCCH Resource. Table 184 presents the set of information elements belonging to the PUCCH Resource configuration. If the *intraSlotFrequencyHopping* information element is included then it indicates that frequency hopping is enabled. Excluding this information element indicates that frequency hopping is disabled. When frequency hopping is enabled, the positions of the 2 frequency domain hops are defined by the *startingPRB* and *secondHopPRB* information elements within Table 184, i.e. the frequency domain positions are not calculated but are signalled explicitly. These positions can be located anywhere within the relevant Bandwidth Part

7.3.2 PUCCH FORMAT 1

- PUCCH Format 1 is used to transfer 1 or 2 HARQ acknowledgements and/or a Scheduling Request (SR), i.e. the same information content as PUCCH Format 0
- It occupies 1 Resource Block in the frequency domain and between 4 and 14 symbols in the time domain. This means that PUCCH Format 1 occupies between 48 and 168 Resource Elements. Transmission across an increased number of symbols can be used to improve coverage
- PUCCH Format 1 is able to use Frequency hopping. i.e. the first subset of symbols are transmitted using one part of the channel bandwidth while the second subset of symbols is transmitted using another part of the channel bandwidth. Frequency hopping is always applied when PUCCH Format 1 is used prior to the allocation of dedicated PUCCH resources, i.e. when using the common PUCCH resource configuration provided by SIB 1. Otherwise, Frequency hopping can be enabled/disabled by the Base Station
- PUCCH Format 1 uses a Demodulation Reference Signal (DMRS) so not all Resource Elements are available for the payload. The DMRS allows the Base Station receiver to use coherent detection. The DMRS occupies every second symbol allocated to PUCCH Format 1, i.e. symbols 0, 2, 4, 6, etc where symbol 0 is the first symbol allocated to PUCCH Format 1
- In contrast to PUCCH Format 0, PUCCH Format 1 does not use 'sequence selection' to transfer the information content. Instead, it uses a combination of modulation and PUCCH resource selection. This concept relies upon the UE being configured with at least 1 PUCCH resource for HARQ acknowledgements and at least 1 PUCCH resource for Scheduling Requests. The general concept is illustrated in Figure 257

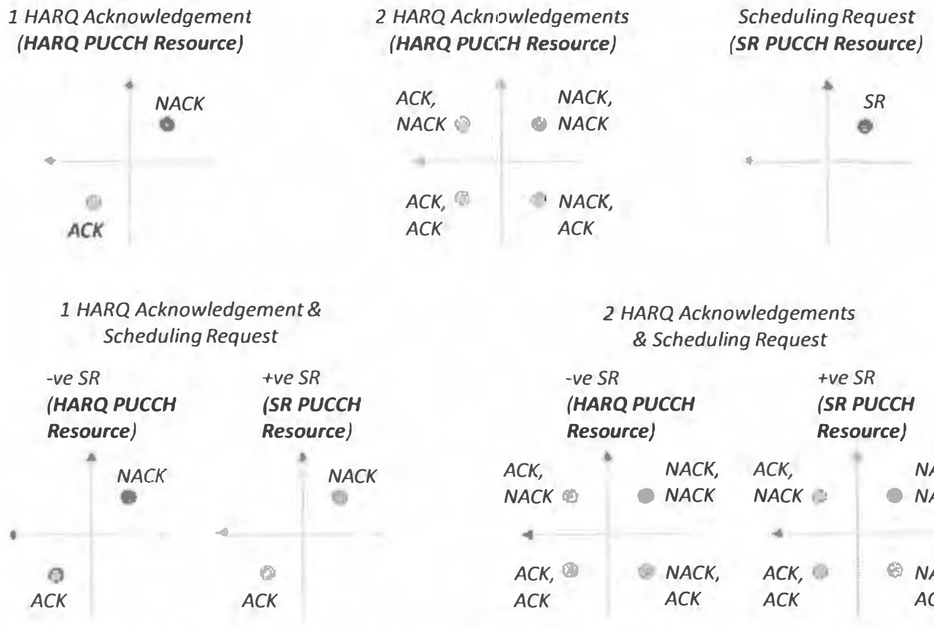


Figure 257 – Combination of modulation symbols and PUCCH resource selection

★ A single HARQ acknowledgement is signalled using BPSK with a PUCCH resource which has been configured for sending HARQ acknowledgements. Two HARQ acknowledgements are signalled using QPSK with a PUCCH resource which has been configured for sending HARQ acknowledgements

★ A Scheduling Request is signalled using BPSK with a PUCCH resource which has been configured for sending Scheduling Requests. In this case, the information bit is set to 0 so the UE always transfers the same BPSK modulation symbol

★ The combination of a single HARQ acknowledgement and a Scheduling Request is signalled using a combination of BPSK and PUCCH resource selection. BPSK is applied to a PUCCH resource which has been configured for sending HARQ acknowledgements if the Scheduling Request is negative. Otherwise, BPSK is applied to a PUCCH resource which has been configured for sending Scheduling Requests if the Scheduling Request is positive. The transmission of a single HARQ acknowledgement and Scheduling Request is applicable when a single downlink packet requires acknowledgement, and the timing of that acknowledgement coincides with the timing of a periodic Scheduling Request opportunity

★ Similarly, the combination of two HARQ acknowledgements and a Scheduling Request is signalled using a combination of QPSK and PUCCH resource selection. QPSK is applied to a PUCCH resource which has been configured for sending HARQ acknowledgements if the Scheduling Request is negative. Otherwise, QPSK is applied to a PUCCH resource which has been configured for sending Scheduling Requests if the Scheduling Request is positive. This scenario is applicable when two downlink packets require acknowledgement, and the timing of those acknowledgements coincides with the timing of a periodic Scheduling Request opportunity

★ The allocation of a PUCCH resource corresponds to the allocation of a sequence, an Orthogonal Cover Code (OCC) and a Resource Block, i.e. a PUCCH resource configured for HARQ acknowledgements may be allocated sequence 'x', OCC 'y' and Resource Block 'z', while a PUCCH resource configured for Scheduling Requests may be allocated sequence 'a', OCC 'b' and Resource Block 'c'

★ Figure 258 illustrates the overall process used to generate PUCCH Format 1. This figure assumes that PUCCH Format 1 has been configured to occupy 8 symbols (4 symbols occupied by the Demodulation Reference Signal (DMRS) and 4 symbols occupied by the payload). The process is illustrated without and with frequency hopping

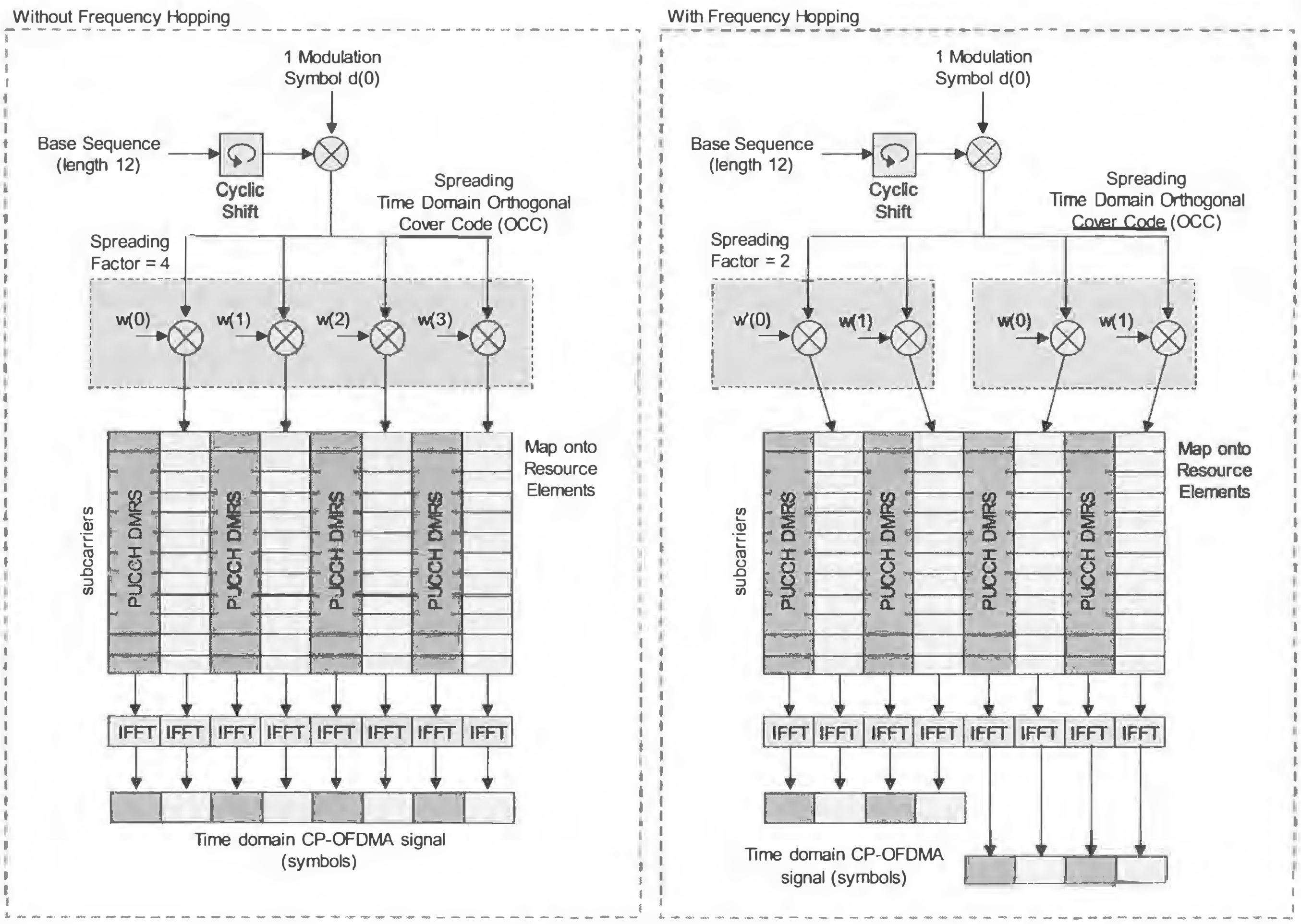


Figure 258 – Generation of PUCCH Format 1

★ The single modulation symbol is multiplied by a sequence of length 12. Similar to PUCCH Format 0, this sequence is generated by applying a time domain cyclic shift to a 'base sequence'. The equation for applying the cyclic shift is the same as that used for PUCCH

Format 0. This equation is repeated below, where α represents the cyclic shift and $\bar{r}_{u,v}(n)$ represents the sequence of length 12. The combination of α and n provides the series of frequency domain phase shifts which generate the time domain cyclic shift

$$r_{u,v}^{(\alpha,\delta)}(n) = e^{j\alpha n} \times \bar{r}_{u,v}(n) \qquad\qquad 0 \leq n < 12$$

★ 3GPP TS 38.211 specifies the cyclic shift (phase shift) using the equation shown below:

$$\alpha = \frac{2\pi}{12} \times \left[\left(\overset{\text{Initial cyclic shift}}{m_0} + \overset{\text{Function based upon pseudo random sequence}}{n_{cs}(n_{s,f}^{\mu}, l + l')}\right) mod\ 12\right]$$

★ This equation differs from the one used for PUCCH Format 0 because it does not include the m_{cs} variable. In the case of PUCCH Format 0, m_{cs} transfers the information content. In the case of PUCCH Format 1, the information content is transferred using the modulation symbol and resource selection, i.e. m_{cs} is not required for PUCCH Format 1

★ The equation for α generates values within the set: {0, 2, 3, … 9, 10, 11} × 2π/12. The value of m_0 represents the initial cyclic shift which is provided to the UE as part of the PUCCH resource configuration. The PUCCH resource configuration for PUCCH Format 1 is presented in Table 185

PUCCH-Resource		
pucch-ResourceId	0 to 127	
startingPRB	0 to 274	
intraSlotFrequencyHopping	enabled	
secondHopPRB	0 to 274	
format	*PUCCH-format1*	
	initialCyclicShift	0 to 11
	nrofSymbols	4 to 14
	startingSymbolIndex	0 to 10
	timeDomainOCC	0 to 6

Table 185 – PUCCH resource information for PUCCH Format 1

★ If PUCCH Format 1 is used prior to the allocation of dedicated PUCCH resources, i.e. when using the common PUCCH resource configuration provided by SIB 1, then the initial cyclic shift is selected from the set shown in Table 182 based upon the rules described below that table

★ Returning to the equation for α, the function $n_{CS}(n_{s,f}^{\mu}, l + l')$ provides 'cyclic shift hopping'. This function is based upon a pseudo random sequence which is initialised by the cell level *hoppingId* information element signalled as part of the common PUCCH configuration presented in Table 181. Configuring *hoppingId* at a cell level means that all UE within the cell generate the same pseudo random sequence and follow the same cyclic shift hopping pattern

★ The sequence to which the cyclic shift is applied ($\bar{r}_{u,v}(n)$ in the equation above) is selected in two steps. The first step selects a group of sequences. There are 30 groups of sequences and these groups are indexed using the variable '*u*'. The second step selects a sequence from within the group. There is only a single sequence within each group with length 12. So in the case of PUCCH Format 1, the same sequence is always selected from each group. This sequence is indexed using the variable '*v*' = 0

★ The selection of 'u' depends upon the use of group hopping which is configured using the *pucch-GroupHopping* information element signalled as part of the common PUCCH configuration presented in Table 181. This information element can be configured with values of 'neither', 'enable' or 'disable'. The value of 'disable' is used to disable group hopping and enable sequence hopping from within the group. In the case of PUCCH Format 1, there is only a single sequence within each group so sequence hopping is not applicable. The index of the group 'u' is calculated as:

$$u = \left(f_{gh} + f_{ss}\right) mod\ 30$$

★ In all cases, $f_{ss} = n_{ID}$ mod 30, where n_{ID} is the *hoppingId* signalled within the common PUCCH configuration presented in Table 181

★ If *pucch-GroupHopping* is set to 'neither' then $f_{gh} = 0$. This means that neither the group nor the sequence change over time

★ If *pucch-GroupHopping* is set to 'enable' then f_{gh} is based upon a pseudo random sequence which is initialised at the start of each radio frame using the result of ROUND DOWN (n_{ID} / 30), where n_{ID} is the *hoppingId*. This means that the group changes over time. All UE within the cell use the same pseudo random sequence so all UE follow the same hopping pattern

★ Returning to Figure 258, multiplying the modulation symbol by the sequence of length 12, generates another sequence of length 12. This new sequence is spread prior to mapping onto the set of Resource Elements. The spreading operation uses an Orthogonal Cover Code (OCC) to generate multiple sequences from the original sequence. 3GPP TS 38.211 specifies spreading factors which range from 1 to 7. The number of sequences generated by the spreading operation is equal to the spreading factor. The example in Figure 258 illustrates a spreading factor of 4 when frequency hopping is disabled, and a spreading factor of 2 when frequency hopping is enabled

★ The spreading factor is also equal to the multiplexing capacity. For example, there are 4 Orthogonal Cover Codes with spreading factor 4, which can be allocated to 4 different UE. Higher spreading factors offer higher multiplexing capacities but occupy an increased number of symbols. The overall multiplexing capacity of PUCCH Format 1 is the combination of the cyclic shift and Orthogonal Cover Code multiplexing capacities, i.e. 12 × Spreading Factor

★ The Orthogonal Cover Codes (OCC) used for spreading are generated using the following expression:

$$w(m) = e^{j2\pi\, \varphi(m)/N_{SF}}\ , \quad \text{where } N_{SF} \text{ is the spreading factor}$$

★ The values of $\varphi(m)$ are presented in Table 186. The UE selects a row based upon the spreading factor required to populate the set of PUCCH time domain symbols. The UE selects a column based upon the value of *timeDomainOCC*, provided within the PUCCH Format 1 resource configuration (shown in Table 185). For example, if using a spreading factor of 3 with *timeDomainOCC* = 2 then the input sequence is multiplied by $e^{j2\pi\, 0/3}$ to generate the sequence which populates the first symbol. A duplicate of the input sequence is multiplied by $e^{j2\pi\, 2/3}$ to generate the sequence which populates the second symbol. And another duplicate of the input sequence is multiplied by $e^{j2\pi\, 1/3}$ to generate the sequence which populates the third symbol

Spreading Factor	$\varphi(m)$						
	Code 0	Code 1	Code 2	Code 3	Code 4	Code 5	Code 6
1	0						
2	0 0	0 1					
3	0 0 0	0 1 2	0 2 1				
4	0 0 0 0	0 2 0 2	0 0 2 2	0 2 2 0			
5	0 0 0 0 0	0 1 2 3 4	0 2 4 1 3	0 3 1 4 2	0 4 3 2 1		
6	0 0 0 0 0 0	0 1 2 3 4 5	0 2 4 0 2 4	0 3 0 3 0 3	0 4 2 0 4 2	0 5 4 3 2 1	
7	0 0 0 0 0 0 0	0 1 2 3 4 5 6	0 2 4 6 1 3 5	0 3 6 2 5 1 4	0 4 1 5 2 6 3	0 5 3 1 6 4 2	0 6 5 4 3 2 1

Table 186 – Orthogonal Cover Codes (OCC) used for spreading

★ Table 187 presents the division of time domain symbols between the Demodulation Reference Signal (DMRS) and the payload for each duration of PUCCH Format 1. Symbols are equally distributed between the DMRS and payload when the total number of symbols is even. In the case of frequency hopping, the first number within Table 187 corresponds to the allocation within the first frequency hop, while the second number corresponds to the allocation within the second frequency hop. The spreading factor is equal to the number of symbols allocated for the payload

PUCCH Format 1 Duration (symbols)	Without Frequency Hopping			With Frequency Hopping		
	Symbols for DMRS	Symbols for Payload	OCC Spreading Factor	Symbols for DMRS	Symbols for Payload	OCC Spreading Factor
4	2	2	2	1, 1	1, 1	1, 1
5	3			1, 2		
6		3	3	2, 1	1, 2	1, 2
7	4			2, 2		
8		4	4	2, 2	2, 2	2, 2
9	5			2, 3		
10		5	5	3, 2	2, 3	2, 3
11	6			3, 3		
12		6	6	3, 3	3, 3	3, 3
13	7			3, 4		
14		7	7	4, 3	3, 4	3, 4

Table 187 – Division of symbols between Demodulation Reference Signal and payload with and without frequency hopping

★ The frequency domain location of PUCCH Format 1 is determined by the information within the PUCCH resource configuration presented in Table 185. Transmission always starts within the uplink Bandwidth Part at the Resource Block indicated by *startingPRB*. If frequency hopping is enabled (indicated by inclusion of the *intraSlotFrequencyHopping* flag) then the second transmission position is indicated by *secondHopPRB*

7.3.3 PUCCH FORMAT 2

- PUCCH Format 2 is used to transfer HARQ acknowledgements and/or a Scheduling Request (SR) and/or Channel State Information (CSI) reports
- It occupies between 1 and 16 Resource Blocks in the frequency domain and either 1 or 2 symbols in the time domain. This means that PUCCH Format 2 occupies between 12 and 384 Resource Elements. Transmission across 2 symbols and a larger number of Resource Blocks can be used to improve coverage. The Resource Blocks used by PUCCH Format 2 are contiguous
- Frequency hopping is possible when PUCCH Format 2 occupies 2 symbols, i.e. the first symbol is transmitted using one part of the channel bandwidth while the second symbol is transmitted using another part of the channel bandwidth. Frequency hopping can be enabled/disabled by the Base Station
- PUCCH Format 2 uses a Demodulation Reference Signal (DMRS) so not all Resource Elements are available for the payload. The DMRS allows the Base Station receiver to use coherent detection. The DMRS occupies every third subcarrier allocated to PUCCH Format 2, i.e. subcarriers 1, 4, 7, 10, etc where subcarrier 0 is the first subcarrier allocated to PUCCH Format 2
- Transferring uplink control information on PUCCH Format 2 has similarities with transferring application data on the PUSCH, i.e. the process involves code block segmentation, the addition of CRC bits, channel coding, rate matching and code block concatenation. This process is illustrated in Figure 259. PUCCH Format 2 does not use cyclic shifts nor Orthogonal Cover Codes (OCC) so does not support multiplexing of UE within shared Resource Blocks

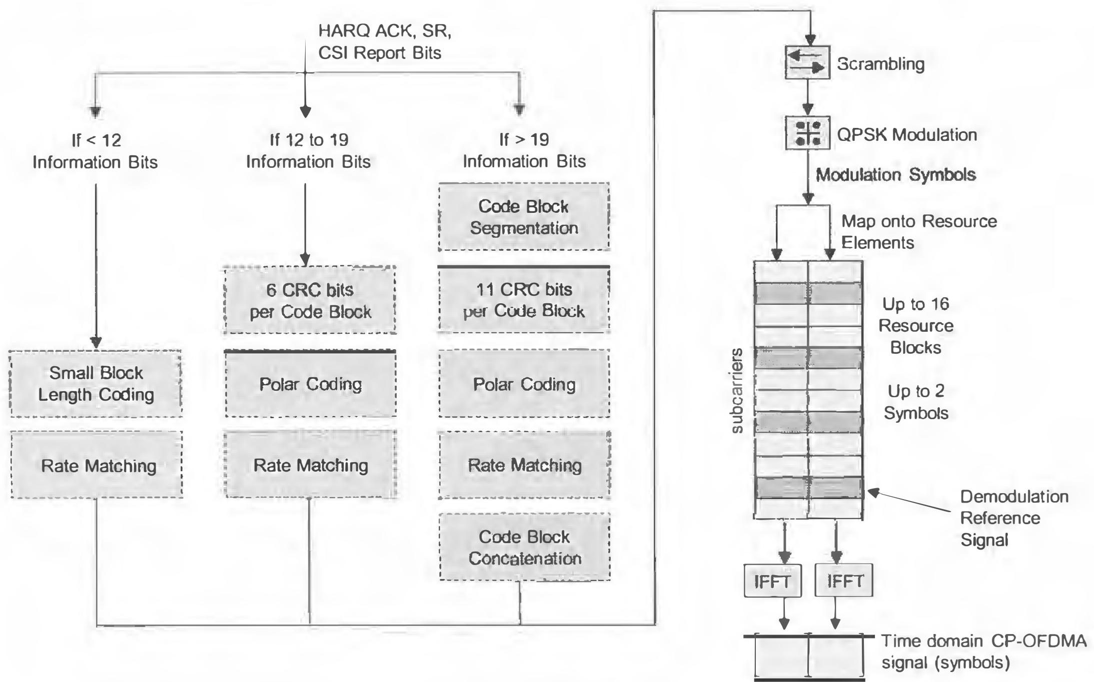


Figure 259 – Generation of PUCCH Format 2

- If there are less than 12 bits of uplink control information to be transferred then code block segmentation is not necessary and no Cyclic Redundancy Check (CRC) bits are added. Channel coding for small block lengths is used to generate redundancy. This is based upon Reed-Muller Block coding which increases the block size to 32 bits. Rate matching is used to ensure that the number of bits fits exactly within the allocated Resource Blocks and symbols. This involves repetition when the number of bits needs to be increased
- If there are between 12 and 19 bits of uplink control information then code block segmentation is not necessary but 6 CRC bits are added to allow error detection at the Base Station. Polar Coding is used as a channel coding technique to help protect the information as it is transferred across the air-interface. Rate matching is used to ensure that the number of bits fits exactly within the allocated Resource Blocks and symbols
- If there are more than 19 bits of uplink control information to be transferred then code block segmentation may be applied depending upon the number of bits to be transferred. Segmentation generates a maximum of 2 code blocks. 11 CRC bits are added to allow error detection at the base Station. Polar Coding is used as a channel coding technique to help protect the information as it is transferred across the air-interface. Rate matching is used to ensure that the number of bits fits exactly within the allocated Resource Blocks and symbols
- Scrambling is applied to randomise the transmitted bit stream. This helps to randomise intercell interference towards neighbouring cells. The scrambling sequence generator is initialised using: $(n_{RNTI} \times 2^{15}) + n_{ID}$, where n_{RNTI} is the UE specific Cell Radio Network Temporary Identifier (C-RNTI) and n_{ID} is the value of *dataScramblingIdentityPUSCH* from the PUSCH configuration

information. If *dataScramblingIdentityPUSCH* has not been provided to the UE then n_{ID} is set equal to the value of the Physical layer Cell Identity (PCI). Both have a range from 0 to 1023

★ The resultant bit stream is modulated using QPSK before mapping onto the set of Resource Elements. The Demodulation Reference Signal (DMRS) occupies 4 Resource Elements within each Resource Block. This leaves 8 Resource Elements available for the scrambled data. The scrambled data populates all of the allocated Resource Elements within the first symbol before populating all of the allocated Resource Elements within the second symbol

★ The PUCCH resource configuration for PUCCH Format 2 is presented in Table 188. Transmission always starts within the uplink Bandwidth Part at the Resource Block indicated by *startingPRB*. If the transmission has a duration of 2 symbols and if frequency hopping is enabled (indicated by the inclusion of the *intraSlotFrequencyHopping* flag) then the second symbol is transmitted at the Resource Block indicated by *secondHopPRB*

PUCCH-Resource		
pucch-ResourceId	0 to 127	
startingPRB	0 to 274	
intraSlotFrequencyHopping	enabled	
secondHopPRB	0 to 274	
format	*PUCCH-format2*	
	nrofPRBs	1 to 16
	nrofSymbols	1 to 2
	startingSymbolIndex	0 to 13

Table 188 – PUCCH resource information for PUCCH Format 2

★ The *nrofPRBs* information element defines the maximum number of Resource Blocks which can be used by PUCCH Format 2. The actual PUCCH transmission can occupy less Resource Blocks if the payload is relatively small, or the maximum specified coding rate is relatively high. The UE evaluates its Resource Block requirement using the maximum coding rate specified by the Base Station. The maximum coding rate is signalled using the *maxCodeRate* information element within the PUCCH Format configuration. This information element is presented in Table 189

PUCCH-FormatConfig	
interslotFrequencyHopping	enabled
additionalDMRS	true
maxCodeRate	0.08, 0.15, 0.25, 0.35, 0.45, 0.6, 0.8
nrofSlots	2, 4, 8
pi2BPSK	enabled
simultaneousHARQ-ACK-CSI	true

Table 189 – PUCCH Format configuration information

★ The UE transmits the maximum number of Resource Blocks defined by *nrofPRBs* if the following is true:

$$(Payload + CRC\ Bits) > (nrofPRBs - 1) \times 8 \times N_{sym}^{PUCCH} \times 2 \times maxCodeRate$$

If this equation is satisfied then it indicates that the maximum coding rate would be exceeded if the payload and CRC bits were to be transferred using less than the maximum number of Resource Blocks. The '8' within this equation corresponds to the number of Resource Elements per Resource Block available to transfer the payload after accounting for the Demodulation Reference Signal. The '2' corresponds to the number of bits which can be transferred by a single Resource Element when using QPSK. N_{sym}^{PUCCH} corresponds to the number of symbols allocated to PUCCH Format 2

★ Otherwise, the UE transmits the minimum number of Resource Blocks which satisfies:

$$(Payload + CRC\ Bits) \leq M_{RB,min}^{PUCCH} \times 8 \times N_{sym}^{PUCCH} \times 2 \times maxCodeRate$$

This equation identifies the minimum number of Resource Blocks which can be allocated to the PUCCH without exceeding the maximum coding rate

★ The *interslotFrequencyHopping*, *additionalDMRS*, *nrofSlots* and *pi2BPSK* information elements within the PUCCH Format configuration are not applicable to PUCCH Format 2. Inclusion of the *simultaneousHARQ-ACK-CSI* information element indicates that simultaneous transmission of HARQ acknowledgements and CSI reports is enabled. Simultaneous transmission is disabled if this information element is excluded

7.3.4 PUCCH FORMAT 3

★ PUCCH Format 3 is used to transfer HARQ acknowledgements and/or a Scheduling Request (SR) and/or Channel State Information (CSI) reports

★ It occupies between 1 and 16 Resource Blocks in the frequency domain and between 4 and 14 symbols in the time domain. This means that PUCCH Format 3 occupies between 48 and 2688 Resource Elements. Transmission across an increased number of symbols and a larger number of Resource Blocks can be used to improve coverage

★ The Resource Blocks used by PUCCH Format 3 are contiguous. 3GPP TS 38.211 specifies that it must be possible to calculate the number of Resource Blocks using the following expression: $2^{\alpha} \times 3^{\beta} \times 5^{\gamma}$, where α, β and γ are non-negative integers. This means that PUCCH Format 3 can use 1, 2, 3, 4, 5, 6, 8, 9, 10, 12, 15 or 16 Resource Blocks. This requirement is imposed to help reduce the implementation complexity of the Transform Precoding applied to PUCCH Format 3

★ PUCCH Format 3 is able to use Frequency hopping. i.e. the first subset of symbols are transmitted using one part of the channel bandwidth while the second subset of symbols is transmitted using another part of the channel bandwidth. Frequency hopping can be enabled/disabled by the Base Station

★ PUCCH Format 3 uses a Demodulation Reference Signal (DMRS) so not all Resource Elements are available for the payload. The DMRS allows the Base Station receiver to use coherent detection. The DMRS occupies specific symbols belonging to the PUCCH. These symbols are illustrated in Figure 260

★ When the PUCCH is configured to occupy 4 symbols, the symbols allocated to the DMRS depend upon whether or not frequency hopping is enabled. When frequency hopping is disabled then only a single symbol is allocated to the DMRS to minimise the overhead. When frequency hopping is enabled, two symbols are allocated to the DMRS to ensure that each frequency hopping position includes a DMRS symbol. When the PUCCH is configured to use more than 4 symbols, the symbols allocated to the DMRS do not depend upon the use of frequency hopping because there is already at least one DMRS symbol within each half of the PUCCH

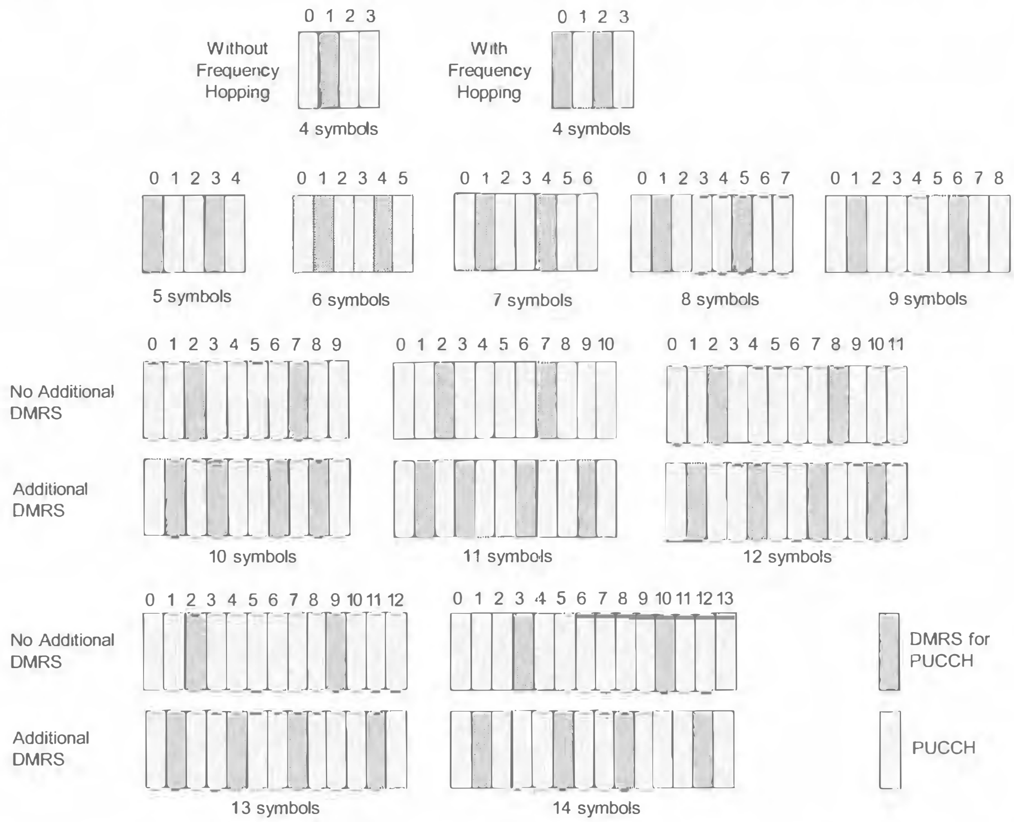


Figure 260 – Symbols allocated to the DMRS for PUCCH Format 3

★ When the PUCCH is allocated 10 or more symbols, then additional DMRS symbols can be configured by including the *additionalDMRS* information element within the PUCCH Format configuration information presented in Table 190. The number of symbols allocated to the DMRS is doubled when the use of additional DMRS symbols is configured

PUCCH-FormatConfig	
interslotFrequencyHopping	enabled
additionalDMRS	true
maxCodeRate	0.08, 0.15, 0.25, 0.35, 0.45, 0.6, 0.8
nrofSlots	2, 4, 8
pi2BPSK	enabled
simultaneousHARQ-ACK-CSI	true

Table 190 – PUCCH Format configuration information

★ Prior to modulation, the payload of PUCCH Format 3 is processed in a similar way to the payload of PUCCH Format 2, i.e. the process involves code block segmentation, the addition of CRC bits, channel coding, rate matching and code block concatenation. This process is illustrated in Figure 261. PUCCH Format 3 does not use cyclic shifts nor Orthogonal Cover Codes (OCC) so does not support multiplexing of UE within shared Resource Blocks

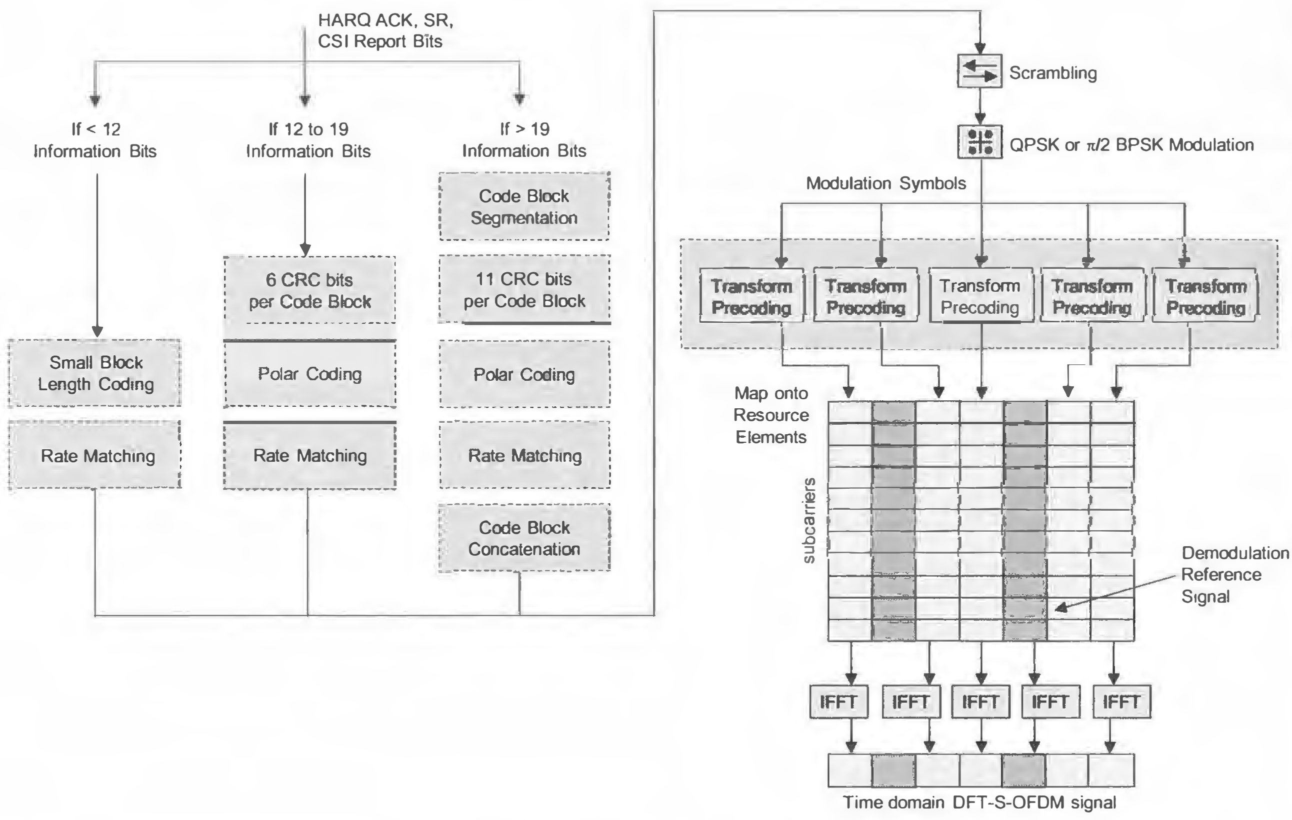


Figure 261 – Generation of PUCCH Format 3

★ If there are less than 12 bits of uplink control information to be transferred then code block segmentation is not necessary and no Cyclic Redundancy Check (CRC) bits are added. Channel coding for small block lengths is used to generate redundancy. This is based upon Reed-Muller Block coding and increases the block size to 32 bits. Rate matching is used to ensure that the number of bits fits exactly within the allocated Resource Blocks and symbols. This involves repetition when the number of bits needs to be increased

★ If there are between 12 and 19 bits of uplink control information then code block segmentation is not necessary but 6 CRC bits are added to allow error detection at the Base Station. Polar Coding is used as a channel coding technique to help protect the information as it is transferred across the air-interface. Rate matching is used to ensure that the number of bits fits exactly within the allocated Resource Blocks and symbols

★ If there are more than 19 bits of uplink control information to be transferred then code block segmentation may be applied depending upon the number of bits to be transferred. Segmentation generates a maximum of 2 code blocks. 11 CRC bits are added to allow error detection at the base Station. Polar Coding is used as a channel coding technique to help protect the information as it is transferred across the air-interface. Rate matching is used to ensure that the number of bits fits exactly within the allocated Resource Blocks and symbols

★ Scrambling is applied to randomise the transmitted bit stream. This helps to randomise intercell interference towards neighbouring cells. The scrambling sequence generator is initialised using: $(n_{RNTI} \times 2^{15}) + n_{ID}$, where n_{RNTI} is the UE specific Cell Radio

Network Temporary Identifier (C-RNTI) and n_{ID} is the value of *dataScramblingIdentityPUSCH* from the PUSCH configuration information. If *dataScramblingIdentityPUSCH* has not been provided to the UE then n_{ID} is set equal to the value of the Physical layer Cell Identity (PCI). Both have a range from 0 to 1023

★ PUCCH Format 3 supports both QPSK and π/2 BPSK modulation schemes. π/2 BPSK is described in section 2.7. QPSK transfers 2 bits per symbol whereas π/2 BPSK transfers 1 bit per symbol. This means that QPSK provides a higher capacity and can accommodate increased levels of channel coding redundancy for a specific Resource Block allocation. π/2 BPSK is a lower order modulation which reduces the SINR requirement for correct symbol detection. It also has a lower Peak-to-Average Power Ratio (PAPR) which helps the UE to operate more efficiently and with a higher average power. The Base Station uses the PUCCH Format configuration information presented in Table 190 to indicate which modulation scheme should be used. Inclusion of the *pi2BPSK* information element indicates that π/2 BPSK should be used. Otherwise QPSK is used

★ The modulation symbols are divided into groups, where the number of groups equals the number of symbols used to transfer the payload. Transform Precoding is then applied to each group of modulation symbols. Transform Precoding applies a Fast Fourier Transform (FFT) and the results of this calculation are mapped onto the set of subcarriers. The inclusion of Transform Precoding means that PUCCH Format 3 uses Discrete Fourier Transform Spread Orthogonal Frequency Division Multiplexing (DFT-S-OFDM) as an air-interface waveform (rather than CP-OFDM). The 'Transform Precoding' operation requires additional computational complexity but decreases the relatively high Peak to Average Power (PAPR) associated with CP-OFDM

★ The PUCCH resource configuration for PUCCH Format 3 is presented in Table 191. Transmission always starts within the uplink Bandwidth Part at the Resource Block indicated by *startingPRB*. If intra-slot frequency hopping is enabled (indicated by the inclusion of the *intraSlotFrequencyHopping* flag) then the number of symbols used for the first frequency hop is given by ROUND DOWN (Total number of Symbols / 2). The remaining symbols are used for the second frequency hop transmitted at the Resource Block indicated by *secondHopPRB*

PUCCH-Resource		
pucch-ResourceId	0 to 127	
startingPRB	0 to 274	
intraSlotFrequencyHopping	enabled	
secondHopPRB	0 to 274	
format	*PUCCH-format3*	
	nrofPRBs	1 to 16
	nrofSymbols	4 to 14
	startingSymbolIndex	0 to 10

Table 191 – PUCCH resource information for PUCCH Format 3

★ The *nrofPRBs* information element defines the maximum number of Resource Blocks which can be used by PUCCH Format 3. The actual PUCCH transmission can occupy less Resource Blocks if the payload is relatively small, or the maximum specified coding rate is relatively high. The UE evaluates its Resource Block requirement using the maximum coding rate specified by the Base Station. The maximum coding rate is signalled using the *maxCodeRate* information element within the PUCCH Format configuration. This information element is presented in Table 190

★ The UE transmits the maximum number of Resource Blocks defined by *nrofPRBs* if the following is true:

$$(Payload + CRC\ Bits) > (nrofPRBs - 1) \times 12 \times N_{sym}^{PUCCH\_payload} \times Q_m \times maxCodeRate$$

If this equation is satisfied then it indicates that the maximum coding rate would be exceeded if the payload and CRC bits were to be transferred using less than the maximum number of Resource Blocks. The '12' within this equation corresponds to the number of Resource Elements per Resource Block. $N_{sym}^{PUCCH\_payload}$ corresponds to the number of symbols available to transfer the payload. Q_m is 1 when using π/2 BPSK and 2 when using QPSK

★ Otherwise, the UE transmits the minimum number of Resource Blocks which satisfies:

$$(Payload + CRC\ Bits) \leq M_{RB,min}^{PUCCH} \times 12 \times N_{sym}^{PUCCH\_payload} \times Q_m \times maxCodeRate$$

This equation identifies the minimum number of Resource Blocks which can be allocated to the PUCCH without exceeding the maximum coding rate

7.3.5 PUCCH FORMAT 4

★ PUCCH Format 4 is used to transfer HARQ acknowledgements and/or a Scheduling Request (SR) and/or Channel State Information (CSI) reports

★ It occupies 1 Resource Block in the frequency domain and between 4 and 14 symbols in the time domain. This means that PUCCH Format 4 occupies between 48 and 168 Resource Elements. Transmission across an increased number of symbols can be used to improve coverage

★ PUCCH Format 4 is able to use Frequency hopping. i.e. the first subset of symbols are transmitted using one part of the channel bandwidth while the second subset of symbols is transmitted using another part of the channel bandwidth. Frequency hopping can be enabled/disabled by the Base Station

★ PUCCH Format 4 uses a Demodulation Reference Signal (DMRS) so not all Resource Elements are available for the payload. The DMRS allows the Base Station receiver to use coherent detection. The DMRS occupies specific symbols belonging to the PUCCH. These symbols are the same as those used for PUCCH Format 3 (illustrated in Figure 260)

★ PUCCH Format 4 allows the same option as PUCCH Format 3 regarding the configuration of additional DMRS symbols, i.e. when the PUCCH is allocated 10 or more symbols, then additional DMRS symbols can be configured by including the *additionalDMRS* information element within the PUCCH Format configuration information. The number of symbols allocated to the DMRS is doubled when the use of additional DMRS symbols is configured

★ Prior to modulation, the payload of PUCCH Format 4 is processed in a similar way to the payloads of PUCCH Formats 2 and 3, i.e. the process involves code block segmentation, the addition of CRC bits, channel coding, rate matching and code block concatenation. This process is illustrated in Figure 262

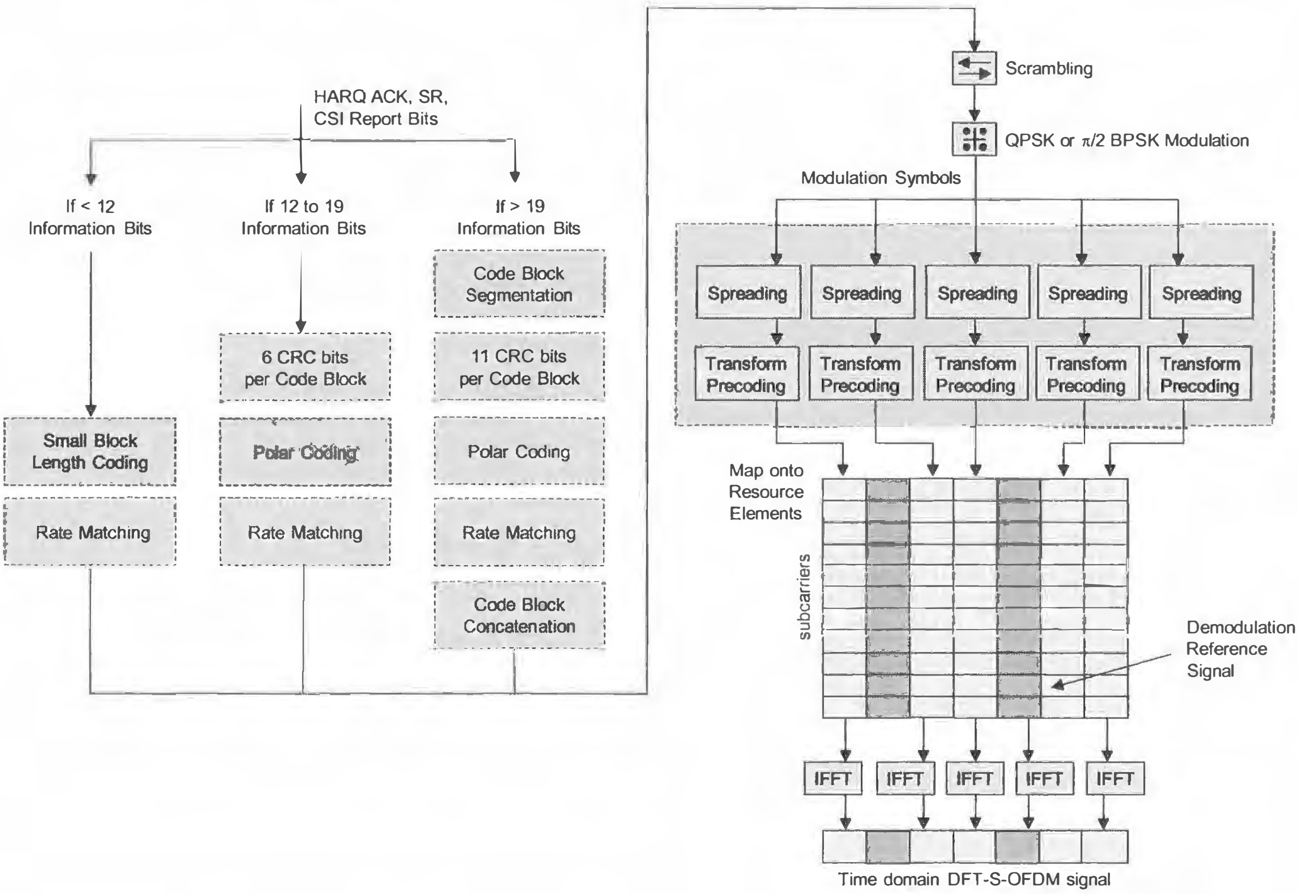


Figure 262 – Generation of PUCCH Format 4

★ PUCCH Format 4 supports both QPSK and π/2 BPSK modulation schemes (the same modulation schemes as PUCCH Format 3). QPSK provides a higher capacity and can accommodate increased levels of channel coding redundancy for a specific Resource Block allocation. π/2 BPSK is a lower order modulation which reduces the SINR requirement for correct symbol detection. It also has a lower Peak-to-Average Power Ratio (PAPR) which helps the UE to operate more efficiently and with a higher average power. The Base Station uses the PUCCH Format configuration information to indicate which modulation scheme should be used. Inclusion of the *pi2BPSK* information element indicates that π/2 BPSK should be used

★ The modulation symbols are divided into groups, where the number of groups equals the number of symbols used to transfer the payload. The number of modulation symbols within each group depends upon the Spreading Factor of the subsequent spreading process. The UE is provided with details of the Spreading Factor within the PUCCH resource information for PUCCH Format 4 (presented in Table 192). The Spreading Factor is specified using the *occ-Length* information element. Spreading Factors of 2 and 4 are supported

PUCCH-Resource		
pucch-ResourceId	0 to 127	
startingPRB	0 to 274	
intraSlotFrequencyHopping	enabled	
secondHopPRB	0 to 274	
format	*PUCCH-format4*	
	nrofSymbols	4 to 14
	occ-Length	2, 4
	occ-Index	0, 1, 2, 3
	startingSymbolIndex	0 to 10

Table 192 – PUCCH resource information for PUCCH Format 4

★ Figure 263 illustrates the spreading procedure when the Spreading Factor is 2. PUCCH Format 4 uses a single Resource Block, i.e. a set of 12 subcarriers. The Spreading Factor of 2 means that there are 6 modulation symbols within each group prior to spreading. The 6 modulation symbols are multiplied with an Orthogonal Cover Code (OCC) of length 2. This generates an output of length 12 which then matches the number of available subcarriers. 3GPP TS 38.211 specifies 2 OCC of length 2. This means that 2 UE can be multiplexed and share the same Resource Block allocation. Figure 263 illustrates that the first OCC is {1, 1}, while the second OCC is {1, -1}. The Base Station provides the UE with instructions regarding which OCC to apply using the *occ-Index* information element shown in Table 192

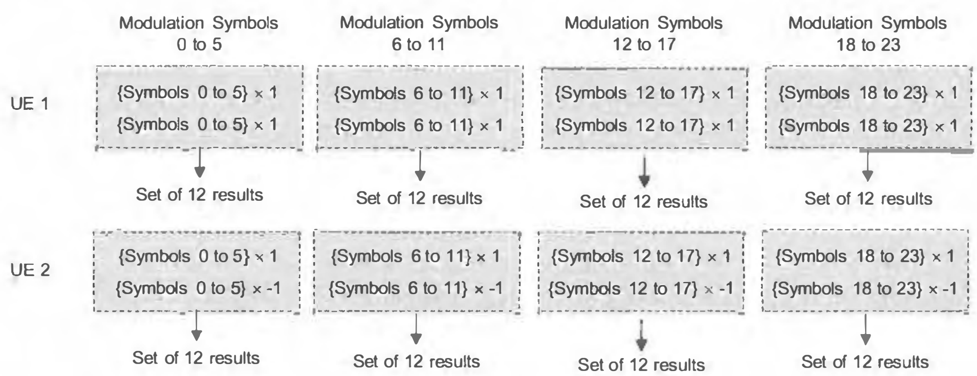


Figure 263 – Spreading for 2 UE multiplexed using Spreading Factor 2

★ When using a Spreading Factor of 4, there are 3 modulation symbols within each group prior to spreading. The 3 modulation symbols are multiplied with an OCC of length 4. This generates an output of length 12 which then matches the number of available subcarriers. 3GPP TS 38.211 specifies 4 OCC of length 4. This means that 4 UE can be multiplexed and share the same Resource Block allocation. The set of 4 OCC are {1, 1, 1, 1}, {1, -j, -1, j}, {1, -1, 1, -1} and {1, j -1, -j}

★ The Spreading Factor of 4 increases the multiplexing capacity of PUCCH Format 4 but decreases the capacity available to each individual UE. Increasing the Spreading Factor from 2 to 4 reduces the number of modulation symbols which are mapped onto each DFT-S-OFDM symbol from 6 to 3

★ Transform Precoding is then applied to each group of spread modulation symbols. Transform Precoding applies a Fast Fourier Transform (FFT) and the results of this calculation are mapped onto the set of subcarriers. The inclusion of Transform Precoding means that PUCCH Format 4 uses DFT-S-OFDM as an air-interface waveform rather than CP-OFDM. The 'Transform Precoding' operation requires additional computational complexity but decreases the relatively high Peak to Average Power (PAPR) associated with CP-OFDM

★ The PUCCH resource configuration for PUCCH Format 4 is presented in Table 192. Transmission always starts within the uplink Bandwidth Part at the Resource Block indicated by *startingPRB*. If intra-slot frequency hopping is enabled (indicated by the inclusion of the *intraSlotFrequencyHopping* flag) then the number of symbols used for the first frequency hop is given by ROUND DOWN (Total number of Symbols / 2). The remaining symbols are used for the second frequency hop transmitted at the Resource Block indicated by *secondHopPRB*

7.3.6 PUCCH REPETITION

- The long PUCCH Formats (Formats 1, 3 and 4) can be configured for repetition across multiple slots. Repetition across multiple slots improves the reliability and coverage of the PUCCH. The short PUCCH Formats (Formats 0 and 2) are designed for low latency applications so repetition across multiple slots is not appropriate, i.e. repetition increases latency
- The Base Station enables PUCCH repetition by including the *nrofSlots* information element within the PUCCH Format configuration information. This information element is presented in Table 193. It can be configured with a value of 2, 4 or 8. Excluding the information element indicates that PUCCH repetition is disabled
- The value of *nrofSlots* indicates the total number of transmissions. For example, the value of 8 indicates that the UE transmits the uplink control information on the PUCCH a total of 8 times (a first transmission followed by 7 repetitions)

PUCCH-FormatConfig	
interslotFrequencyHopping	enabled
additionalDMRS	true
maxCodeRate	0.08, 0.15, 0.25, 0.35, 0.45, 0.6, 0.8
nrofSlots	2, 4, 8
pi2BPSK	enabled
simultaneousHARQ-ACK-CSI	true

Table 193 – PUCCH Format configuration information

- Each repetition of the PUCCH occupies the same number of symbols as the first transmission (defined by the *nrofSymbols* information element within the PUCCH Resource information). In addition, each repetition of the PUCCH uses the same starting symbol within each slot (defined by the *startingSymbolIndex* within the PUCCH Resource information)
- When using repetition, there is a choice between disabling frequency hopping, enabling intra-slot frequency hopping and enabling inter-slot frequency hopping. Intra-slot and inter-slot frequency hopping are illustrated in Figure 264. Intra-slot and inter-slot frequency hopping cannot be enabled together.
- When using intra-slot frequency hopping, the *startingPRB* and *secondHopPRB* information elements define the positions of the PUCCH in the same way as when PUCCH repetition is disabled. The frequency hopping pattern is repeated in every slot
- When using inter-slot frequency hopping, the *startPRB* information element defines the position of the PUCCH during even numbered slots, while the *secondHopPRB* information element defines the position of the PUCCH during odd numbered slots. Slot numbering starts at 0 within the first slot of the PUCCH transmission

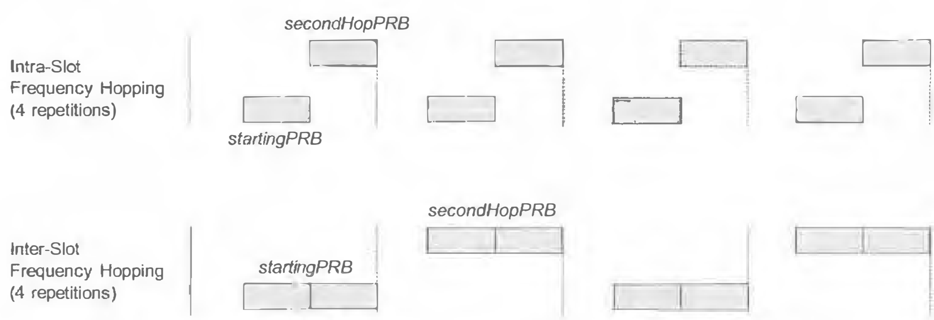


Figure 264 – Intra-slot and Inter-slot frequency hopping with PUCCH repetition

- The PUCCH is not transmitted during a slot if the UE determines that the slot does not have sufficient available symbols for the PUCCH transmission
- 3GPP References: TS 38.213, TS 38.211, TS 38.212, TS 38.331

7.4 PHYSICAL UPLINK SHARED CHANNEL

★ The Physical Uplink Shared Channel (PUSCH) is used to transfer end-user application data and Signalling Radio Bearer (SRB) messages. Application data belongs to the user plane, while SRB messages belong to the control plane

★ In addition, the PUSCH can be used to transfer control information generated by the set of radio network protocol stack layers. For example, the MAC layer can add a range of MAC Control Elements (MAC CE) including Buffer Status Reports and Power Headroom Reports. The MAC Control Elements which can be transferred using the PUSCH are listed in Table 194

Buffer Status Report	Single Entry Power Headroom Report
C-RNTI	Multiple Entry Power Headroom Report
Configured Grant Confirmation	

Table 194 – MAC Control Elements which can be transferred using the PUSCH

★ In addition, the Physical layer can add Uplink Control Information (UCI) to the PUSCH. This UCI includes HARQ Acknowledgements and Channel State Information (CSI)

★ Figure 265 summarises the content transferred by the PUSCH

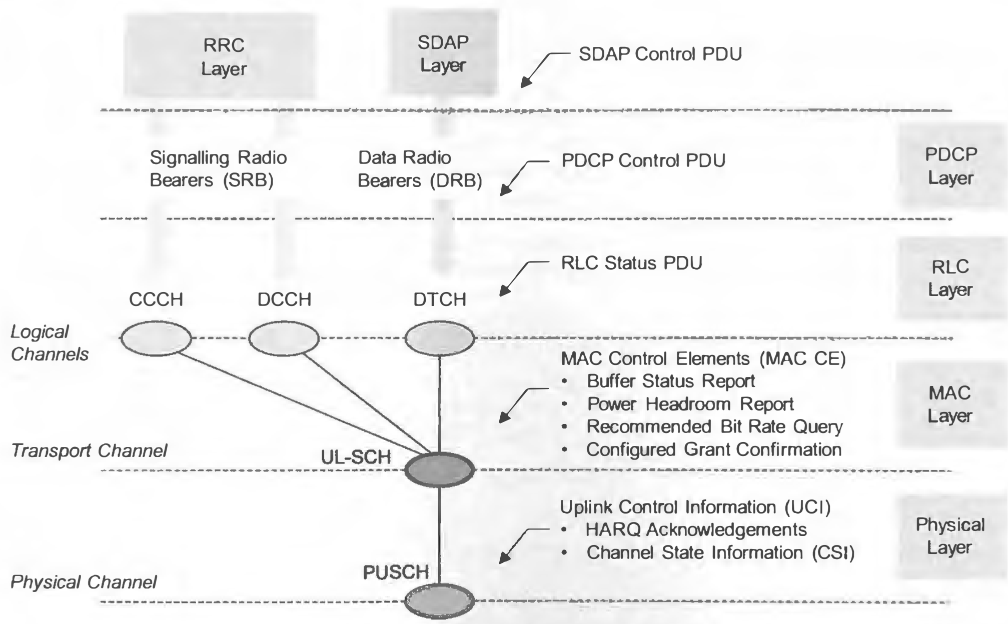


Figure 265 – Content transferred by the PUSCH

★ A UE can transmit the PUSCH using either a CP-OFDM or DFT-S-OFDM waveform (it is mandatory for all UE to support both waveforms). This is in contrast to the PDSCH which only supports the CP-OFDM waveform. Both waveforms are described in section 2.9. DFT-S-OFDM uses Transform Precoding to 'spread' the modulation symbols prior to mapping onto the set of subcarriers. Transform Precoding is a Discrete Fourier Transform (DFT) operation which reduces the Peak to Average Power Ratio (PAPR). It allows the UE to transmit with a higher average power and thus improve uplink coverage performance

★ The PUSCH can use the $\pi/2$ BPSK, QPSK, 16QAM, 64QAM and 256QAM modulation schemes. The $\pi/2$ BPSK modulation scheme is only permitted when Transform Precoding is enabled, i.e. when using the DFT-S-OFDM waveform. It is a low order modulation scheme with a low PAPR so helps to improve coverage. Section 2.7 describes the set of modulation schemes in greater detail

★ The PUSCH uses antenna ports 0 to 11. These are the same as those used by the Demodulation Reference Signal (DMRS). An individual UE can use up to 4 ports to transfer 4 layers of uplink data, i.e. 4×4 MIMO. The full set of ports can be utilised by allocating them across a group of UE for Multi-User MIMO

★ The PUSCH is always transmitted in combination with a DMRS. It may also be configured to be transmitted in combination with a Phase Tracking Reference Signal (PTRS)

★ Cell specific configuration information for the PUSCH is broadcast within System Information Block 1 (SIB1) using the *PUSCH-ConfigCommon* parameter structure presented in Table 195

PUSCH-ConfigCommon		
groupHoppingEnabledTransformPrecoding	enabled	
pusch-TimeDomainAllocationList	SEQUENCE (1 to 16 instances)	
	k2	0 to 32
	mappingType	typeA, typeB
	startSymbolAndLength	0 to 127
msg3-DeltaPreamble	-1 to 6	
p0-NominalWithGrant	-202 to 24	

Table 195 – *PUSCH-ConfigCommon* parameter structure

★ The *groupHoppingEnabledTransformPrecoding* information element specifies whether or not group hopping is to be applied when selecting a Zadoff-Chu sequence for the PUSCH DMRS. Within the context of the PUSCH, group hopping is only applicable when Transform Precoding is enabled (DFT-S-OFDM waveform). When Transform Precoding is disabled (CP-OFDM), a pseudo random sequence based upon a length-31 Gold sequence is used for the DMRS. This random sequence does not rely upon group selection, nor sequence selection from within a group

★ The *pusch-TimeDomainAllocationList* defines a look-up table with rows which can be selected when making a time domain resource allocation. Each row specifies a slot offset (K_2), a PUSCH Mapping Type, a starting symbol and a number of allocated symbols (the length). This look-up table is used in combination with 2 other similar look-up tables – one standardised by 3GPP within TS 38.214 (Default Table 'A'), and another which is included within the *pusch-Config* parameter structure. Selection between these 3 look-up tables and their subsequent use is described in section 7.4.4.1

★ The *msg3-DeltaPreamble* and *p0-NominalWithGrant* information elements are both associated with power control. The former specifies the transmit power difference between the most recent PRACH preamble and MSG3. This information element uses a mapping which defines the actual value as 2 × signalled value. *p0-NominalWithGrant* specifies the target received power for the PUSCH open loop power control calculation when using dynamic grants. This parameter is restricted to even values

★ UE specific configuration information for the PUSCH can be provided using the *PUSCH-Config* parameter structure presented in Table 196. The Base Station uses dedicated signalling to forward this parameter structure to the UE

PUSCH-Config		
dataScramblingIdentityPUSCH	0 to 1023	
txConfig	codebook, nonCodebook	
dmrs-UplinkForPUSCH-MappingTypeA	SetupRelease { DMRS-UplinkConfig }	
dmrs-UplinkForPUSCH-MappingTypeB	SetupRelease { DMRS-UplinkConfig }	
pusch-PowerControl	PUSCH-PowerControl	
frequencyHopping	intraSlot, interSlot	
frequencyHoppingOffsetLists	1 to 4 instances of {1 to 274}	
resourceAllocation	resourceAllocationType0, resourceAllocationType1, dynamicSwitch	
pusch-TimeDomainAllocationList	SEQUENCE (1 to 16 instances)	
	k2	0 to 32
	mappingType	typeA, typeB
	startSymbolAndLength	0 to 127
pusch-AggregationFactor	n2, n4, n8	
mcs-Table	qam256, qam64LowSE	
mcs-TableTransformPrecoder	qam256, qam64LowSE	
transformPrecoder	enabled, disabled	
codebookSubset	fullyAndPartialAndNonCoherent, partialAndNonCoherent, nonCoherent	
maxRank	1 to 4	
rbg-Size	config2	
uci-OnPUSCH	SetupRelease { UCI-OnPUSCH }	
tp-pi2BPSK	enabled	

Table 196 – *PUSCH-Config* parameter structure

★ *dataScramblingIdentityPUSCH* can be used to initialise the pseudo random sequence which scrambles the PUSCH payload prior to modulation. *dataScramblingIdentityPUSCH* is applicable if the RNTI used to address the UE on the PDCCH is a C-RNTI, MCS-C-RNTI or CS-RNTI, and if the PUSCH is not scheduled using DCI Format 0_0 in a Common Search Space. Otherwise, the PCI is used to initialise the pseudo random sequence. Scrambling uses the pseudo random sequence to 'randomly' change some bits from '1' to '0' and other bits from '0' to '1'. The order of the bits is not changed. The objective of scrambling is to randomise the bit stream and thus randomise the intercell interference experienced by neighbouring cells. The impact of intercell interference is reduced if the interference appears random

★ *txConfig* instructs the UE to use either 'codebook' based transmission or 'non-codebook' based transmission. These two transmission schemes are described in section 8. If *txConfig* is excluded from *PUSCH-Config*, the UE transmits the PUSCH using a single antenna port and PUSCH resources are allocated using DCI Format 0_0

★ *dmrs-UplinkForPUSCH-MappingTypeA* and *dmrs-UplinkForPUSCH-MappingTypeB* provide configuration information for DMRS Types A and B. The DMRS Type is indicated for each PUSCH transmission using the 'Time Domain Resource Assignment' field within the PDCCH Downlink Control Information. The 'Time Domain Resource Assignment' field points to a row within a look-up table which includes a column for the DMRS Type. The parameter sets belonging to *dmrs-DownlinkForPDSCH-MappingTypeA* and *dmrs-DownlinkForPDSCH-MappingTypeB* are described in section 7.5.1

★ *pusch-PowerControl* provides the parameter set presented in Table 266 (section 13.3.1)

★ *frequencyHopping* instructs the UE to apply either intra-slot or inter-slot frequency hopping. If *frequencyHopping* is excluded from *PUSCH-Config*, the UE does not apply frequency hopping. Intra-slot frequency hopping is applicable to both single slot transmission and multi-slot transmission. In contrast, inter-slot frequency hopping is only applicable to multi-slot transmission. Multi-slot transmission is configured by including the *pusch-AggregationFactor* which allows transmissions to be repeated across 2, 4 or 8 slots

★ *frequencyHoppingOffsetLists* provides 2 Resource Block offsets when frequency hopping is used within a Bandwidth Part which is smaller than 50 PRB. Otherwise, *frequencyHoppingOffsetLists* provides 4 Resource Block offsets when frequency hopping is to be used within a larger Bandwidth Part. Figure 266 illustrates the concept of intra-slot frequency hopping which divides the time domain resource allocation into two sections. The first section uses the Resource Block allocation provided by the 'Frequency Domain Resource Assignment' within the DCI. The second section applies a Resource Block offset according to an entry selected from the *frequencyHoppingOffsetLists*. The entry is selected using either 1 or 2 bits from within the 'Frequency Domain Resource Assignment' (1 bit is used if there are 2 entries within the list, and 2 bits are used if there are 4 entries within the list). Modulo arithmetic is used when adding the offset to the original Resource Block assignment to ensure that the result remains within the Bandwidth Part

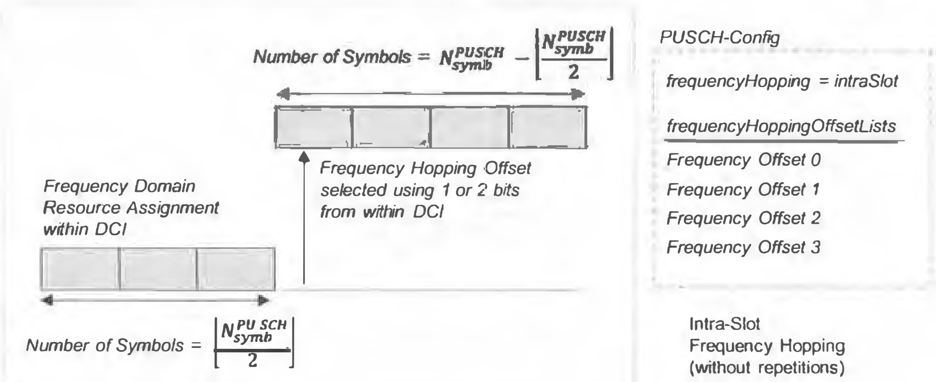


Figure 266 – Intra-slot Frequency Hopping for the PUSCH

★ In the case of inter-slot frequency hopping, transmissions during even numbered slots use the original Resource Block assignment, whereas transmissions during odd numbered slots use the Resource Block assignment with the offset applied

★ *resourceAllocation* configures the UE to expect either a specific Resource Allocation Type within DCI Format 0_1, or a dynamic switching between Resource Allocation Types. DCI Format 0_0 always uses Resource Allocation Type 1 so does not require any configuration. When using DCI Format 0_1 with dynamic switching, an additional bit is included within the 'Frequency Domain Resource Assignment' field to indicate the Resource Allocation Type

★ *pusch-TimeDomainAllocationList* provides a look-up table which has the same format as the look-up table provided by *PUSCH-ConfigCommon* (presented in Table 195). Each row specifies a slot offset (K_2), a PUSCH Mapping Type, a starting symbol and a number of allocated symbols (the length). These two tables are used in combination with Default table 'A' standardised by 3GPP within TS 38.214. Selection between these look-up tables and their subsequent use is described in section 7.4.4.1

★ *mcs-Table* specifies the Modulation and Coding Scheme (MCS) table to be applied when the PUSCH is used without Transform Precoding (CP-OFDM). Similarly, *mcs-TableTransformPrecoder* specifies the MCS table to be applied when the PUSCH is used with Transform Precoding (DFT-S-OFDM). In both cases, there is a choice of 3 MCS tables. Selection of the 256QAM and 64QAM Low Spectral Efficiency tables can be signalled explicitly. Exclusion of the information element indicates selection of the 64QAM table. MCS tables are presented in section 7.4.1

★ *transformPrecoder* determines whether or not Transform Precoding is applied when an uplink resource allocation is received using DCI Format 0_1. If *transformPrecoder* is excluded, or if the resource allocation is received using DCI Format 0_0 then the use of Transform Precoding depends upon the value of *msg3-transformPrecoder* shown within Table 255 (section 13.1.1)

- *codebookSubset* is applicable to the Codebook Based Transmission Scheme described in section 8.1. It specifies the subset of the codebook which is to be used when sending Transmitted Precoding Matrix Indicator (TPMI) values to the UE within DCI Format 0_1. The value must be aligned with the UE capability, e.g. if the UE has reported a capability of 'non-coherent' then the Base Station should not configure a value of *fullyAndPartialAndNonCoherent* nor *partialAndNonCoherent*
- *maxRank* specifies the maximum transmission rank to be allocated to the UE. The value of *maxRank* is used for Codebook Based Transmission when selecting an appropriate look-up table for the 'Precoding Information and Number of Layers' field within DCI Format 0_1
- *rbg-Size* defines the size of the Resource Block Groups (RBG) used for uplink Resource Allocation Type 0. Resource Allocation Type 0 uses a bitmap to allocate specific RBG. The size of the bitmap is equal to the number of RBG within the uplink Bandwidth Part. *rbg-Size* represents a pointer to a column belonging to a look-up table standardised by 3GPP TS 38.214. This look-up table is presented as Table 208 in section 7.4.4.2.1. Configuration 1 is selected by excluding *rbg-Size* from *PUSCH-Config*. Configuration 1 corresponds to smaller RBG sizes which provide the Base Station with increased scheduling flexibility but these smaller RBG increase the size of the bitmap within DCI Format 0_1 when using Resource Allocation Type 0
- *uci-OnPUSCH* can be used to provide a semi-static configuration for a set of *BetaOffsets*. These offsets impact the number of Resource Elements allocated to Uplink Control Information (UCI) which is multiplexed onto the PUSCH. Alternatively, *uci-OnPUSCH* can be used to provide multiple sets of *BetaOffsets* which are then selected dynamically using the 'Beta Offset Indicator' within DCI Format 0_1
- *tp-pi2BPSK* is used to enable the π/2 BPSK modulation scheme when Transform Precoding is enabled. QPSK is used to replace π/2 BPSK within the MCS tables when π/2 BPSK is disabled
- 3GPP References: TS 38.331, TS 38.212, TS 38.213, TS 38.314, TS 38.321

7.4.1 MODULATION AND CODING SCHEME

- The Modulation and Coding Scheme (MCS) is allocated by the Link Adaptation algorithm within the Base Station. The allocated MCS is signalled to the UE on the PDCCH using DCI Format 0_0 or 0_1
- 3GPP has specified 5 MCS tables for the PUSCH (summarised in Table 197). The first 3 tables are shared with the PDSCH, while the last 2 tables are only used by the PUSCH. Only a single table includes the 256QAM modulation scheme. This table can be used either with, or without Transform Precoding. The last 2 tables can only be used with Transform Precoding. 3GPP has specified MCS tables 3 and 5 for applications and which require lower coding rates for reliable data transfer, e.g. applications belonging to the Ultra Reliable Low Latency Communications (URLLC) category. These tables include entries which have low Spectral Efficiency (SE), i.e. a reduced coding rate which corresponds to increased channel coding redundancy

	MCS Table 1	MCS Table 2	MCS Table 3	MCS Table 4	MCS Table 5
	64QAM	256QAM	Low SE	64QAM Transform Precoding	Low SE Transform Precoding
Shared with PDSCH	Yes	Yes	Yes	No	No
256QAM Supported	No	Yes	No	No	No
π/2 BPSK Supported	No	No	No	Yes	Yes
Used with Transform Precoding	No	Yes or No	No	Yes	Yes
Minimum Spectral Efficiency	0.2344	0.2344	0.0586	0.2344	0.0586
Maximum Spectral Efficiency	5.5547	7.4063	4.5234	5.5547	4.5234

Table 197 – Summary of MCS tables available to the PUSCH

- MCS Tables 1 to 3 are presented within Table 91 (Section 3.6.1). MCS Tables 4 and 5 are presented within Table 198
- The lower MCS indices within Tables 4 and 5 have a dependency upon the variable 'q'. The value of 'q' determines whether the modulation scheme is π/2 BPSK or QPSK. The value of 'q' is set to 1 and π/2 BPSK is used if the *tp-pi2BPSK* information element is included within the *PUSCH-Config* parameter structure. Otherwise the value of 'q' is set to 2 and QPSK is used. The value of 'q' impacts the coding rate because it is assumed that the same packet size is transferred for both values of 'q'. Increasing the modulation order by setting q = 2 increases the capacity of the air-interface and so decreases the coding rate. The Spectral Efficiency does not depend upon the value of 'q' because the same number of bits are transferred for both values of 'q'
- The 'Spectral Efficiency' is calculated as the product of the 'Modulation Order' and the 'Target Code Rate'. The Spectral Efficiency increases with MCS. This corresponds to larger transport block sizes and transferring more information bits across the air-interface. This Spectral Efficiency does not account for the number of MIMO layers, i.e. it represents the Spectral Efficiency per layer

MCS Index Table 4 64QAM Transform Precoding			
MCS Index	Modulation Order	Target Code Rate	Spectral Efficiency
0	'q' = 1 or 2	0.234 / q	0.2344
1	'q' = 1 or 2	0.307 / q	0.3066
2	2 (QPSK)	0.188	0.3770
3	2 (QPSK)	0.245	0.4902
4	2 (QPSK)	0.301	0.6016
5	2 (QPSK)	0.370	0.7402
6	2 (QPSK)	0.438	0.8770
7	2 (QPSK)	0.514	1.0273
8	2 (QPSK)	0.588	1.1758
9	2 (QPSK)	0.663	1.3262
10	4 (16QAM)	0.332	1.3281
11	4 (16QAM)	0.369	1.4766
12	4 (16QAM)	0.424	1.6953
13	4 (16QAM)	0.479	1.9141
14	4 (16QAM)	0.540	2.1602
15	4 (16QAM)	0.602	2.4063
16	4 (16QAM)	0.643	2.5703
17	6 (64QAM)	0.455	2.7305
18	6 (64QAM)	0.505	3.0293
19	6 (64QAM)	0.554	3.3223
20	6 (64QAM)	0.602	3.6094
21	6 (64QAM)	0.650	3.9023
22	6 (64QAM)	0.702	4.2129
23	6 (64QAM)	0.754	4.5234
24	6 (64QAM)	0.803	4.8164
25	6 (64QAM)	0.853	5.1152
26	6 (64QAM)	0.889	5.3320
27	6 (64QAM)	0.926	5.5547
28	'q'	Reserved	
29	2 (QPSK)	Reserved	
30	4 (16QAM)	Reserved	
31	6 (64QAM)	Reserved	

MCS Index Table 5 Low Spectral Efficiency Transform Precoding			
MCS Index	Modulation Order	Target Code Rate	Spectral Efficiency
0	'q' = 1 or 2	0.059 / q	0.0586
1	'q' = 1 or 2	0.078 / q	0.0781
2	'q' = 1 or 2	0.098 / q	0.0977
3	'q' = 1 or 2	0.125 / q	0.1250
4	'q' = 1 or 2	0.152 / q	0.1523
5	'q' = 1 or 2	0.193 / q	0.1934
6	2 (QPSK)	0.117	0.2344
7	2 (QPSK)	0.153	0.3066
8	2 (QPSK)	0.188	0.3770
9	2 (QPSK)	0.245	0.4902
10	2 (QPSK)	0.301	0.6016
11	2 (QPSK)	0.370	0.7402
12	2 (QPSK)	0.438	0.8770
13	2 (QPSK)	0.514	1.0273
14	2 (QPSK)	0.588	1.1758
15	2 (QPSK)	0.663	1.3262
16	4 (16QAM)	0.369	1.4766
17	4 (16QAM)	0.424	1.6953
18	4 (16QAM)	0.479	1.9141
19	4 (16QAM)	0.540	2.1602
20	4 (16QAM)	0.602	2.4063
21	4 (16QAM)	0.643	2.5703
22	4 (16QAM)	0.683	2.7305
23	4 (16QAM)	0.754	3.0156
24	6 (64QAM)	0.554	3.3223
25	6 (64QAM)	0.602	3.6094
26	6 (64QAM)	0.650	3.9023
27	6 (64QAM)	0.754	4.5234
28	'q'	Reserved	
29	2 (QPSK)	Reserved	
30	4 (16QAM)	Reserved	
31	6 (64QAM)	Reserved	

Table 198 – Additional MCS Tables for the PUSCH

★ The highest MCS values within each table are associated with specific modulation schemes but are shown as 'Reserved'. These MCS values are used for re-transmissions. For example, a UE being requested to complete a re-transmission using 16QAM within the 64QAM table will be allocated MCS 30

★ The Base Station instructs the UE to select a specific MCS table using a combination of RRC signalling and Physical layer signalling. RRC signalling is used to configure the *mcs-Table* and *mcs-TableTransformPrecoder* information elements within the *PUSCH-Config* (Table 196) and *configuredGrantConfig* (Table 210) parameter structures. This corresponds to a semi-static configuration which requires further RRC signalling for modification. Physical layer signalling uses a dynamic selection of the RNTI which scrambles the CRC bits belonging to the PDCCH payload, e.g. switching between the C-RNTI and MCS-C-RNTI can influence the selection of the MCS table. The decision process for selecting the appropriate MCS table is presented in Figure 267

★ The *mcs-Table* and *mcs-TableTransformPrecoder* information elements can be configured with values of 'qam256' or 'qam64LowSE'. These information elements can be excluded to indicate the use of a 64QAM MCS table

★ If dynamic grants are allocated, Transform Precoding is enabled or disabled using the *transformPrecoder* information element within the *PUSCH-Config* parameter structure (Table 196). Similarly, if Configured Grants are allocated then Transform Precoding is enabled or disabled using the *transformPrecoder* information element within the *configuredGrantConfig* parameter structure (Table 210)

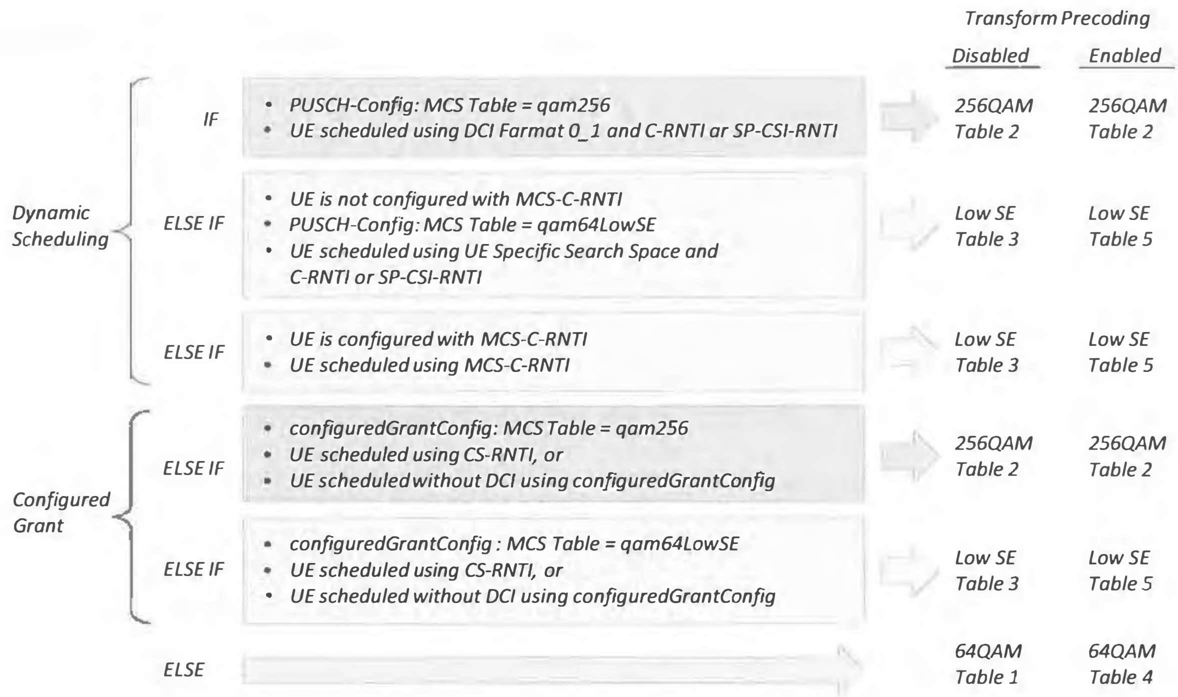


Figure 267 – MCS Table selection for the PUSCH

7.4.2 TRANSPORT BLOCK SIZE

★ A transport block is a packet of data which is passed between the MAC and physical layers. It is passed downwards at the transmitter and upwards at the receiver. A transport block undergoes physical layer processing at the transmitter before being mapped onto the PUSCH for transfer across the air-interface

★ A UE must determine the transport block size after receiving an uplink resource allocation. The Base Station must determine the same transport block size when attempting to decode the received data

★ The process used to determine the transport block size for the PUSCH is the same as the equivalent process for the PDSCH (described in section 3.6.2). The process starts by quantifying the number of Resource Elements which are available for data transfer within the bandwidth of a single Resource Block. 3GPP TS 38.214 specifies the following equation for this purpose:

$$N'_{RE} = 12 \times N^{sh}_{symb} - N^{PRB}_{DMRS} - N^{PRB}_{oh}$$

★ N^{PRB}_{oh} represents any additional overhead which reduces the number of Resource Elements available for data transfer, e.g. the Phase Tracking Reference Signal (PTRS). In the case of the PUSCH, the value of N^{PRB}_{oh} is provided using the *xOverhead* information element within the *PUSCH-ServingCellConfig* parameter structure shown in Table 199. The UE assumes an overhead of 0 if the Base Station does not configure this information element. A value of 0 is always assumed when transmitting MSG3

★ N^{sh}_{symb} is the number of symbols within the slot which have been allocated to the UE

★ N^{PRB}_{DMRS} is the number of Resource Elements per Resource Block which are allocated to the Demodulation Reference Signal (DMRS). This includes the overhead of Resource Elements within DMRS symbols which are unavailable for data transfer due to DMRS transmissions on other antenna ports, multi-user MIMO or Transform Precoding

PUSCH-ServingCellConfig		
CodeBlockGroupTransmission	maxCodeBlockGroupsPerTransportBlock	n2, n4, n6, n8
rateMatching	limitedBufferRM	
xOverhead	xoh6, xoh12, xoh18	

Table 199 – PUSCH-ServingCellConfig parameter structure

★ The remainder of the process is described in section 3.6.2

★ 3GPP References: TS 38.214, TS 38.331

7.4.3 PHYSICAL LAYER PROCESSING

★ The Physical layer processes a single Transport Block for each resource allocation. In the uplink direction, a maximum of 4 layers can be generated for MIMO. These 4 layers are generated from a single Transport Block rather than from multiple Transport Blocks. This approach can reduce the requirement for HARQ feedback, i.e. a single HARQ acknowledgement can be used for each Transport Block. However, in this case a negative HARQ acknowledgement leads to the re-transmission of a relatively large block of data. Code Block Groups (CBG) can be configured to allow HARQ acknowledgements and re-transmissions to operate on groups of Transport Block segments rather than complete Transport Blocks. Code Block Groups are described in section 13.5

★ This section describes the Physical layer processing for the PUSCH in two parts. The first part (illustrated in Figure 268) is based upon the multiplexing and channel coding specified within 3GPP TS 38.212. The second part (illustrated in Figure 275) is based upon the subsequent physical channel processing and modulation specified within 3GPP TS 38.211

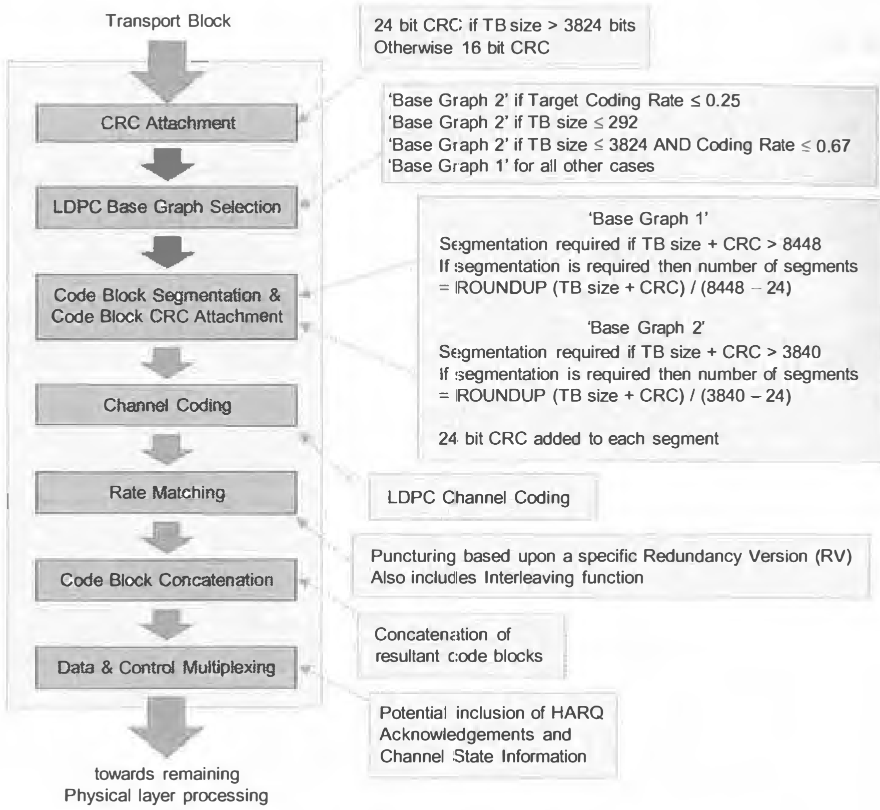


Figure 268 – Physical layer processing for the PUSCH (part 1)

★ Cyclic Redundancy Check (CRC) bits are attached to provide an error detection capability at the Base Station. They do not provide an error correction capability. The Base Station uses the CRC bits to determine whether or not the received Transport Block includes any bit errors. A negative HARQ acknowledgement is returned if any errors are detected. For a specific number of CRC bits, the probability of an undetected error increases as the Transport Block size increases. This provides the justification for using a larger set of CRC bits for larger Transport Block sizes. The PUSCH uses a 24 bit CRC for Transport Block sizes > 3824 bits, and a 16 bit CRC for Transport Block sizes ≤ 3824 bits. In contrast, the 4G PUSCH always uses a 24 bit CRC

★ The Physical layer then completes 'Base Graph' selection for the Low Density Parity Check (LDPC) channel coding. This selection is necessary prior to the channel coding itself because it determines the maximum code block size and thus impacts the requirement for segmentation. The maximum code block size is the maximum number of bits which the channel coding algorithm can accept. Blocks of data larger than this upper limit must be segmented before channel coding. Channel coding is then applied individually to each segment. Restricting the code block size handled by the channel coding algorithm helps to limit the encoding complexity at the UE

★ 'Base Graph' selection uses a combination of coding rate and Transport Block size thresholds. These thresholds are illustrated in Figure 269. Base Graph 2 is selected if the target coding rate is less than 0.25, or if the transport block size is less than 292 bits, or if the transport block size is less than 3824 bits AND the target coding rate is less than 0.67. Otherwise, Base Graph 1 is selected

★ The combination of Transport Block and CRC bits is then segmented if necessary. When segmentation is required, additional sets of CRC bits are attached to each segment. This allows the Base Station to complete error detection for each individual segment. Each additional CRC has a length of 24 bits. Base Graph 1 supports a maximum code block size of 8448 bits, whereas Base Graph 2 supports a maximum code block size of 3840 bits. If the Transport Block and CRC is less than the maximum code block size then segmentation is not required. If segmentation is required then the number of segments is given by ROUNDUP [(Transport Block size

+ CRC) / (maximum code block size – 24)]. The value of 24 is subtracted from the maximum code block size to provide capacity for the additional CRC to be added after segmentation

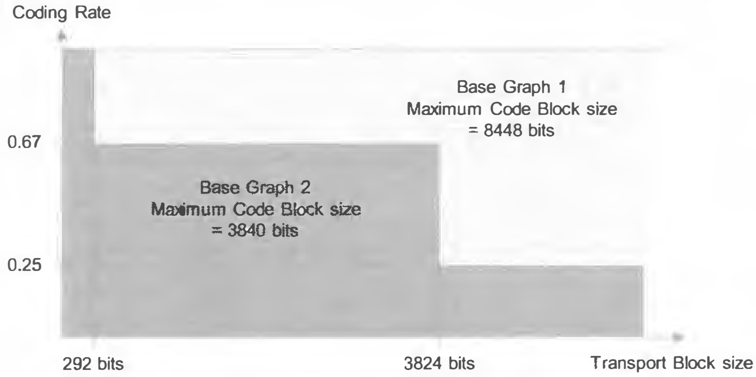


Figure 269 – Base Graph selection for LDPC channel coding

★ The code block segmentation phase is also responsible for ensuring that each code block has an appropriate number of bits for channel coding, i.e. in addition to requiring that the maximum code block size is not exceeded, channel coding also requires that code blocks have specific sizes. This may require the addition of filler bits, which are flagged as being 'NULL' entries. These 'NULL' entries are subsequently removed after channel coding. At the start of this operation, a variable K' is set equal to the segment size

- o if segmentation has not been required then there is a single segment which has a size equal to (Transport Block size + CRC size).
- o if segmentation has been required then each segment has a size equal to [(Transport Block size + CRC size) / Number of Segments] + Additional CRC size of 24

★ A table of 'Lifting Sizes' are used to identify an allowed code block size. These 'Lifting Sizes' are used during the channel coding process to increase the dimensions of the parity check matrix. The table of 'Lifting Sizes' is presented as Table 200. At this stage, the rows are not differentiated and all 'Lifting Sizes' within the table are considered to belong to a single group

LDPC Lifting Set Index	Set of Lifting Sizes (Z)	LDPC Lifting Set Index	Set of Lifting Sizes (Z)
0	2, 4, 8, 16, 32, 64, 128, 256	4	9, 18, 36, 72, 144, 288
1	3, 6, 12, 24, 48, 96, 192, 384	5	11, 22, 44, 88, 176, 352
2	5, 10, 20, 40, 80, 160, 320	6	13, 26, 52, 104, 208
3	7, 14, 28, 56, 112, 224	7	15, 30, 60, 120, 240

Table 200 – Sets of Lifting Sizes for LDPC channel coding

★ If Base Graph 1 has been selected then the minimum Lifting Size (Z) which satisfies: $22 \times Z \geq K'$, is selected. The final code block size is then set equal to $22 \times Z$

★ If Base Graph 2 has been selected then the minimum Lifting Size (Z) which satisfies: $K_b \times Z \geq K'$ is selected. The final code block size is then set equal to $10 \times Z$. The value of K_b depends upon (Transport Block size + CRC size). If greater than 640 bits then $K_b = 10$, else if greater than 560 bits then $K_b = 9$, else if greater than 192 bits then then $K_b = 8$, else $K_b = 6$

★ The code block segmentation stage is complete once the 'NULL' entries have been added to generate a code block size which can be processed by the channel coding stage. Figure 270 summarises the code block segmentation stage

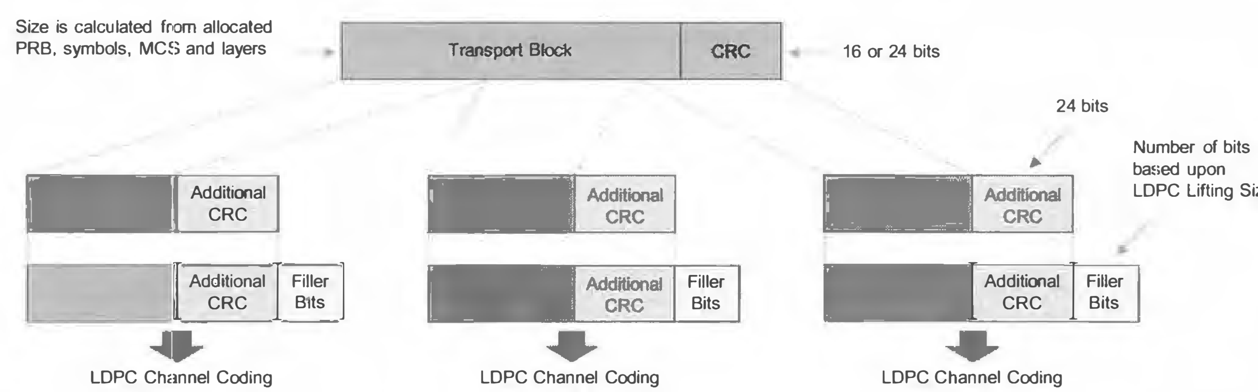


Figure 270 – Code Block segmentation and Code Block CRC attachment

★ 3GPP selected Low Density Parity Check (LDPC) coding for the PUSCH. This was selected as an alternative to Turbo coding which has been used for the PUSCH in 4G and HSUPA in 3G. LDPC channel coding is characterised by its sparse parity check matrix. This means that the matrix used to generate the set of parity bits has a relatively small number of '1's, i.e. it has a Low Density of 1's. This Low Density characteristic helps to reduce the complexity of both encoding and decoding. Reduced complexity translates to lower power consumption and a smaller area of silicon. The LDPC solution selected by 3GPP is scalable to support a wide range of code block sizes and a wide range of coding rates. LDPC and Turbo coding offer similar performance in terms of their error correction capabilities

★ The principle of the LDPC channel coding used for the PUSCH is illustrated in Figure 271. The 'Base Graph' defines a matrix which has dimensions of 46 rows × 68 columns when using Base Graph 1, and 42 rows × 52 columns when using Base Graph 2. This matrix is expanded by a factor equal to the selected 'Lifting Size' (Z). Each '0' within the Base Graph is replaced by a Z × Z matrix of '0's. Each '1' within the Base Graph is replaced by a circularly shifted Z × Z identity matrix. This leads to a Parity Check matrix which has dimensions of 46Z rows × 68Z columns when using Base Graph 1, and 42Z rows × 52Z columns when using Base Graph 2

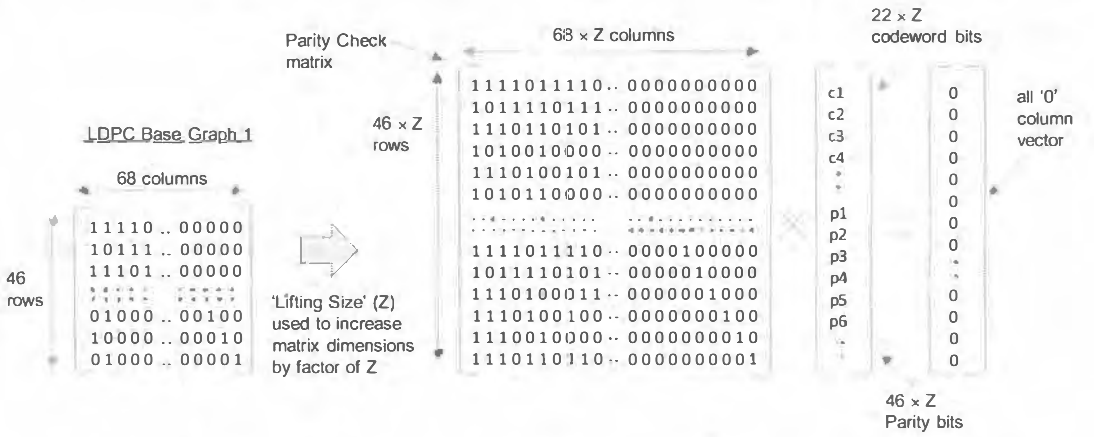


Figure 271 – Low Density Parity Check matrix used to generate Parity bits (shown for Base Graph 1)

★ The parity bits are calculated such that the product of the Parity Check matrix with the codeword/parity bit vector generates an all '0' vector. Any codeword bits which were previously flagged as 'NULL' are translated into '0's for the purposes of calculating the parity bits. However, these codeword bits remain flagged as 'NULL' within the output codeword/parity bit vector

★ In the case of Base Graph 1, there are 22Z codeword bits so 46Z parity bits are generated (the sum must equal the number of columns within the Parity Check matrix). In the case of Base Graph 2, there are 10Z codeword bits so 42Z parity bits are generated

★ When using Base Graph 1, the output from the channel coding has 66Z bits after providing an input of 22Z bits, i.e. a coding rate of 0.33. It should be noted that the codeword/parity bit vector has a length of 68Z bits. The first 2Z bits from the codeword are punctured to reduce the size to 66Z bits

★ When using Base Graph 2, the output from the channel coding has 50Z bits after providing an input of 10Z bits, i.e. a coding rate of 0.20. Similar to Base Graph 1, the first 2Z bits from the codeword are punctured to reduce the length of the codeword/parity bit vector from 52Z to 50Z

★ The output from Channel Coding is forwarded to the Rate Matching function. The Rate Matching function processes each channel coded segment separately. Rate Matching is completed in 2 stages: Bit Selection and Bit Interleaving. Bit Selection reduces the number of channel coded bits to match the capacity of the allocated air-interface resources. Bit Interleaving re-orders the bit sequence

★ Bit Selection starts by writing the set of 'N' bits belonging to a specific channel coded segment into a circular buffer. The size of the circular buffer can have a dependency upon the UE capability. 3GPP has specified the concept of Limited Buffer Rate Matching (LBRM) to cater for devices which have a limited capacity for buffering large code blocks. LBRM helps to reduce the cost of the device by reducing the requirement for memory. The drawback is a potentially reduced performance when transferring large code blocks. LBRM does not impact performance when transferring smaller code blocks, i.e. these code blocks can be fully accommodated by the circular buffer

★ A UE signals its capability in terms of LBRM using the *pusch-LBRM* information element shown in Table 201. If the UE supports LBRM, the Base Station can provide the instruction to use LBRM within the *PUSCH-ServingCellConfig* shown in Table 202. If LBRM is not used, the circular buffer has a size given by, $N_{cb} = 'N'$, i.e. the circular buffer accommodates all bits from the channel coding. If LBRM is used then the circular buffer has a potentially reduced size given by, $N_{cb} = \min(N, N_{ref})$, where N_{ref} = ROUND DOWN [TB_Size_{LBRM} / ($Number\_of\_Segments_{LBRM}$ × 0.67)]. TB_Size_{LBRM} and $Number\_of\_Segments_{LBRM}$ are calculated assuming a maximum number of layers, a maximum modulation order, a maximum coding rate and a maximum Resource Block allocation

Phy-ParametersFRX-Diff	
pusch-LBRM	supported

Table 201 – *pusch-LBRM* information element within the *Phy-ParametersFRX-Diff* parameter structure

PUSCH-ServingCellConfig		
codeBlockGroupTransmissions	SetupRelease { PUSCH-CodeBlockGroupTransmission }	
	maxCodeBlockGroupsPerTransportBlock	n2, n4, n6, n8
rateMatching	limitedBufferRM	
xOverhead	xoh6, xoh12, xoh18	

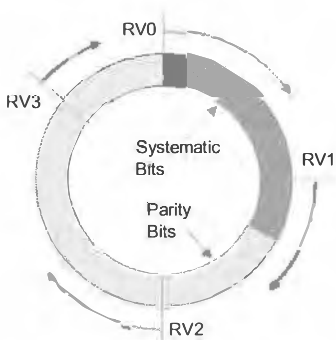
Table 202 – *rateMatching* information element within the *PUSCH-ServingCellConfig* parameter structure

★ If the circular buffer size is limited by 'N_{ref}' then only a subset of the channel coded bits are written into the circular buffer. The bits which are excluded are never transmitted across the air-interface. This reduces the scope for gains from HARQ incremental redundancy

★ Figure 272 illustrates the concept of the circular buffer. The Systematic Bits are written into the buffer first, followed by the Parity Bits. Systematic Bits correspond to the original codeword prior to channel coding, whereas Parity Bits correspond to the additional bits generated by channel coding. Transferring large codewords while using LBRM leads to the exclusion of the last section of Parity Bits

★ The Bit Selection process extracts a subset of bits from the circular buffer using a specific starting position. The starting position depends upon the Redundancy Version (RV). In the case of dynamic resource allocations, the Redundancy Version is indicated within the Downlink Control Information (DCI). In the case of Configured Grants, Redundancy Version patterns can be specified for autonomous transmission repetitions. These patterns are specified using the *repK-RV* information element presented in Table 210

★ 3GPP TS 38.212 specifies the starting position for each Redundancy Version, as presented in Figure 272. RV0, RV1 and RV2 have starting positions which are 0, 25 and 50 % around the circular buffer. RV3 has a starting position which is ~85 % around the circular buffer. The starting position for RV3 has been moved towards the starting position for RV0 to increase the number of Systematic Bits which are captured by an RV3 transmission. This approach has been adopted to allow 'self-decoding' when either RV0 or RV3 is transmitted, i.e. the receiver can decode the original transport block after receiving only a single standalone transmission of RV0 or RV3. RV1 and RV2 do not allow 'self-decoding'. These RV require another transmission using a different RV to allow decoding of the transport block



Redundancy Version (RV)	Starting Positions for reading bits out of buffer: Base Graph 1	Base Graph 2
0	0	0
1	$\left\lfloor \frac{17N_{cb}}{66Z} \right\rfloor \times Z$	$\left\lfloor \frac{13N_{cb}}{50Z} \right\rfloor \times Z$
2	$\left\lfloor \frac{33N_{cb}}{66Z} \right\rfloor \times Z$	$\left\lfloor \frac{25N_{cb}}{50Z} \right\rfloor \times Z$
3	$\left\lfloor \frac{56N_{cb}}{66Z} \right\rfloor \times Z$	$\left\lfloor \frac{43N_{cb}}{50Z} \right\rfloor \times Z$

Figure 272 – Reading bits from circular buffer using Redundancy Versions (RV)

★ The bits transmitted by each Redundancy Version will overlap to some extent, e.g. the bits extracted using RV0 will pass the starting position for RV1. The number of bits which are extracted depends upon the quantity of allocated Resource Elements, the modulation scheme and the number of layers. The 'NULL' entries which were added during code block segmentation remain present within the circular buffer but these entries are now skipped when extracting the set of bits for transmission

★ Bit Interleaving is applied once the set of bits have been extracted from the circular buffer. Bit Interleaving involves the stream of bits being read into a table row-by-row, and then being read out of the table column-by-column. The number of rows belonging to the table is set equal to the modulation order. This means that each column corresponds to a single modulation symbol. The concept of interleaving is illustrated in Figure 273

Data read in row-by-row

1, 2, 3, 4, 5, 6, 7, 8,...

1	2	3	4	5	6	7	8	9	10
11	12	13	14	15	16	17	18	19	20
21	22	23	24	25	26	27	28	29	30
31	32	33	34	35	36	37	38	39	40

Number of rows is equal to the modulation order, i.e. each column maps onto a single modulation symbol

Data read out column-by-column

1, 11, 21, 31, 2, 12, 22, 32, 3, 13, 23, ...

Figure 273 – Row-In Column-Out table used for Bit Interleaving

★ Interleaving helps to avoid bursts of contiguous bit errors at the input of the channel decoder at the receiver. The performance of the decoder is improved when bit errors are distributed at random rather than in contiguous groups. Figure 274 illustrates an example of a single modulation symbol being received in error due to the fading channel conditions. This example is based upon 16QAM so there are 4 bits associated with the modulation symbol. It is possible that there is only a single bit error when this modulation symbol is received in error. Gray coding is used to ensure that there is only a single bit error when a modulation symbol is mis-detected as a neighbouring modulation symbol. The concept of Gray coding for 16QAM is illustrated in Figure 124 (section 2.7). However, for the purposes of this example, it is assumed that the modulation symbol is completely mis-detected and all 4 bits are received in error. Figure 274 illustrates that after de-interleaving at the receiver, the set of 4 bit errors are distributed across the code block. This helps to improve the error correction capability of the LDPC decoder

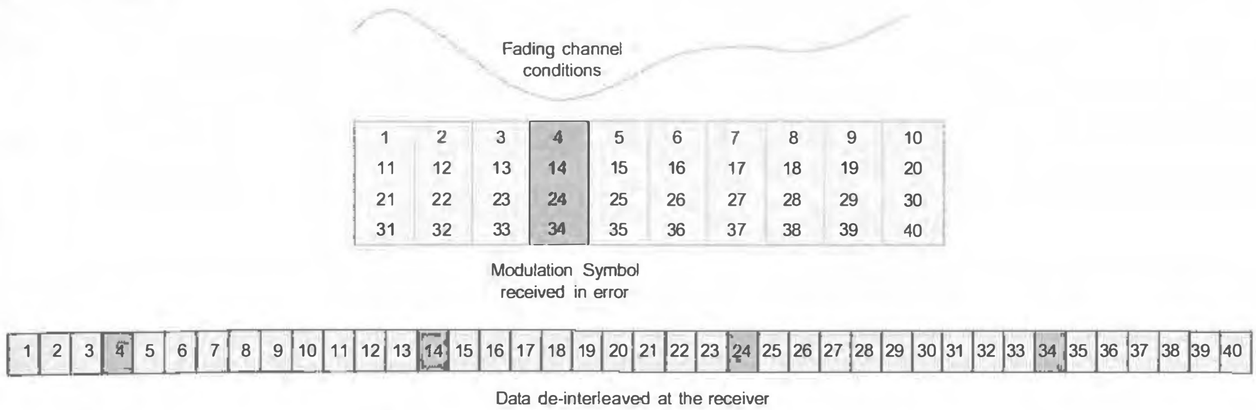


Figure 274 – Distribution of bit errors after de-interleaving

★ Code Block Concatenation is applied after Rate Matching. This simply involves concatenating the set of code blocks into a single larger code block

★ The final stage illustrated in Figure 268 involves the multiplexing of uplink data with Uplink Control Information (UCI). This stage is not required if there is no UCI to transfer. Within the context of the PUSCH, UCI refers to HARQ Acknowledgements and Channel State Information(CSI) reports. It is also possible that UCI is transferred by the PUSCH without any data.

★ The UCI undergoes its own Physical layer processing before being multiplexed with the data. UCI payloads of less than 12 bits do not have a CRC attached before channel coding. Coding which maximises Euclidean distance is applied to UCI payloads of 1 or 2 bits. Reed-Muller Block coding is used for UCI payloads from 3 to 11 bits. This coding increases the number of bits to 32. UCI payloads ranging from 12 to 19 bits have a 6 bit CRC added before Polar channel coding. UCI payloads of 20 bits or more have an 11 bit CRC added before Polar channel coding

★ When multiplexing the data and UCI on the PUSCH, the UCI is placed within specific symbols. HARQ acknowledgements are treated as having the highest priority and are placed immediately after the first DMRS symbol. Placing the HARQ acknowledgements close to a DMRS symbol helps to ensure that the channel estimate derived from the DMRS is valid for the HARQ acknowledgements. CSI reports are placed in the first allocated PUSCH symbols which do not include the DMRS

★ The second part of the Physical layer processing for the PUSCH is illustrated in Figure 275. This part is based upon procedures specified by 3GPP TS 38.211

★ The scrambling operation does not change the order of the bits. Instead, it switches some of the '1's into '0's and some of the '0's into '1's. The switching is done using a modular 2 summation between the original bit stream and a pseudo random sequence. A '1' in the pseudo random sequence causes the corresponding bit to switch, whereas a '0' leaves the bit with its original value. The objective of scrambling is to randomise the bit sequence and thus randomise the interference generated by the PUSCH. Interference has less impact when it is randomised and appears closer to white noise

★ The scrambling operation makes an exception for 2 special types of bit. These special types of bit are introduced when channel coding 1 or 2 bits of Uplink Control Information (UCI), i.e. 1 or 2 HARQ acknowledgements have been multiplexed onto the PUSCH. They are referenced as 'x' and 'y' placeholder bits within 3GPP TS 38.211 and TS 38.212. These bits are carefully set to maximise the Euclidean distance to neighbouring symbols. Maximising the Euclidean distance helps to improve the decoding performance. Scrambling would randomise the bits and thus the Euclidean distance would no longer be maximised

★ The pseudo random sequence used to complete the scrambling procedure is initialised using the *dataScramblingIdentityPUSCH* if it has been configured, and the UE has been addressed using a C-RNTI, MCS-C-RNTI or CS-RNTI, and the resource allocation was not provided using DCI Format 0_0 in a Common Search Space. Otherwise, the pseudo random sequence is initialised using the PCI. The *dataScramblingIdentityPUSCH* belongs to the *PUSCH-Config* parameter structure presented in Table 196

★ Modulation changes the bit sequence ('1's and '0's) into a modulation symbol sequence (complex numbers representing the set of modulation symbols). $\pi/2$ BPSK maps 1 bit onto each modulation symbol. This modulation scheme is only available when Transform Precoding is applied to generate the DFT-S-OFDM waveform. QPSK maps 2 bits onto each modulation symbol; 16QAM maps 4 bits onto each modulation symbol; 64QAM maps 6 bits onto each modulation symbol; and 256QAM maps 8 bits onto each modulation symbol. The appropriate modulation scheme is identified by selecting a row within a specific MCS table. The row is selected using the

MCS field within DCI Format 0_0 or 0_1. The MCS table is selected using a combination of RRC configuration information and the type of RNTI used to address the UE when providing the resource allocation. Modulation is described in section 2.7 while the MCS tables are presented in section 7.4.1

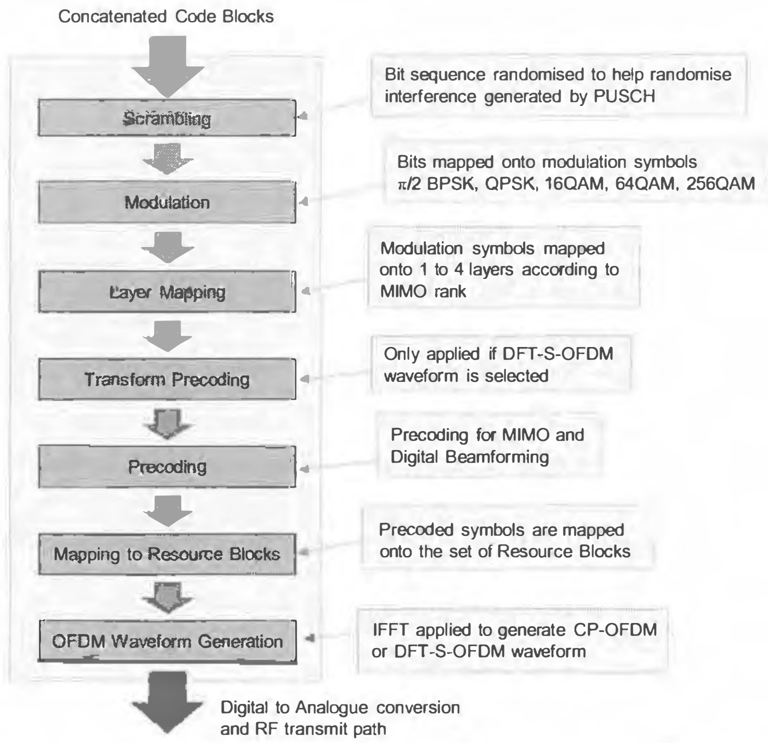


Figure 275 – Physical layer processing for the PUSCH (part 2)

★ Layer mapping is used to distribute the set of modulation symbols across the layers which are used for MIMO. If the resource allocation has been provided using DCI Format 0_0 then there is only a single transmission layer and layer mapping is not required. In contrast, DCI Format 0_1 uses the 'Precoding Information & Number of Layers' field to allocate between 1 and 4 MIMO layers. The layer mapping procedure is illustrated in Figure 276. The procedure distributes the stream of modulation symbols across the layers in a round robin fashion

★ The use of 1 to 4 layers requires a single codeword as an input, i.e. the Physical layer processes a single Transport Block. In the case of 4G, 3GPP release 8 supports only single layer transmission in the uplink direction. 3GPP release 10 requires 4G to process 2 codewords when generating more than 2 layers. The number of codewords determines the trade-off between the HARQ acknowledgement signalling load and the volume of data which must be re-transmitted when a codeword is received in error. For example, if 2 codewords are used to generate 4 layers then the receiver must return 2 HARQ acknowledgements (ignoring the use of Code Block Groups). If there is a single bit error then it is necessary to re-transmit only 1 of the codewords. Alternatively, a single large codeword could be used to generate the same 4 layers and in this case, the receiver only has to return 1 HARQ acknowledgement. But a single bit error means that the whole of the larger codeword must be re-transmitted. The use of Code Block Groups (described in section 13.5) moves this trade-off in the direction of using only a single codeword because groups of codeword segments can be re-transmitted rather than whole codewords. But HARQ acknowledgements must be sent for each group of segments so there is an impact upon the HARQ signalling overhead

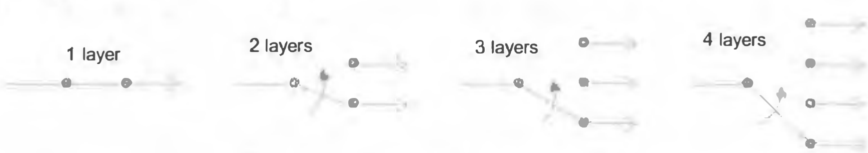


Figure 276 – Layer Mapping for the PUSCH

★ In the case of Dynamic Grants provided by DCI Format 0_0, the Base Station can enable/disable Transform Precoding using the *msg3-transformPrecoder* information element within the *RACH-ConfigCommon*

★ In the case of Dynamic Grants provided by DCI Format 0_1, the Base Station can enable/disable Transform Precoding using the *transformPrecoder* information element within the *PUSCH-Config*. If this information element is not provided to the UE, *msg3-transformPrecoder* within the *RACH-ConfigCommon* is used to enable/disable Transform Precoding

★ In the case of Configured Grants, the Base Station can enable/disable Transform Precoding using the *transformPrecoder* information element within the *ConfiguredGrantConfig*. If this information element is not provided to the UE, *msg3-transformPrecoder* within *RACH-ConfigCommon* is used to enable/disable Transform Precoding

- The inclusion of Transform Precoding means that the UE generates a DFT-S-OFDM waveform rather than a CP-OFDM waveform. DFT-S-OFDM has a lower Peak-to-Average Power Ratio (PAPR) than CP-OFDM. This allows the UE to transmit with a higher average power and so improves the uplink coverage performance. 3GPP has specified that DFT-S-OFDM only supports single stream transmission, i.e. MIMO is not supported. This means that CP-OFDM offers improved throughputs and capacity, while DFT-S-OFDM offers improved coverage
- The optional Transform Precoding stage is followed by an optional Precoding stage. Inclusion of the Precoding stage depends upon the uplink Transmission Scheme and the UE implementation (uplink Transmission Schemes and their Precoding are described in section 8). 'Codebook Based' transmission allows the Base Station to instruct the UE to apply specific precoding matrices standardised by 3GPP. These instructions are based upon uplink measurements from the Sounding Reference Signal (SRS). 'Non-Codebook Based' transmission does not involve the use of precoding matrices standardised by 3GPP. However, the UE can generate its own precoding matrices based upon downlink measurements from the CSI Reference Signal
- The precoded modulation symbols are mapped onto the Resource Elements which belong to the allocated Virtual Resource Blocks within each of the allocated symbols. In the uplink direction, the set of Virtual Resource Blocks are mapped onto the set of Physical Resource Blocks using a non-interleaved mapping, i.e. VRB 'n' is mapped onto PRB 'n'
- The set of Physical Resource Blocks are then used to generate the CP-OFDM or DFT-S-OFDM waveform. Each column of Resource Elements generates a single symbol. The process used to generate the waveform is described in section 2.9
- 3GPP References: TS 38.211, TS 38.212, TS 38.214

7.4.4 RESOURCE ALLOCATIONS

- There are 2 categories of resource allocation in the uplink:
  - Dynamic allocations: which rely upon a PDCCH transmission prior to every PUSCH transmission. The PDCCH transfers Downlink Control Information (DCI) Format 0_0 or 0_1 to specify the allocated resources. The resources can be changed with every transmission so dynamic allocations are very adaptive to the current radio conditions, user requirements and network load. Dynamic allocations have the drawback of increased PDCCH signalling load which creates a system overhead. There are two general categories of dynamic resource allocations:
    - allocations requested by the UE via a Scheduling Request (SR), a Buffer Status Report (BSR) or a Random Access procedure. This approach tends to generate higher latency because the UE may have to wait before being permitted to request the uplink resources, e.g. wait for the start of the next Scheduling Request period, or wait for the next PRACH occasion
    - allocations provided by the Base Station in a proactive manner. In this case, the Base Station provides uplink resource allocations without relying upon a request from the UE. This helps to ensure that uplink resources are available as soon as the UE has uplink data to transfer. This category of resource allocation depends upon the Base Station implementation. The Packet Scheduler typically assigns a low priority to proactive grants so they may be allocated on a best-effort basis. Proactive grants can increase uplink interference levels unless 'skipping' is enabled. This results from UE transmitting packets of padding after receiving a proactive grant while the uplink buffer is empty
  - Configured Grant allocations: which do not require a PDCCH transmission prior to every PUSCH transmission (PDCCH transmissions are still used to request re-transmissions). There are 2 types of Configured Grant allocations:
    - Type 1: the resource allocation is fully configured and released using RRC signalling. Once configured, the UE has a set of periodic opportunities for PUSCH transmission. The PDCCH is only required when requesting a re-transmission. Type 1 resource allocations are intended for applications with longer term requirements because configuration and release is completed at layer 3, i.e. it is relatively slow. For example, Internet of Things (IoT) devices could be provided with a long term resource allocation so small volumes of sporadic uplink data can be transferred without requiring a Scheduling Request nor a subsequent PDCCH resource allocation. Multiple devices can share the same resource allocation when configured with different Demodulation Reference Signal (DMRS) patterns, i.e. the DMRS is used to identify the UE. The probability of collision depends upon the number of devices sharing the resource allocation and the activity factor of those devices
    - Type 2: the resource allocation is partially configured using RRC signalling but is subsequently activated and deactivated using PDCCH transmissions. The PDCCH provides the time and frequency resource allocation so this can change with each activation. Once activated, the UE has a set of periodic opportunities for PUSCH transmission. Type 2 resource allocations can be used for applications which require rapid activation/deactivation. For example, a voice service could use the PDCCH to activate a periodic resource allocation while a user is speaking and then deactivate those resources when the user is listening
- Both the Dynamic and Configured Grant categories use the time and frequency domain resource allocations described within the following sub-sections. These resource allocations are either included within the DCI on the PDCCH, or in the case of Type 1 Configured Grants, provided by RRC signalling. The DCI content transferred using the PDCCH is presented within sections 3.5.4 and 3.5.5. Configured Grants are further described within section 7.4.4.3

7.4.4.1 TIME DOMAIN RESOURCE ALLOCATION

★ Time domain resources can be allocated for the PUSCH using Downlink Control Information (DCI) Formats 0_0 and 0_1. DCI is transferred to the UE using the PDCCH physical channel. Alternatively, in the case of Type 1 Configured Grants, time domain resources are allocated for the PUSCH using RRC signalling

★ The '*Time Domain Resource Assignment*' field within the DCI defines a pointer towards a row within a look-up table. Similarly, the '*timeDomainAllocation*' information element within the RRC signalling protocol defines a pointer towards a row within a look-up table. The look-up table includes up to 16 rows and defines the slot offset (K_2), the PUSCH Mapping Type, the starting symbol and the number of allocated symbols (the length)

★ There is a choice of 3 look-up tables:

- o 'Default Table A' standardised by 3GPP within TS 38.214. This table is not sent to the UE because it is standardised. There are 2 versions of this table to cater for both the normal and extended cyclic prefixes
- o *pusch-TimeDomainAllocationList* configured within *pusch-ConfigCommon*. This table can be broadcast within SIB1 or provided to the UE using dedicated signalling
- o *pusch-TimeDomainAllocationList* configured within *pusch-Config*. This table can be provided using dedicated signalling

★ The rules used to select the appropriate look-up table are presented in Table 203. There is a dependency upon the RNTI, the Search Space and the availability of each table. The dependency upon RNTI and Search Space do not apply when the PUSCH is scheduled using a Random Access Response. Type 1 Configured Grants use the rules which are applicable to the UE Specific Search Space

★ The look-up table standardised by 3GPP ('Default Table A') for the normal cyclic prefix is presented as Table 204. The Slot Offset values presented in this table are increased by an additional offset when the PUSCH is used for MSG3 transmission after receiving a Random Access Response. The additional offset depends upon the subcarrier spacing and is specified as 2, 3, 4 or 6 slots for subcarrier spacings of 15, 30, 60 and 120 kHz respectively. In general, the slot offset increases for the higher subcarrier spacings because the slots have a shorter duration

<table>
<tr><th>RNTI</th><th>PDCCH Search Space</th><th>pusch-ConfigCommon includes pusch-TimeDomainAllocationList</th><th>pusch-Config includes pusch-TimeDomainAllocationList</th><th>Look-up Table</th></tr>
<tr><td colspan="2" rowspan="2">PUSCH Scheduled by Random Access Response</td><td>No</td><td>-</td><td>Default A</td></tr>
<tr><td>Yes</td><td>-</td><td>pusch-ConfigCommon</td></tr>
<tr><td rowspan="2">C-RNTI, TC-RNTI</td><td rowspan="2">Common Search Space associated with CORESET 0</td><td>No</td><td>-</td><td>Default A</td></tr>
<tr><td>Yes</td><td>-</td><td>pusch-ConfigCommon</td></tr>
<tr><td rowspan="3">C-RNTI, CS-RNTI</td><td rowspan="2">Common Search Space not associated with CORESET 0</td><td>No</td><td>No</td><td>Default A</td></tr>
<tr><td>Yes</td><td>No</td><td>pusch-ConfigCommon</td></tr>
<tr><td>UE Specific Search Space</td><td>No or Yes</td><td>Yes</td><td>pusch-Config</td></tr>
</table>

Table 203 – Rules for selecting the look-up table for time domain resource allocation

<table>
<tr><th rowspan="2">Row Index</th><th colspan="4">Slot Offset (K₂) per Subcarrier Spacing</th><th rowspan="2">PUSCH Mapping Type</th><th rowspan="2">Start Symbol</th><th rowspan="2">Length (symbols)</th></tr>
<tr><th>15 kHz</th><th>30 KHz</th><th>60 kHz</th><th>120 kHz</th></tr>
<tr><td>1</td><td rowspan="7">1</td><td rowspan="7">1</td><td rowspan="7">2</td><td rowspan="7">3</td><td rowspan="3">A</td><td rowspan="3">0</td><td>14</td></tr>
<tr><td>2</td><td>12</td></tr>
<tr><td>3</td><td>10</td></tr>
<tr><td>4</td><td rowspan="4">B</td><td>2</td><td>10</td></tr>
<tr><td>5</td><td rowspan="3">4</td><td>10</td></tr>
<tr><td>6</td><td>8</td></tr>
<tr><td>7</td><td>6</td></tr>
<tr><td>8</td><td rowspan="3">2</td><td rowspan="3">2</td><td rowspan="3">3</td><td rowspan="3">4</td><td rowspan="3">A</td><td rowspan="3">0</td><td>14</td></tr>
<tr><td>9</td><td>12</td></tr>
<tr><td>10</td><td>10</td></tr>
<tr><td>11</td><td rowspan="3">3</td><td rowspan="3">3</td><td rowspan="3">4</td><td rowspan="3">5</td><td rowspan="3">A</td><td rowspan="3">0</td><td>14</td></tr>
<tr><td>12</td><td>12</td></tr>
<tr><td>13</td><td>10</td></tr>
<tr><td>14</td><td>1</td><td>1</td><td>2</td><td>3</td><td>B</td><td>8</td><td>6</td></tr>
<tr><td>15</td><td rowspan="2">4</td><td rowspan="2">4</td><td rowspan="2">5</td><td rowspan="2">6</td><td rowspan="2">A</td><td rowspan="2">0</td><td>14</td></tr>
<tr><td>16</td><td>10</td></tr>
</table>

Table 204 – 'Default A' look-up table for time domain resource allocation (normal cyclic prefix)

★ When using dynamic resource allocations, the Slot Offset (K_2) determines the slot containing the resource allocation according to the following expression:

$$PUSCH\ Slot\ Number = \left\lfloor n \times \frac{PUSCH\ Subcarrier\ Spacing}{PDCCH\ Subcarrier\ Spacing} \right\rfloor + K_2$$

★ 'n' is the PDCCH slot number during which the resource allocation was received. The value of 'n' is scaled according to the relative PDCCH and PUSCH numerologies. This scaling maps the PDCCH slot number onto the corresponding PUSCH slot number. For example, if the PDCCH and PUSCH are transmitted using the same numerology then the scaling factor equals 1 because the PDCCH and PUSCH share the same slot numbering. If the PDCCH subcarrier spacing is 15 kHz while the PUSCH subcarrier spacing is 30 kHz then the scaling factor is 2 because the PUSCH slots have half the duration of the PDCCH slots. The ROUNDDOWN function ensures that the scaled slot number is always an integer

★ The Slot Offset within 'Default Table A' is always > 0, i.e. the resource allocation is always within a slot which occurs after the slot containing the resource allocation. The look-up tables which are configured by RRC signalling can include Slot Offsets of 0. This provides support for self-contained slots

★ Type 1 Configured Grants do not use the slot offset. Instead, they use the *timeDomainOffset* information element from within the *ConfiguredGrantConfig* parameter structure. This information element is an input to an expression presented in section 7.4.4.3. Type 2 Configured Grants use the slot offset to determine the value of $Slot_{start}$ which is then used as an input to an expression presented in section 7.4.4.3

★ The PUSCH Mapping Type determines the allowed combinations of PUSCH Starting Symbol (S) and Length (L). Table 205 presents the starting symbols and lengths which are allowed for each Mapping Type. The length is defined as a duration in terms of symbols. A single resource allocation is always contained within a single slot and so the sum of the Starting Symbol index and the Length does not exceed 14 when using the normal cyclic prefix, and 12 when using the extended cyclic prefix

PUSCH Mapping Type	Normal Cyclic Prefix (14 symbols per slot)			Extended Cyclic Prefix (12 symbols per slot)		
	S	L	S + L	S	L	S + L
Type A	0	4 to 14	4 to 14	0	4 to 12	4 to 12
Type B	0 to 13	1 to 14	1 to 14	0 to 11	1 to 12	1 to 12

Table 205 – Allowed combinations of Starting Symbol (S) and Length (L)

★ The PUSCH Mapping Type has an impact upon the Resource Elements allocated to the Demodulation Reference Signal (DMRS). The DMRS is always present within the first allocated symbol when using Mapping Type B. This corresponds to a 'Front Loaded' configuration which allows the Base Station receiver to estimate the uplink channel response in advance of receiving the uplink data. When using Mapping Type A, the DMRS can be configured to be located within either symbol 2 or symbol 3. Section 7.5.1 provides greater detail regarding the impact of the Mapping Type upon the DMRS

★ When using 'Default Table A', the Starting Symbol and Length are specified explicitly within each row. When using a look-up table configured by the RRC layer, the Starting Symbol and Length are jointly coded as a Start and Length Indicator Value (SLIV). This means the look-up tables configured by the RRC layer have the columns presented in Table 206

Row Index	Slot Offset (K_2)	PUSCH Mapping Type	Start and Length Indicator Value (SLIV)
1 to 16	0 to 32	Type A or B	0 to 127

Table 206 – Variables within RRC configured look-up tables for PUSCH time domain resource allocation

★ The 'Start and Length Indicator Value' (SLIV) is used to deduce both the resource allocation starting symbol (S) and the number of consecutive symbols belonging to the resource allocation (L). The SLIV is coded according to the following rules:

if $(L - 1) \leq 7$ then $SLIV = 14 \times (L - 1) + S$

else $SLIV = 14 \times (14 - L + 1) + (14 - 1 - S)$ where $0 < L \leq 14 - S$

★ The SLIV coding has been designed to minimise the range of numerical values, i.e. to minimise the number of bits required to signal the SLIV. The set of values associated with the SLIV is presented in Table 98 (section 3.6.4.1)

★ A UE can be configured to transmit the PUSCH with repetition. In this case, the UE transmits repetitions of the uplink transport block across consecutive slots. There is one repetition within each slot and each repetition uses the same allocation of symbols. The '*pusch-AggregationFactor*' information element indicates the level of repetition and can be configured with values of 2, 4 or 8 slots. The PUSCH is limited to a single transmission layer when repetition is used, i.e. it is intended to improve coverage and should not be required at locations where the PUSCH is able to benefit from multiple transmission layers

★ 3GPP References: TS 38.214, TS 38.212, TS 38.331

7.4.4.2 FREQUENCY DOMAIN RESOURCE ALLOCATION

- Frequency domain resources can be allocated for the PUSCH using Downlink Control Information (DCI) Formats 0_0 and 0_1. DCI is transferred to the UE using the PDCCH physical channel. Alternatively, in the case of Type 1 Configured Grants, frequency domain resources are allocated for the PUSCH using RRC signalling
- The '*Frequency Domain Resource Assignment*' field within the DCI is used to specify the set of allocated Resource Blocks. Similarly, the '*frequencyDomainAllocation*' information element within the RRC signalling protocol can be used to specify the set of allocated Resource Blocks when using Configured Grants
- 3GPP has specified 2 schemes for the allocation of frequency domain resources:
  - Type 0: uses a bitmap to allocate specific Resource Block Groups (RBG). An RBG is a set of contiguous Virtual Resource Blocks. The allocated RBG do not need to be contiguous. This scheme cannot be used in combination with DCI Format 0_0. In addition, this scheme cannot be used in combination with Transform Precoding. Transform Precoding is used to improve coverage by reducing the Peak to Average Power Ratio (PAPR). Non-contiguous Resource Block allocations tend to increase the PAPR and so are not aligned with the use of Transform Precoding
  - Type 1: uses a Resource Indication Value (RIV) to allocate a contiguous set of Virtual Resource Blocks. This scheme can be used in combination with both DCI Formats 0_0 and 0_1
- The release 15 version of the 3GPP specifications uses a non-interleaved mapping between Virtual Resource Blocks and Physical Resource Blocks. This means that Virtual Resource Block 'n' maps onto Physical Resource Block 'n', i.e. the mapping function has no impact and the Physical Resource Block allocation is the same as the Virtual Resource Block allocation
- The Base Station can use RRC signalling to specify which resource allocation scheme will be used. This information is included within the *PUSCH-Config* when using dynamic resource allocations and within the *configuredGrantConfig* when using Configured Grants. The relevant part of these parameter structures is presented in Table 207

Parameter Structure	Information Element	Range
PUSCH-Config	resourceAllocation	Type0, Type1, dynamicSwitch
ConfiguredGrantConfig	resourceAllocation	Type0, Type1, dynamicSwitch

Table 207 – Information elements used to indicate the type of resource allocation

- Both parameter structures use the same set of values for the *resourceAllocation* information element. The type of resource allocation can be fixed by signalling a value of 'Type0' or 'Type1'. Alternatively, the type of resource allocation can be flexible if the 'dynamicSwitch' value is signalled. Type 1 Configured Grants do not use the 'dynamicSwitch' value because resources are allocated by the RRC layer within the *ConfiguredGrantConfig* parameter structure. Type 2 Configured Grants can use the 'dynamicSwitch' value because the resource allocation scheme can change with each activation/deactivation cycle
- When using the 'dynamicSwitch' value, 1 extra bit is added to the '*Frequency Domain Resource Assignment*' field within the DCI to indicate the scheme being used
- When receiving a frequency domain resource allocation, the UE starts by identifying the Bandwidth Part. The UE then proceeds to identify the resource allocation within that Bandwidth Part. RRC signalling can be used to configure up to 4 Bandwidth Parts per serving cell, in addition to the Initial Bandwidth Part
- DCI Format 0_1 can include the '*Bandwidth Part Indicator*' field which represents a pointer towards one of the configured Bandwidth Parts (this field has a length of up to 2 bits). If the DCI does not include a '*Bandwidth Part Indicator*' then the UE assumes that the Resource Block allocation is within the current active Bandwidth Part. The UE makes an exception when DCI Format 0_0 is decoded within the common search space for CORESET 0. In this case, the UE assumes that the resource allocation is within the initial Bandwidth Part
- 3GPP TS 38.101-1 introduces the concept of an 'almost contiguous' Resource Block allocation. A resource allocation is categorised as 'almost contiguous' if the following conditions are satisfied:

$$N_{RB\_gap} \,/\, (N_{RB\_alloc} + N_{RB\_gap}) \leq 0.25 \quad \text{AND} \quad (N_{RB\_alloc} + N_{RB\_gap}) > X$$

  where, 'X' = {106, 51, 24} for subcarrier spacings of 15, 30 and 60 kHz respectively. N_{RB_alloc} is the total number of allocated Resource Blocks, and N_{RB_gap} is the total number of unallocated Resource Blocks between allocated Resource Blocks

- Within Frequency Range 1, when using the CP-OFDM waveform, 'almost contiguous' Resource Block allocations are permitted but otherwise non-contiguous Resource Block allocations are not permitted. A UE is permitted to increase its Maximum Power Reduction (MPR) when its resource allocation is categorised as 'almost contiguous'
- Within Frequency Range 2, when using the CP-OFDM waveform, resource allocations must be contiguous within a component carrier
- 3GPP References: TS 38.214, TS 38.331, TS 38.211, TS 38.212, TS 38.101-1

7.4.4.2.1 UPLINK RESOURCE ALLOCATION TYPE 0

★ Uplink resource allocation Type 0 can be signalled on the PDCCH using DCI Format 0_1. It can also be signalled as part of an RRC message providing a Type 1 Configured Grant. This type of resource allocation uses a bitmap to indicate a set of allocated Resource Block Groups (RBG), i.e. resources are allocated in terms of RBG rather than individual Resource Blocks

★ A Resource Block Group (RBG) is a set of contiguous Virtual Resource Blocks (VRB) within a Bandwidth Part. The number of Resource Blocks within an RBG is dependent upon the Bandwidth Part size and the '*rbg-Size*' information element provided within the *PUSCH-Config* shown in Table 196. The '*rbg-Size*' parameter can be set to either 'config1' or 'config2'. The relationship between the Bandwidth Part size, the value of '*rbg-Size*' and the resultant RBG size is presented in Table 208

Bandwidth Part Size (Resource Blocks)	Configuration 1 RBG Sizes (Resource Blocks)	Configuration 2 RBG Sizes (Resource Blocks)
1 to 36	2	4
37 to 72	4	8
73 to 144	8	16
145 to 275	16	16

Table 208 – Resource Block Group (RBG) Sizes

★ The length of the bitmap used to provide the resource allocation depends upon the number of RBG within the Bandwidth Part. There is 1 bit for each RBG. The RBGs at the lower and upper ends of the Bandwidth Part may contain fewer Resource Blocks. This depends upon the position of the Bandwidth Part within the set of Common Resource Blocks. Figure 277 presents some example Bandwidth Part positions to illustrate the possibility of having smaller RBG at each end of the Bandwidth Part. Smaller RBG are generated when the end of the Bandwidth Part does not coincide with an integer multiple of the RBG size from the perspective of Common Resource Block numbering

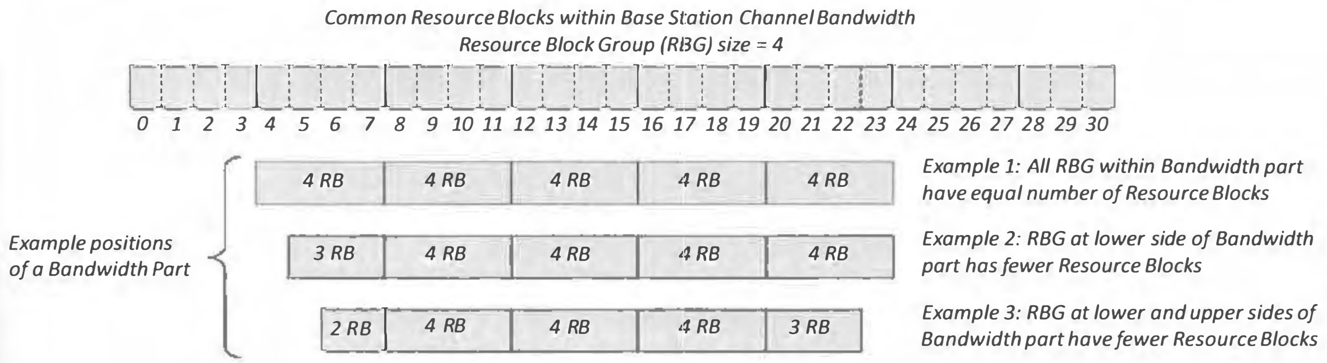


Figure 277 – Example sets of RBG within a Bandwidth Part

★ Figure 278 illustrates an example bitmap allocating a set of RBG when the RBG size is 4. This example has a smaller RBG at the upper end of the Bandwidth Part

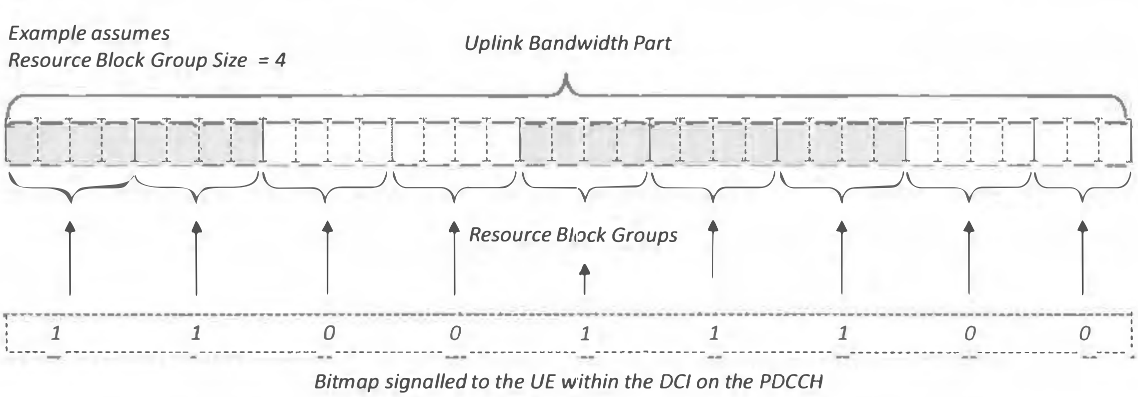


Figure 278 – Use of a bitmap to allocate Resource Block Groups (RBG) within the Active Carrier Bandwidth Part

★ 3GPP References: TS 38.214, TS 38.331, TS 38.212

7.4.4.2.2 UPLINK RESOURCE ALLOCATION TYPE 1

★ Uplink resource allocation type 1 can be signalled on the PDCCH using either DCI Format 0_0 or Format 0_1. It can also be signalled as part of an RRC message providing a Type 1 Configured Grant. This type of resource allocation uses a Resource Indication Value (RIV) to indicate a set of allocated Virtual Resource Blocks (VRB) within the active Bandwidth Part. These Virtual Resource Blocks are subsequently mapped onto a set of Physical Resource Blocks (PRB) using a 'non-interleaved' mapping

★ The allocated VRB are always contiguous. This means that the allocated Physical Resource Blocks (PRB) are also contiguous because VRB 'n' is mapped onto PRB 'n'

★ The Resource Indication Value (RIV) provides the starting Virtual Resource Block (RB_{start}) and the number of consecutive allocated Virtual Resource Blocks (L_{RBs}). The RIV is coded according to the following rules:

if $(L_{RBs} - 1) \leq \lfloor N^{size}_{BWP} / 2 \rfloor$ then $RIV = N^{size}_{BWP} \times (L_{RBs} - 1) + RB_{start}$

else $RIV = N^{size}_{BWP} \times (N^{size}_{BWP} - L_{RBs} + 1) + (N^{size}_{BWP} - 1 - RB_{start})$

where $1 \leq L_{RBs} \leq N^{size}_{BWP} - RB_{start}$

★ The RIV coding is similar to the coding used for the 'Start and Length Indicator Value' (SLIV) described in section 7.4.4.1 for the time domain resource allocation. An example of the RIV coding is presented in Table 209. This example assumes that the Bandwidth Part includes 14 Resource Blocks

Starting Allocated Resource Block (RB_{start})	Number of Allocated Resource Blocks (L_{RBs})																			
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
0	0	20	40	60	80	100	120	140	160	180	200	199	179	159	139	119	99	79	59	39
1	1	21	41	61	81	101	121	141	161	181	201	198	178	158	138	118	98	78	58	
2	2	22	42	62	82	102	122	142	162	182	202	197	177	157	137	117	97	77		
3	3	23	43	63	83	103	123	143	163	183	203	196	176	156	136	116	96			
4	4	24	44	64	84	104	124	144	164	184	204	195	175	155	135	115				
5	5	25	45	65	85	105	125	145	165	185	205	194	174	154	134					
6	6	26	46	66	86	106	126	146	166	186	206	193	173	153						
7	7	27	47	67	87	107	127	147	167	187	207	192	172							
8	8	28	48	68	88	108	128	148	168	188	208	191								
9	9	29	49	69	89	109	129	149	169	189	209									
10	10	30	50	70	90	110	130	150	170	190										
11	11	31	51	71	91	111	131	151	171											
12	12	32	52	72	92	112	132	152												
13	13	33	53	73	93	113	133													
14	14	34	54	74	94	114														
15	15	35	55	75	95															
16	16	36	56	76																
17	17	37	57																	
18	18	38																		
19	19																			

Table 209 – Example coding of Resource Indication Value (RIV)

★ In this example, the RIV ranges from 0 to 209 so 8 bits are required to signal the frequency domain resource allocation. In general, the number of bits required to signal the frequency domain resource allocation is given by;

$$\lceil LOG_2(N^{BWP}_{RB} \times (N^{BWP}_{RB} + 1) / 2 \rceil \text{ bits}$$

where, N^{BWP}_{RB} is the number of Resource Blocks within the Bandwidth Part

★ 3GPP References: TS 38.214, TS 38.331, TS 38.212

7.4.4.3 CONFIGURED GRANTS

- A UE can be configured to allow uplink transmission on the PUSCH without having to receive individual resource allocations on the PDCCH. A UE configured in this way is not free to transmit on any Resource Block at any time, but is configured to allow periodic transmission on a specific set of Resource Blocks. This is known as a 'Configured Grant' resource allocation. It is sometimes referred to as a 'Grant Free' resource allocation
- Configured Grant resource allocations are suitable for some specific use cases. Three examples are illustrated in Figure 279:
  - end-user applications which have a predictable and periodic traffic pattern. For example, speech codecs generate packets every 20 ms. A Configured Grant resource allocation can be used to provide the UE with PUSCH resources once every 20 ms without having to periodically consume PDCCH capacity
  - end-user applications which have a requirement for low latency, e.g. those belonging to the category known as Ultra Reliable Low Latency Communications (URLLC). A UE typically has to request uplink resources by transmitting a Scheduling Request on the PUCCH, and then wait until a resource allocation is received on the PDCCH before being able to transmit on the PUSCH. A UE provided with a Configured Grant only needs to wait until its next periodic resource allocation, i.e. the maximum delay is determined by the period of the Configured Grant resource allocation. Resource allocation periods can be set as low as 2 symbols to minimise latency
  - end-user applications characterised as Machine Type Communication (MTC) tend to generate small and infrequent uplink packets. Configured Grant resource allocations allow a group of devices to share the same set of periodic resources. Those devices can then transmit without having to request capacity, i.e. with reduced signalling to help conserve battery life. The probability of collision will be low as long as the number of devices sharing the resources is not too high

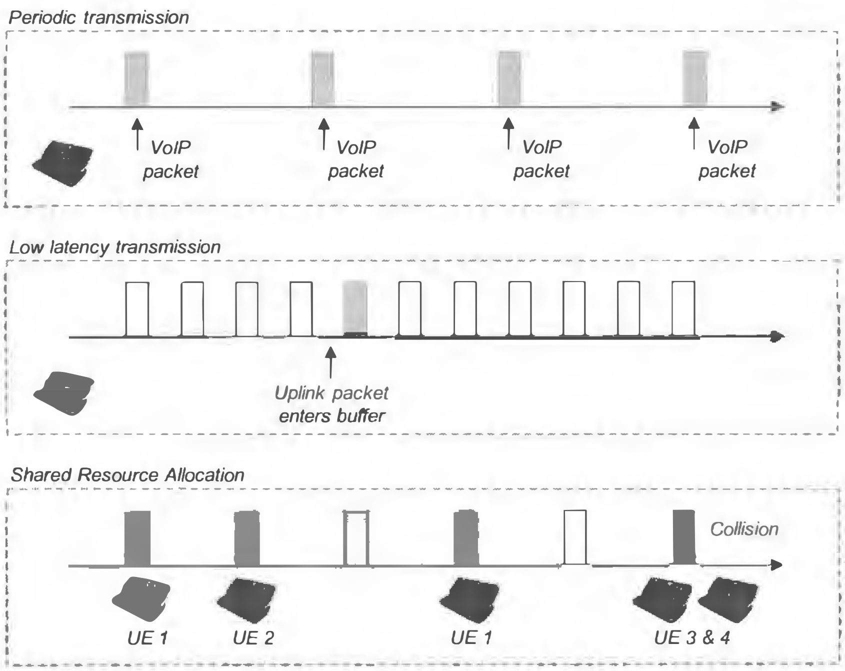


Figure 279 – Example applications for Configured Grant resource allocations

- A drawback of Configured Grant resource allocation is that UE are configured to use a specific time and frequency domain resource, and also a specific Modulation and Coding Scheme (MCS). This means that the benefits of dynamic Packet Scheduling and Link Adaptation are lost. A channel aware Packet Scheduler dynamically allocates Resource Blocks to the UE according to the current channel conditions. At time instant '1' Resource Blocks 'A to B' may have the best channel conditions, whereas at time instant '2' Resource Blocks 'C to D' may have the best channel conditions. Normally, the Packet Scheduler can dynamically change the allocated Resource Blocks according to the changing channel conditions. In the case of Configured Grant resource allocations, the allocated Resource Blocks do not change over time and so will not always be the optimal set of Resource Blocks. Similarly, Link Adaptation normally adjusts the MCS according to the channel conditions. In the case of Configured Grant resource allocation, the UE is allocated a fixed MCS which must be sufficiently low to cope with the worst conditions that the UE is likely to experience
- 3GPP has specified an 'Uplink Skipping' rule for Configured Grant resource allocations. This means that a UE only transmits on the PUSCH when it has data to send, i.e. if the uplink buffers are empty then the UE does not transmit anything. If this Uplink Skipping rule had not been specified then UE would create dummy packets out of padding whenever the uplink buffers became empty and would transmit these dummy packets across the air-interface. Uplink Skipping reduces uplink interference levels. It also allows the Configured Grant resource allocation to be shared with other UE

★ 3GPP has specified 2 categories of Configured Grant within release 15:

- o Type 1 Configured Grants are fully configured using RRC signalling and do not require any layer 1 signalling on the PDCCH. The UE is able to start transmitting on the Configured Grants as soon as the RRC signalling procedure has completed. The Configured Grants remain available until further RRC signalling reconfigures the UE
- o Type 2 Configured Grants use a combination of RRC signalling and layer 1 signalling on the PDCCH. RRC signalling provides a subset of the resource allocation information. The remaining information is provided by the PDCCH which also acts as an activation trigger. A subsequent PDCCH transmission can be used as a deactivation trigger

★ Type 2 Configured Grants have many similarities with Semi Persistent Scheduling (SPS) which is described for the downlink in section 3.6.4.3. These grants can be rapidly activated and deactivated due to the use of layer 1 signalling on the PDCCH, e.g. during a speech call, they could be activated when the user starts to talk and deactivated when the user starts to listen

★ The RRC parameter structure used to allocate a Configured Grant is presented in Table 210. The *rrc-ConfiguredUplinkGrant* information element is excluded for a Type 2 Configured Grant because the information is subsequently provided by the PDCCH

configuredGrantConfig		
frequencyHopping	mode1, mode 2	
cg-DMRS-Configuration	DMRS-UplinkConfig	
mcs-Table	qam256, qam64LowSE	
mcs-TableTransformPrecoder	qam256, qam64LowSE	
uci-OnPUSCH	SetupRelease { CG-UCI-OnPUSCH }	
resourceAllocation	resourceAllocationType0, resourceAllocationType1, dynamicSwitch	
rbg-Size	config2	
powerControlLoopToUse	n0, n1	
p0-PUSCH-Alpha	P0-PUSCH-AlphaSetId	
transformPrecoder	enabled	
nrofHARQ-Processes	1 to 16	
repK	n1, n2, n4, n8	
repK-RV	s1-0231, s2-0303, s3-0000	
periodicity	2, 7, 1x14, 2x14, 4x14, 5x14, 8x14, 10x14, 16x14, 20x14, 32x14, 40x14, 64x14, 80x14, 128x14, 160x14, 256x14, 320x14, 512x14, 640x14, 1024x14, 1280x14, 2560x14, 5120x14, 6, 1x12, 2x12, 4x12, 5x12, 8x12, 10x12, 16x12, 20x12, 32x12, 40x12, 64x12, 80x12, 128x12, 160x12, 256x12, 320x12, 512x12, 640x12, 1280x12, 2560x12 symbols	
configuredGrantTimer	1 to 64	
rrc-ConfiguredUplinkGrant (only included for Type 1 Configured Grant)	timeDomainOffset	0 to 5119
	timeDomainAllocation	0 to 15
	frequencyDomainAllocation	Bit String - 18 bits
	antennaPort	0 to 31
	Dmrs-SeqInitialization	0, 1
	precodingAndNumberOfLayers	0 to 63
	Srs-ResourceIndicator	0 to 15
	mcsAndTBS	0 to 31
	frequencyHoppingOffset	1 to 274
	pathlossReferenceIndex	0 to 3

Table 210 – Parameter structure used to allocate a Configured Grant

★ The *frequencyHopping* information element indicates the use of either intra-slot frequency hopping (mode 1) or inter-slot frequency hopping (mode 2). Frequency hopping is disabled if this information element is excluded

★ The *cg-DMRS-Configuration* information element configures the Demodulation Reference Signal (DMRS) for the PUSCH according to the description provided in section 7.5.1

★ The *mcs-Table* and *mcs-TableTransformPrecoder* information elements indicate which Modulation and Coding Scheme (MCS) table should be used when the PUSCH is transmitted without Transform Precoding and with Transform Precoding respectively. PUSCH transmissions using Configured Grants are not restricted in terms of MCS table selection, i.e. 64QAM, 256QAM and Low Spectral Efficiency tables can be allocated

★ The *uci-OnPUSCH* information element configures the resources to be used when transferring Uplink Control Information (UCI)

★ The *resourceAllocation* information element specifies the type of frequency domain resource allocation. Type 1 Configured Grants can be configured to use either a Type 0 resource allocation (based upon a bitmap) or Type 1 resource allocation (based upon a Resource Indication Value (RIV)). They cannot be configured with the 'dynamicSwitch' option because they do not use the PDCCH and so they do not have a mechanism for dynamic switching. In the case of Type 1 Configured Grants, the frequency domain resource allocation itself is lower down the *ConfiguredGrantConfig* parameter structure, i.e. *frequencyDomainAllocation*. Type 2 Configured Grants can use the 'Type 0', 'Type 1 or 'dynamicSwitch' option. In this case, the PDCCH can be used to dynamically switch between Type 0 and Type 1 resource allocations

★ The *rbg-Size* information element defines the Resource Block Group (RBG) size by indicating either 'config1' or 'config2'. Excluding this information element indicates 'config1', while including it indicates 'config2'. Table 208 within section 7.4.4.2.1 presents the set of RBG sizes associated with each configuration

★ The *powerControlLoopToUse* and *p0-PUSCH-Alpha* information elements provide information related to PUSCH power control

★ The *transformPrecoder* information element indicates whether or not Transform Precoding is enabled for the PUSCH

★ The *nrofHARQ-Processes* information element defines the number of uplink HARQ processes within the range 1 to 16. This information element is used as an input when identifying the HARQ process identity for a specific PUSCH transmission. In the case of dynamic resource allocations on the PDCCH, the HARQ process identity is specified using a 4 bit field within the Downlink Control Information (DCI). In the case of Configured Grants, the HARQ process has to be calculated because the UE does not receive DCI in advance of each transmission. The HARQ process identity is calculated using the following expression:

HARQ Process ID = [ROUNDDOWN (Current_Symbol / *periodicity*)] MOD *nrofHARQ-Processes*

where, Current_Symbol = (SFN × SlotsPerFrame × SymbolsPerSlot) + (SlotNumber × SymbolsPerSlot) + SymbolNumber

SlotsPerFrame depends upon the numerology, i.e. 10 for 15 kHz subcarrier spacing, 20 for 30 kHz subcarrier spacing, etc. SymbolsPerSlot is 14 for the normal cyclic prefix and 12 for the extended cyclic prefix. The SFN, SlotNumber and SymbolNumber correspond to the System Frame Number (SFN), slot number and symbol number within which the PUSCH starts

★ HARQ process numbering is shared between dynamic and configured grants. This means that a dynamic grant cannot re-use a HARQ process identity to transfer a new packet in parallel to a configured grant using the same identity

★ The *repK* information element indicates the level of repetition for each PUSCH transmission. Repetitions are autonomous and do not require the UE to wait for a request from the Base Station. They provide a capability similar to TTI Bundling in LTE. Repetition levels of 2, 4 or 8 can be used to improve reliability. They can also be used to reduce latency because they generate additional transmission opportunities. Figure 280 illustrates the concept of using repetitions to reduce latency

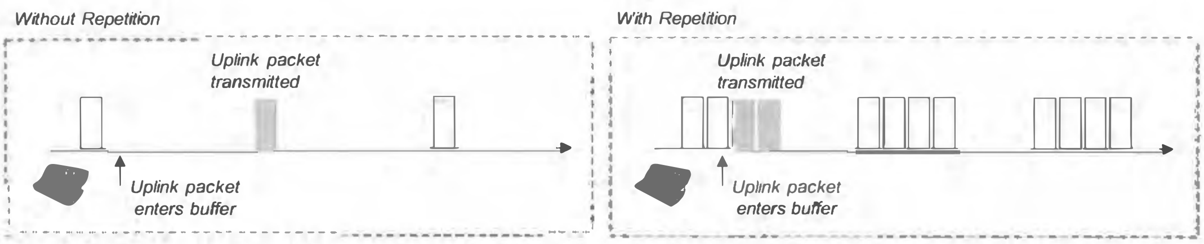


Figure 280 – Using repetition to increase transmission opportunities and reduce latency

★ When using repetitions to reduce latency, it is important to consider the Redundancy Version (RV) which defines the puncturing pattern applied to the data after channel coding. If Chase Combining is adopted then each repetition uses the same RV, i.e. the same puncturing pattern. In this case, the RV must generate an output which is self-decodable (it is possible to decode the data without requiring another transmission using a different RV). The *repK-RV* information element within Table 210 allows the RV pattern of 0000 to be configured for Chase Combining. This means that RV = 0 is used for all repetitions. RV = 0 corresponds to the RV which generates the output which is easiest to self decode. This option minimises latency because transmission can start from any repetition occasion, with the exception of the final occasion when using repetition level 8. This restriction is specified by 3GPP to ensure that there is at least some Chase Combining gain when using repetition level 8, i.e. it avoids the Base Station receiving a single repetition within the last transmission occasion. The permitted transmission starting positions for the 0000 RV pattern is illustrated in Figure 281

★ Figure 281 also illustrates the permitted transmission starting positions when using Incremental Redundancy. Incremental Redundancy means that different repetitions use different RV. The *repK-RV* information element within Table 210 allows RV patterns of 0231 and 0303 to be configured for Incremental Redundancy. The 0231 RV pattern maximises performance in terms of decoding reliability. It is not intended to reduce latency and so 3GPP specifies that transmissions must always start from the first repetition occasion. The 0303 RV pattern provides a balance between decoding performance and latency reduction. In this case, transmissions can start from any occasion using RV0, and there is at least some Incremental Redundancy gain after combining. Both RV0 and RV3 are self-decodable so decoding remains possible if the Base Station is only able to receive a single transmission

★ Repetitions are transmitted in consecutive slots, with the same symbol allocation in each slot. The UE does not transmit a specific repetition if it includes symbols which are configured for the downlink

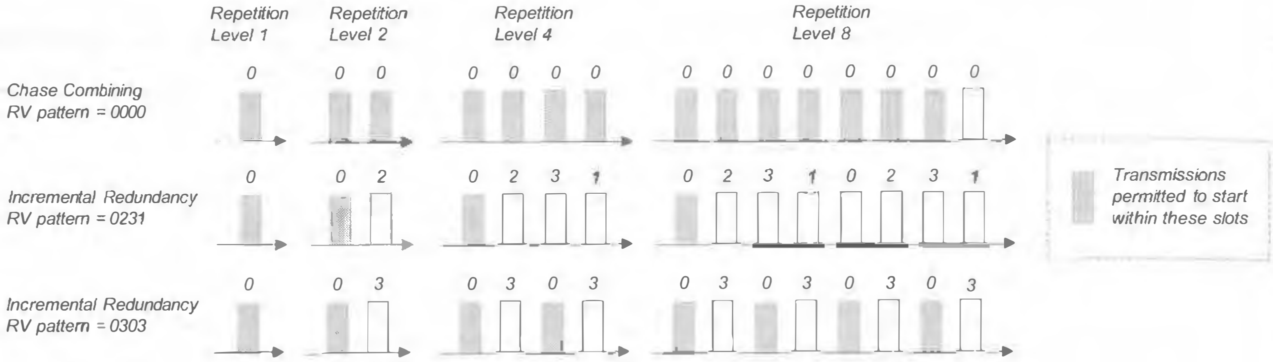


Figure 281 – Permitted transmission starting positions for each repetition level and RV pattern

- ★ The period between Configured Grant resource allocations is defined using the periodicity information element within Table 210. This period includes a single resource allocation if the repetition level = 1, and multiple resource allocations if the repetition level > 1. 3GPP has defined a specific set of periods for each subcarrier spacing (presented in Table 211). Short periods are specified for low latency applications, e.g. periods of 2 and 7 symbols. Long periods are specified for delay tolerant applications, e.g. 640 slots which corresponds to 640 ms when using the 15 kHz subcarrier spacing

Subcarrier Spacing	Cyclic Prefix	Grant Free Resource Allocation Period (symbols)
15 kHz ($\mu = 0$)	Normal	2, 7, n × 14, where n = {1, 2, 4, 5, 8, 10, 16, 20 ,32, 40, 64, 80, 128, 160, 320, 640}
30 kHz ($\mu = 1$)	Normal	2, 7, n × 14, where n = {1, 2, 4, 5, 8, 10, 16, 20 ,32, 40, 64, 80, 128, 160, 256, 320, 640, 1280}
60 kHz ($\mu = 2$)	Normal	2, 7, n × 14, where n = {1, 2, 4, 5, 8, 10, 16, 20 ,32, 40, 64, 80, 128, 160, 256, 320, 512, 640, 1280, 2560}
60 kHz ($\mu = 2$)	Extended	2, 6, n × 12, where n = {1, 2, 4, 5, 8, 10, 16, 20 ,32, 40, 64, 80, 128, 160, 256, 320, 512, 640,1280, 2560}
120 kHz ($\mu = 3$)	Normal	2, 7, n × 14, where n = {1, 2, 4, 5, 8, 10, 16, 20 ,32, 40, 64, 80, 128, 160, 256, 320, 512, 640, 1024, 1280, 2560, 5120}

Table 211 – Configured Grant resource allocation Periods for each Subcarrier Spacing

- ★ When using Configured Grant Type 1, a transmission occasion starts when the following equation is satisfied:

$$\text{SFN} \times \text{SlotsPerFrame} \times \text{SymbolsPerSlot}) + (\text{SlotNumber} \times \text{SymbolsPerSlot}) + \text{SymbolNumber} = (\mathit{timeDomainOffset} \times \text{SymbolsPerSlot} + \text{S} + \text{N} \times \mathit{periodicity})\ \text{MOD}\ (1024 \times \text{SlotsPerFrame} \times \text{SymbolsPerSlot})$$

  where, *timeDomainOffset* and *periodicity* are both specified within the *ConfiguredGrantConfig* parameter structure. 'S' corresponds to the starting symbol deduced from the *timeDomainAllocation* information element. 'N' is an integer corresponding to the N^{th} transmission occasion

- ★ When using Configured Grant Type 2, a transmission occasion starts when the following equation is satisfied:

$$\text{SFN} \times \text{SlotsPerFrame} \times \text{SymbolsPerSlot}) + (\text{SlotNumber} \times \text{SymbolsPerSlot}) + \text{SymbolNumber} = [(\text{SFN}_{\text{start}} \times \text{SlotsPerFrame} \times \text{SymbolsPerSlot} + \text{Slot}_{\text{start}} \times \text{SymbolsPerSlot} + \text{Symbol}_{\text{start}}) + \text{N} \times \mathit{periodicity}]\ \text{MOD}\ (1024 \times \text{SlotsPerFrame} \times \text{SymbolsPerSlot})$$

  where, $\text{SFN}_{\text{start}}$, $\text{Slot}_{\text{start}}$ and $\text{Symbol}_{\text{start}}$ are the SFN, slot and symbol during which the first PUSCH transmission occurs according to the resource allocation within the activation PDCCH

- ★ The *configuredGrantTimer* within Table 210 defines the period that a UE waits for a re-transmission request after transmitting an uplink packet. This timer runs independently for each HARQ process. The UE assumes a positive acknowledgement if the timer expires. This allows the UE to subsequently transfer a new packet using the same HARQ process. This concept is illustrated in Figure 282. The timer should be set long enough to allow sufficient time for the Base Station to receive the uplink packet and to schedule a re-transmission request. Setting the timer too long can increase latency because the UE cannot re-use a HARQ process for a new transmission until a positive acknowledgement has been assumed for the previous transmission

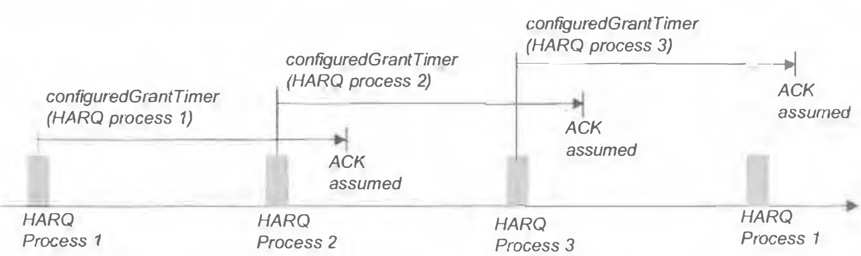


Figure 282 – Configured Grant Timer applied to 3 HARQ processes

★ The Base Station requests re-transmissions using the PDCCH, i.e. dynamic grants are used to allocate resources for re-transmissions. The New Data Indicator (NDI) field within the PDCCH is used to indicate that a re-transmission is being requested. Normally, the NDI is toggled between 0 and 1 to indicate that a new transmission is requested, or kept at the same value to indicate that a re-transmission is requested. This approach requires a previous value of NDI so the UE can determine if it has toggled or remained the same. In the case of Configured Grants, there is no previous value because the PDCCH was not used to schedule the original transmission. In the case of Configured Grants, an NDI value of 1 indicates that a re-transmission is requested

★ Figure 283 illustrates the concept of re-transmission requests for Configured Grants. The *configuredGrantTimer* is re-started for each re-transmission to allow time for further re-transmission requests. Figure 283 illustrates only a single HARQ process to simplify the picture. In reality, the re-transmissions belonging to one HARQ process can be completed in parallel to the transmissions belonging to other HARQ processes

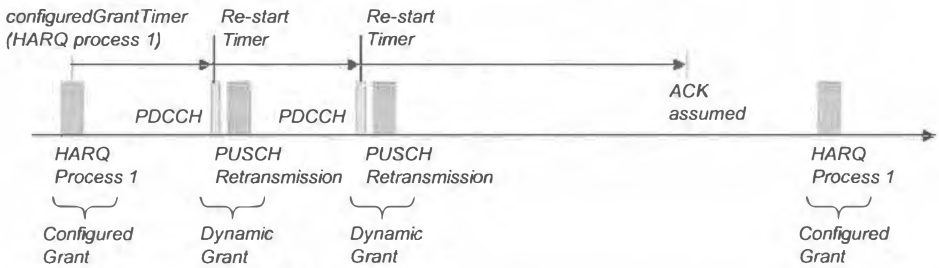


Figure 283 – Re-transmission requests for configured grants

★ The PDCCH is addressed to the UE using a Configured Scheduling Radio Network Temporary Identifier (CS-RNTI), i.e. the CRC bits are scrambled using the CS-RNTI. The CS-RNTI is not allocated to the UE within the *ConfiguredGrantConfig* parameter structure presented in in Table 210. Instead, it is allocated using the *PhysicalCellGroupConfig* parameter structure. This indicates that a single CS-RNTI is applicable to all cells belonging to a cell group (either a Master Cell Group (MCG) or Secondary Cell Group (SCG))

★ In the case of Type 2 Configured Grants, the PDCCH is used to activate and deactivate the grants. Either DCI Format 0_0 or 0_1 can be used for activation, whereas only DCI Format 0_0 can be used for deactivation. Activation is indicated by setting the New Data Indicator (NDI), the HARQ Process Number and the Redundancy Version (RV) fields to 0. Deactivation is indicated by setting the same fields to 0 but also setting the Modulation and Coding Scheme (MCS) and Resource Block Assignment to all 1's. In the case of activation, the PDCCH provides the resource allocation for the Type 2 Configured Grants. This means that Type 2 Configured Grants can change resource allocation with every activation/deactivation cycle

★ In the case of Type 2 Configured Grants, a UE acknowledges the reception of activation and deactivation PDCCH using a Configured Grant Confirmation MAC Control Element (CE). This MAC Control Element does not have any payload. It uses the 6-bit Logical Channel Identity (LCID) field within a MAC subheader to identify itself as a Configured Grant Confirmation (using bit string 110111). This acknowledgement is important because it provides the Base Station with confirmation that the activation or deactivation command has been successfully received. If a UE fails to receive a deactivation command then the UE is likely to continue transmitting on the previously allocated resources

★ If the Base Station allocates Configured Grants such that multiple UE share the same set of time and frequency resources then the Base Station must blindly detect which UE is transmitting during each transmission opportunity (or detect that no UE is transmitting). The Base Station uses the PUSCH Demodulation Reference Signal (DMRS) to differentiate between the set of UE. Each UE can be allocated a different DMRS to allow identification

★ 3GPP References: TS 38.321, 38.212, 38.214, 38.213, 38.331

7.4.4.4 PROACTIVE GRANTS

★ The uplink Packet Scheduler can provide a UE with proactive scheduling grants. These resource allocations do not rely upon the UE transmitting a Scheduling Request. They are used to improve latency by helping to ensure that a UE has uplink resources available as soon as data arrives in the UE transmit buffer. The allocation of proactive scheduling grants depends upon the Base Station implementation. They may be provided to specific subscribers or they may be provided for specific services. In both cases, the Base Station decides when to allocate them

★ Figure 284 provides a comparison between dynamic grants and proactive grants. This comparison assumes that the UE completes a period of uplink data transfer before becoming inactive, and then subsequently having a requirement to transmit one further uplink packet. In the case of dynamic grants, the UE transmits a Scheduling Request to inform the Base Station that it requires an uplink resource allocation. The UE is not free to transmit the Scheduling Request at any time, and has to wait until the start of its next Scheduling Request cycle. This period of waiting can have a significant impact upon latency and will depend upon the configured Scheduling Request period. If the Scheduling Request period is 20 ms then the average waiting time will be 10 ms (the waiting time will depend upon the timing of the uplink packet arrival relative to the Scheduling Request cycle). Once the Scheduling Request has been transmitted, the UE must wait for the uplink resource allocation on the PDCCH. This delay will depend upon the periodicity of the Search Space used to accommodate the PDCCH and the Base Station load. There may be a queuing delay if the Base Station is serving a large volume of traffic. The UE then has to wait for the Slot Offset before transmitting its uplink packet on the PUSCH. The Slot Offset is part of the time domain resource allocation provided by the PDCCH

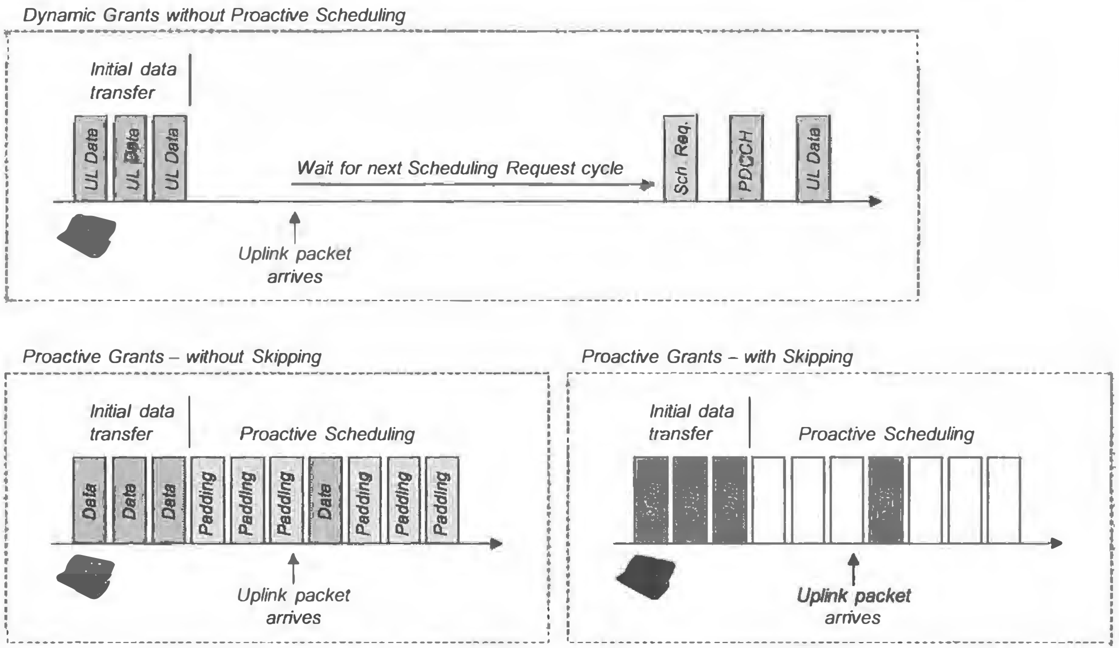


Figure 284 – Comparison of Dynamic Grants and Proactive Grants

★ Figure 284 illustrates two scenarios for proactive grants. The first scenario does not benefit from 'skipping'. In this case, the UE is required to transmit an uplink packet within each resource allocation. Initially, the UE does not have any data to send so it generates uplink packets from padding. This padding is transmitted across the air-interface and contributes to the overall uplink interference. When the uplink packet arrives within the UE transmit buffer, the UE only has to wait until the next proactive grant is received and then it is able to transmit the uplink packet with minimal delay

★ The second scenario for proactive grants benefits from 'skipping'. In this case, the UE is permitted to ignore the proactive grants when it does not have any uplink data to transmit. This avoids generating unnecessary uplink interference and helps to conserve UE battery life. The 'skipping' of proactive grants which have been allocated using a dynamic resource allocation on the PDCCH is an optional UE capability. A UE signals its support for proactive grant skipping using the *skipUplinkTxDynamic* information element shown in Table 212. This information element can be signalled separately for FDD and TDD so the UE may support 'skipping' for one duplexing method but not for the other. In the case, of Configured Grants (described in the previous section) it is mandatory for UE to support 'skipping', i.e. UE do not transmit packets of padding when allocated Configured Grants when there is no uplink data to transmit

extract from *MAC-ParametersXDD-Diff*	
skipUplinkTxDynamic	supported

Table 212 – UE capability information element for 'skipping' of Dynamic Proactive Grants

★ After learning the UE capability, the Base Station can instruct a UE to skip dynamic proactive grants using the *skipUplinkTxDynamic* information element shown in Table 213. This activation flag is not required Configured Grants, i.e. UE will skip Configured Grants by default unless there is uplink data to transfer

extract from *MAC-CellGroupConfig*	
skipUplinkTxDynamic	BOOLEAN

Table 213 – Information element used to enable Proactive Grant 'skipping' for Dynamic Grants

★ Figure 284 illustrates a UE being allocated a continuous stream of proactive grants. The Base Station may decide to allocate proactive grants periodically rather than continuously, e.g. using a period of 10 ms. Providing proactive grants periodically will help to limit the impact upon uplink interference when 'skipping' is not in use. Proactive grants are typically assigned low priority and are often provided on a best effort basis. If a cell is busy and other UE are requesting uplink resources then those UE are likely to have priority. However, specific users may have high priority proactive grants, e.g. Ultra Reliable Low Latency Communication (URLLC) users

★ 3GPP References: TS 38.321, TS 38.331, TS 38.306

7.5 UPLINK REFERENCE SIGNALS

7.5.1 DEMODULATION REFERENCE SIGNAL FOR PUSCH

★ The PUSCH is always transmitted in combination with a Demodulation Reference Signal (DMRS). The DMRS and PUSCH are transmitted using the same precoding and the same antenna ports, i.e. they both experience the same composite propagation channel. The Base Station has knowledge of the sequence transmitted by the DMRS so can deduce the composite propagation channel by comparing the received DMRS with the transmitted DMRS

★ Within this context, the term 'precoding' includes the precoding which is applied for MIMO and beamforming. It does not include Transform Precoding. If Transform Precoding is enabled for the PUSCH (to generate a DFT-S-OFDM waveform), then it is applied to the PUSCH but is not applied to the DMRS. This approach helps to simplify the processing required for channel estimation

★ The DMRS is transmitted within the set of Resource Blocks allocated to the PUSCH. For example, if a UE is allocated 10 Resource Blocks for the PUSCH then both the DMRS and the PUSCH will be transmitted across those 10 Resource Blocks

★ The DMRS is transmitted on the same antenna ports as the PUSCH, i.e. antenna ports within the range 0 to 11

★ If the PUSCH is transmitted without Transform Precoding (CP-OFDM) then a length-31 Gold sequence is used to generate the pseudo random sequence of symbols which populate the DMRS Resource Elements. The pseudo random sequence is initialised using either a scrambling identity or the Physical layer Cell Identity (PCI). Up to 2 scrambling identities can be configured within the *DMRS-UplinkConfig* information presented in Table 214

★ If 2 scrambling identities are configured, the Base Station uses a single bit flag within DCI Format 0_1 to point towards one of the two identities. The first scrambling identity is always used if the Base Station allocates uplink resources using DCI Format 0_0 with a C-RNTI. The PCI is used if neither scrambling identity is configured

DMRS-UplinkConfig		
dmrs-Type	type2	
dmrs-AdditionalPosition	0, 1, 3	
phaseTrackingRS	SetupRelease { PTRS-UplinkConfig }	
maxLength	2	
transformPrecodingDisabled	scramblingID0	0 to 65535
	scramblingID1	0 to 65535
transformPrecodingEnabled	nPUSCH-Identity	0 to 1007
	disableSequenceGroupHopping	disabled
	sequenceHoppingEnabled	enabled

Table 214 – Parameter structure used to configure an uplink DMRS

★ If the PUSCH is transmitted with Transform Precoding (DFT-S-OFDM) then a Zadoff-Chu sequence is used to populate the DMRS Resource Elements. A Zadoff-Chu sequence is used because its lower Peak to Average Power Ratio (PAPR) is better suited to the poor coverage conditions associated with the use of DFT-S-OFDM

★ A UE is allocated a specific Zadoff-Chu sequence to transmit as the DMRS. The length of this sequence is equal to half of the number of subcarriers allocated to the PUSCH (the DMRS always occupies 50 % of the subcarriers when Transform Precoding is applied to the PUSCH). Zadoff-Chu sequences typically have cyclic shifts applied to generate additional sequences, e.g. when using Zadoff-Chu sequences for the PRACH or Sounding Reference Signal (SRS). However, the cyclic shift is fixed to 0 when using Zadoff-Chu sequences for the PUSCH DMRS

★ The Zadoff-Chu sequence is selected in two steps. The first step selects a group of sequences. There are 30 groups of sequences and these groups are indexed using the variable 'u'. The second step selects a sequence from within the group. Each group includes 1 sequence of each length when the length $\leq$ 60, indexed as 'v' = 0. Each group includes 2 sequences of each length when the length > 60, indexed as 'v' = {0, 1}. This means that sequence selection is not required for shorter sequences because there is only 1 sequence within each group. Selection is between 2 sequences when the sequences are longer

★ The group is selected using the equation shown below. This equation has a dependency upon the *disableSequenceGroupHopping* information element shown in Table 214. If *disableSequenceGroupHopping* is included then it indicates that group hopping is disabled, i.e. $f_{gh} = 0$ and the group index is determined by (n_{ID}^{RS}) mod 30. The value of n_{ID}^{RS} is given by the *nPUSCH-Identity* information element if it has been configured and if the PUSCH transmission is not a random access MSG3. Otherwise, the value of n_{ID}^{RS} is given by the PCI. If *disableSequenceGroupHopping* is excluded from the parameter structure then it indicates that group hopping is enabled. In this case, f_{gh} is a pseudo random result which depends upon the slot and symbol timing

Group hopping function   *nPUSCH-Identity* or PCI

$$u = \left(f_{gh} + n_{ID}^{RS}\right) \bmod 30$$

- Selection of a sequence from within a group has a dependency upon the sequence length and the *sequenceHoppingEnabled* information element. If the sequence length is ≤ 60 then there is only a single sequence of the appropriate length within each group and so that single sequence is always selected ($v = 0$). Similarly, if *sequenceHoppingEnabled* is excluded from the parameter structure then the first sequence of the appropriate length is selected ($v = 0$). Otherwise, if *sequenceHoppingEnabled* is included within the parameter structure and the sequence length > 60, then sequence selection is based upon a pseudo random result which depends upon the slot and symbol timing ($v = 0$ or 1)

- The DMRS for the PUSCH has been specified to be flexible and to support a wide range of configurations. These configurations account for the requirements associated with both Single User and Multi-User MIMO. DMRS configurations depend upon the following variables:
  - PUSCH DMRS Configuration Type 1 or Type 2
  - PUSCH Mapping Type A or Type B
  - DMRS Starting Symbol for Mapping Type A
  - Single or Double Symbol DMRS
  - PUSCH DMRS Additional Positions
  - PUSCH Duration

PUSCH DMRS Configuration Type 1 / 2

- The Configuration Type impacts the frequency domain resources used by the DMRS. Configuration Type 1 is always used when Transform Precoding is applied to the PUSCH because it provides a higher density of DMRS Resource Elements. This is better suited to the poor coverage conditions associated with Transform Precoding. Otherwise, the Configuration Type is configured using the *dmrs-Type* information element presented in Table 214 (inclusion of *dmrs-Type* indicates Type 2, while exclusion indicates Type 1)

- Figure 285 illustrates Configuration Type 1 which allocates every 2nd subcarrier to the DMRS. This creates a transmission comb and allows antenna ports to be frequency multiplexed. For example antenna ports 0 and 1 can be frequency multiplexed with antenna ports 2 and 3. Antenna ports sharing the same Resource Elements are differentiated using an Orthogonal Cover Code (OCC) which allows Code Division Multiplexing (CDM)

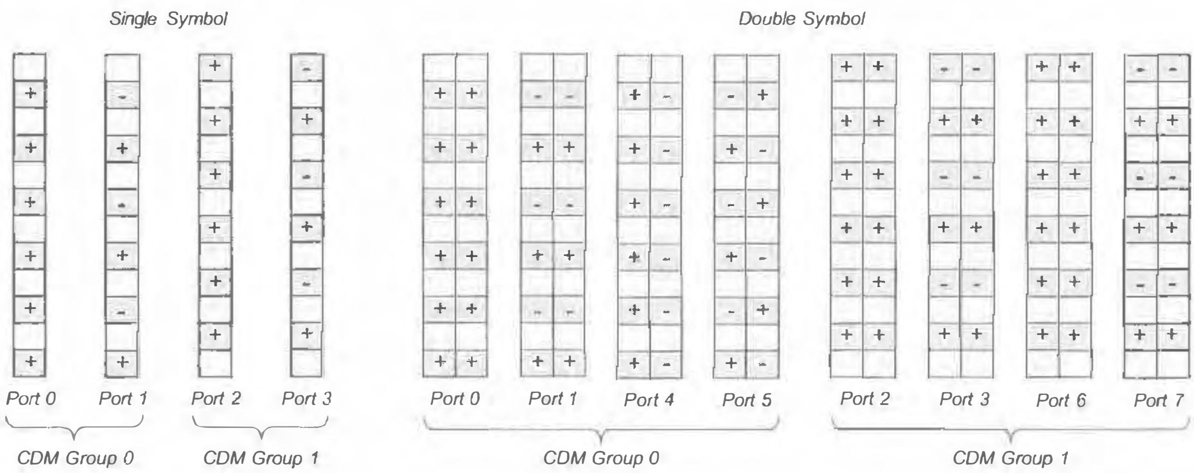


Figure 285 – PUSCH DMRS Configuration Type 1

- First consider the single symbol configurations. A UE transmitting 4 layers of data (rank 4) with Single User MIMO can be allocated antenna ports 0 to 3. These 4 antenna ports fully occupy the DMRS symbol and there are no Resource Elements available to the PUSCH. A UE transmitting a single layer of data (rank 1) with Single User MIMO can be allocated antenna port 0. This antenna port occupies only half of the Resource Elements within the DMRS symbol. A UE transmitting 2 layers of data (rank 2) with Single User MIMO can be allocated antenna ports 0 and 1, i.e. Code Division Multiplexing is prioritised over Frequency Division Multiplexing. This pair of antenna ports occupies only half of the Resource Elements within the DMRS symbol. In both of these cases, the remaining Resource Elements can be used by the PUSCH when Transform Precoding is not applied. The PUSCH cannot be frequency multiplexed with the DMRS when Transform Precoding is applied because the Transform Precoding operation spreads the PUSCH across all of the allocated subcarriers

- In the case of Multi-User MIMO, a first UE could be allocated single layer transmission with port 0, while a second UE is allocated single layer transmission with port 1 and a third UE is allocated single layer transmission with port 2. From the perspective of each UE, only a single port is utilised and each UE may think that it is possible to frequency multiplex the PUSCH within the DMRS symbol. However, this would create PUSCH to DMRS interference. For example, if the UE using antenna port 0 frequency multiplexed the PUSCH with the DMRS then the PUSCH would create interference towards the DMRS belonging to the UE using antenna port 2

★ 3GPP TS 38.212 specifies the 'Antenna Ports' field belonging to Downlink Control Information (DCI) Format 0_1 such that the Base Station can indicate whether or not the PUSCH is to be frequency multiplexed with the DMRS. Table 215 presents an example look-up table which is applicable to Configuration Type 1 with Single Symbol DMRS transmission and Transform Precoding disabled

Signalled Value	Allocated DMRS Port	Number of DMRS CDM Groups without Data
0	0	1
1	1	
2	0	2
3	1	
4	2	
5	3	

Table 215 – Example look-up table for Antenna Port allocation within DCI Format 0_1 (DMRS Configuration Type 1, Single Symbol, Rank 1)

★ In the case of Single User MIMO, the Base Station can signal a value of 0 or 1 to allocate a single port and indicate that the second CDM Group can be used by the PUSCH (only 1 CDM Group is to be transmitted without data). In the case of Multi-User MIMO, the Base Station can signal a value of 2, 3, 4 or 5 to allocate a single port and indicate that the second CDM Group cannot be used by the PUSCH (both CDM Groups are to be transmitted without data)

★ Figure 285 also illustrates the set of double symbol configurations. Using a second symbol allows the number of ports within each CDM group to be doubled from 2 to 4, i.e. a total of 8 antenna ports are supported when using the double symbol configuration. The set of 8 antenna ports cannot be fully utilised by a single UE because 3GPP release 15 supports a maximum of 4 layers per UE. However, the specification of 8 antenna ports increases the scope for Multi-User MIMO allowing up to 8 UE to be allocated a common set of PUSCH resources

★ Figure 286 illustrates Configuration Type 2 which allocates every 3[rd] pair of subcarriers to the DMRS. This reduces the number of subcarriers used by the DMRS relative to Configuration Type 1 and increases the scope for frequency multiplexing. In this case, up to 6 antenna ports can be multiplexed using Single Symbol transmission, and up to 12 antenna ports can be multiplexed using Double Symbol transmission. Configuration Type 2 is only applicable when Transform Precoding is disabled for the PUSCH

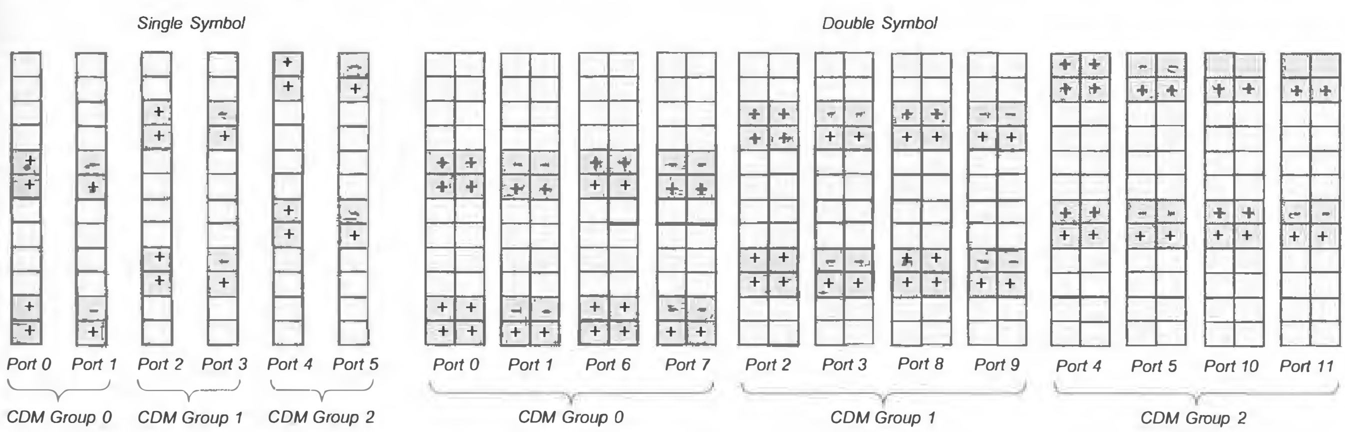


Figure 286 – PUSCH DMRS Configuration Type 2

PUSCH Mapping Type A / B

★ The PUSCH Mapping Type has an impact upon the time domain symbols allocated to the PUSCH. This impacts the symbols allocated to the DMRS because the DMRS can only use a subset of the resources allocated to the PUSCH

★ Selection between Mapping Types A and B is part of the PUSCH time domain resource allocation. Time domain resource allocation is based upon providing a pointer to a row within a look-up table. The look-up table can be a 3GPP standardised table or a configured table. In both cases, the tables include a column for the PUSCH Mapping Type. Examples are shown in Table 204 for a 3GPP standardised look-up table and in Table 206 for a configured look-up table (both in section 7.4.4.1)

★ Table 216 presents the starting symbols and lengths which are allowed for each Mapping Type. The length is defined as a duration in terms of symbols. A single resource allocation is always contained within a single slot and so the sum of the Starting Symbol index and the Length does not exceed 14 when using the normal cyclic prefix, and 12 when using the extended cyclic prefix

	Normal Cyclic Prefix			Extended Cyclic Prefix		
	Starting Symbol (S)	Length (L)	S + L	Starting Symbol (S)	Length (L)	S + L
PUSCH Mapping Type A	0	4 to 14	4 to 14	0	4 to 12	4 to 12
PUSCH Mapping Type B	0 to 13	1 to 14	1 to 14	0 to 11	1 to 12	1 to 12

Table 216 – Allowed combinations of Starting Symbol (S) and Length (L)

★ Resource allocations based upon Mapping Type A always start from the beginning of the slot, i.e. symbol 0. In this case, the first symbol used by the DMRS is configured using the *dmrs-TypeA-Position* information element which can have a value of 2 or 3. The duration of the PUSCH resource allocation is always at least 4 symbols. Figure 287 illustrates examples of the Resource Elements allocated to the DMRS for PUSCH Mapping Type A. These examples assume PUSCH DMRS Configuration Type 1 (every second Resource Element is allocated to the DMRS)

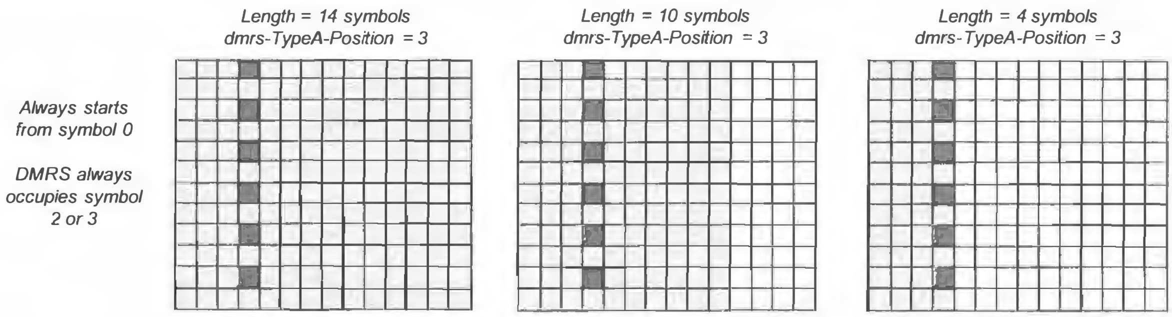


Figure 287 – Example resource allocations using PUSCH Mapping Type A

★ Resource allocations based upon Mapping Type B can start from any symbol within the slot, i.e. symbols 0 to 13 when using the normal cyclic prefix. In this case, the first symbol used by the DMRS is always the first symbol of the resource allocation. This is known as a 'Front Loaded' scheme because the DMRS is at the front of the PUSCH transmission. A 'Front Loaded' scheme can reduce latency because the Base Station can start estimating the propagation channel from the DMRS as soon as the first symbol has been received. PUSCH Mapping Type B allows very short resource allocations with a minimum duration of 1 symbol. Figure 288 illustrates examples of the Resource Elements allocated to the DMRS for PUSCH Mapping Type B. These examples assume PUSCH DMRS Configuration Type 1 (every second Resource Element is allocated to the DMRS)

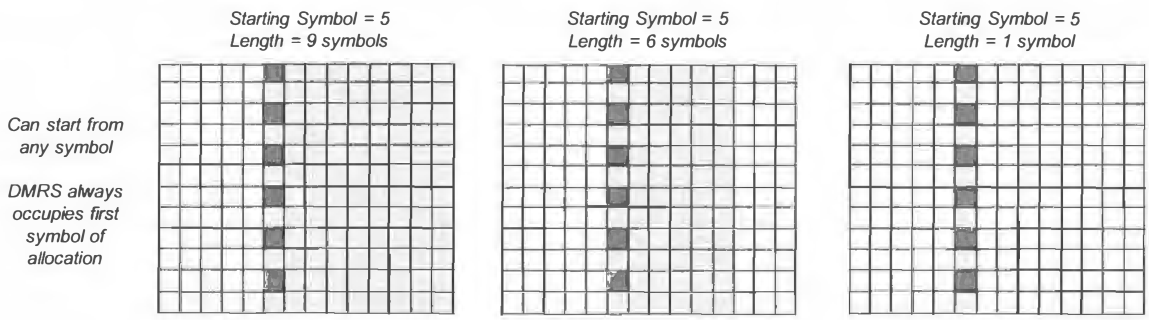


Figure 288 – Example resource allocations using PUSCH Mapping Type B

★ Mapping Type B provides scope for self-contained slots. A self-contained slot includes both the PDCCH which provides the resource allocation and the PUSCH which uses the resource allocation. In this case, it is useful to have a 'Front Loaded' DMRS because it provides the UE with some additional time to process the data to be transferred on the PUSCH. An example of a self-contained slot is illustrated in Figure 289. This example assumes that the final symbol is occupied by the PUCCH to transfer uplink control information

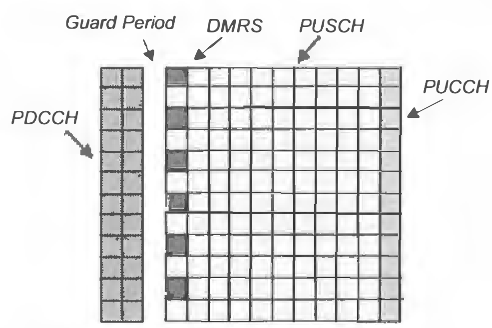


Figure 289 – Example of a self-contained slot

Additional DMRS Positions

★ Mapping Types A and B both allow the DMRS to use additional symbols. Additional DMRS symbols can improve the Base Station channel estimation performance. If a PUSCH transmission includes 2 DMRS symbols then the propagation channel can be measured at 2 time instants and then interpolated between those time instants. Increasing the number of DMRS symbols, reduces the gap between channel estimates and reduces the requirement for long interpolations. This is particularly important for high speed scenarios where the propagation channel can change rapidly and there are large frequency offsets to track. The drawback of additional DMRS symbols is an increased overhead

★ The requirement for additional DMRS symbols can depend upon the subcarrier spacing because higher subcarrier spacings have shorter symbols which allow less time for the propagation channel to change, i.e. higher subcarrier spacings require fewer additional DMRS symbols. For example, 4 DMRS symbols may be required to achieve good performance for very high speed scenarios when using a 30 kHz subcarrier spacing, while 3 DMRS symbols may be sufficient for the same scenario when using the 60 kHz subcarrier spacing

★ The number of additional symbols and their positions are determined using a combination of the *dmrs-AdditionalPosition* parameter (presented in Table 214) and the duration of the PUSCH resource allocation. 3GPP TS 38.211 specifies the look-up table presented as Table 217. The DMRS can use up to 3 additional symbols when the PUSCH resource allocation is relatively long, i.e. a total of 4 symbols. The symbol positions are specified relative to the start of the PUSCH resource allocation. In the case of Mapping Type A, the first symbol allocated to the DMRS is referenced as l_0 which corresponds to the *dmrs-TypeA-Position*

<table>
<tr><th rowspan="3">Duration (symbols)</th><th colspan="4">PUSCH Mapping Type A</th><th colspan="4">PUSCH Mapping Type B</th></tr>
<tr><th colspan="4">dmrs-AdditionalPosition</th><th colspan="4">dmrs-AdditionalPosition</th></tr>
<tr><th>0</th><th>1</th><th>2</th><th>3</th><th>0</th><th>1</th><th>2</th><th>3</th></tr>
<tr><td>< 4</td><td colspan="4">Not Applicable</td><td rowspan="12">0</td><td colspan="3" rowspan="2">0</td></tr>
<tr><td>4</td><td rowspan="11">l_0</td><td colspan="3" rowspan="4">l_0</td></tr>
<tr><td>5</td><td colspan="3" rowspan="3">0, 4</td></tr>
<tr><td>6</td></tr>
<tr><td>7</td></tr>
<tr><td>8</td><td colspan="3" rowspan="2">l_0, 7</td><td rowspan="2">0, 6</td><td colspan="2" rowspan="2">0, 3, 6</td></tr>
<tr><td>9</td></tr>
<tr><td>10</td><td rowspan="3">l_0, 9</td><td rowspan="3">l_0, 6, 9</td><td rowspan="2">l_0, 6, 9</td><td rowspan="2">0, 8</td><td rowspan="2">0, 4, 8</td><td rowspan="5">0, 3, 6, 9</td></tr>
<tr><td>11</td></tr>
<tr><td>12</td><td rowspan="3">l_0, 5, 8, 11</td><td rowspan="3">0, 10</td><td rowspan="3">0, 5, 10</td></tr>
<tr><td>13</td><td rowspan="2">l_0, 11</td><td rowspan="2">l_0, 7, 11</td></tr>
<tr><td>14</td></tr>
</table>

Table 217 – Additional DMRS Symbols for PUSCH Mapping Type A/B (Single Symbol DMRS)

★ Figure 290 illustrates some example PUSCH resource allocations which are configured with additional DMRS symbols. The first two examples are based upon PUSCH Mapping Type A (the DMRS does not occupy the first symbol within the resource allocation). The third example is based upon PUSCH Mapping Type B (the DMRS occupies the first symbol within the resource allocation)

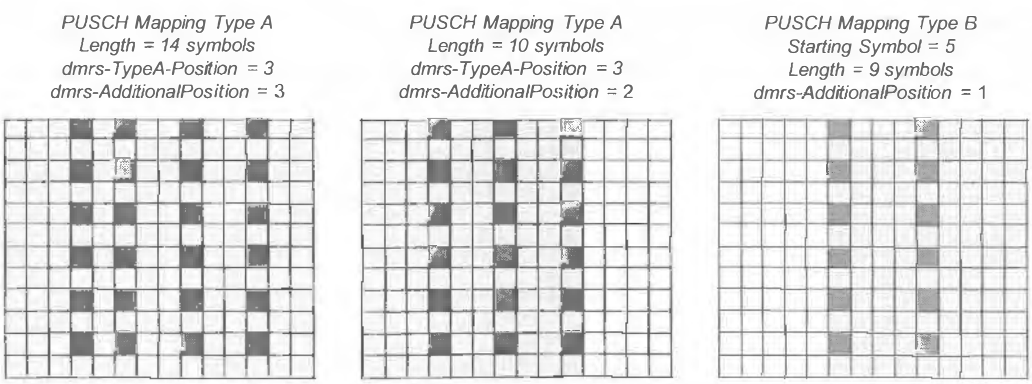


Figure 290 – Example resource allocations with additional DMRS symbols

Double Symbol DMRS

- The concept of 'Double Symbol' DMRS has already been introduced within the section describing Configuration Types 1 and 2. It was illustrated in that section that using a pair of symbols increases the code multiplexing capability of the DMRS, i.e. there are 4 antenna ports per CDM group rather than 2 antenna ports per CDM group. This increases the total number of antenna ports and so increases the scope for Multi-User MIMO
- When allocating Double Symbol DMRS, a different look-up table is applied when configuring additional DMRS positions, i.e. Table 217 is replaced by Table 218. In this case, only values of 0 and 1 are used by the *dmrs-AdditionalPosition* parameter. The maximum number of symbols allocated to the DMRS remains equal to 4
- The use of Double Symbol DMRS can be restricted using the *maxLength* parameter presented in Table 214. If this parameter is excluded from *DMRS-UplinkConfig* then only single symbol transmission is permitted. If *maxLength* is included within *DMRS-UplinkConfig* then both single and double symbol transmission is permitted. In this case, selection between single and double symbol DMRS is controlled by the 'Antenna Ports' field within DCI Format 0_1

<table>
<tr><th rowspan="3">Duration (symbols)</th><th colspan="4">PUSCH Mapping Type A</th><th colspan="4">PUSCH Mapping Type B</th></tr>
<tr><th colspan="4">dmrs-AdditionalPosition</th><th colspan="4">dmrs-AdditionalPosition</th></tr>
<tr><th>0</th><th>1</th><th>2</th><th>3</th><th>0</th><th>1</th><th>2</th><th>3</th></tr>
<tr><td>< 4</td><td colspan="2">Not Applicable</td><td colspan="2" rowspan="11">Not Used</td><td colspan="2" rowspan="2">Not Used</td><td colspan="2" rowspan="11">Not Used</td></tr>
<tr><td>4</td><td rowspan="10">l_0, $l_0 + 1$</td><td rowspan="6">l_0, $l_0 + 1$</td></tr>
<tr><td>5</td><td rowspan="10">0, 1</td><td rowspan="3">0, 1</td></tr>
<tr><td>6</td></tr>
<tr><td>7</td></tr>
<tr><td>8</td><td rowspan="2">0, 1, 5, 6</td></tr>
<tr><td>9</td></tr>
<tr><td>10</td><td rowspan="3">l_0, $l_0 + 1$, 8, 9</td><td rowspan="2">0, 1, 7, 8</td></tr>
<tr><td>11</td></tr>
<tr><td>12</td><td rowspan="3">0, 1, 9, 10</td></tr>
<tr><td>13</td><td rowspan="2">l_0, $l_0 + 1$, 10, 11</td></tr>
<tr><td>14</td></tr>
</table>

Table 218 – Additional DMRS Symbols for PUSCH Mapping Type A/B (Double Symbol DMRS)

- Figure 291 illustrates some example PUSCH resource allocations which are configured with additional DMRS symbols. The first two examples are based upon PUSCH Mapping Type A (the DMRS does not occupy the first symbol within the resource allocation). The third example is based upon PUSCH Mapping Type B (the DMRS occupies the first symbol within the resource allocation)

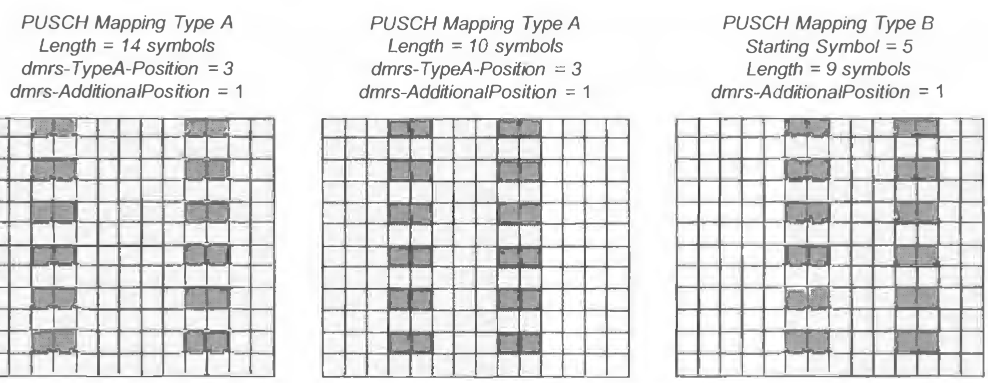


Figure 291 – Example resource allocations with Double Symbol DMRS

- 3GPP References: TS 38.211, TS 38.212, TS 38.213, TS 38.214, TS 38.331

7.5.2 DEMODULATION REFERENCE SIGNAL FOR PUCCH

- ★ PUCCH Formats 1, 2, 3 and 4 are transmitted in combination with a Demodulation Reference Signal (DMRS). This allows coherent detection at the Base Station. PUCCH Format 0 does not use a DMRS and so relies upon non-coherent detection
- ★ Both the PUCCH and the DMRS are transmitted using antenna port 2000
- ★ This section provides an overview of the DMRS. Section 7.3 includes figures to illustrate the PUCCH Resource Elements allocated to the DMRS

7.5.2.1 PUCCH FORMAT 1

- ★ PUCCH Format 1 occupies 1 Resource Block in the frequency domain and between 4 and 14 symbols in the time domain
- ★ The DMRS occupies every second symbol allocated to PUCCH Format 1
- ★ The DMRS is generated from a Zadoff-Chu sequence of length 12, i.e. one entry per subcarrier. The sequence of length 12 is spread to generate multiple sequences of length 12 when the DMRS occupies more than one symbol. For example, a spreading factor of 4 is used to generate 4 sequences of length 12 when the DMRS occupies 4 symbols. The spreading codes are the same as those used for the PUCCH payload and are presented in Table 186

7.5.2.2 PUCCH FORMAT 2

- ★ PUCCH Format 2 occupies between 1 and 16 Resource Blocks in the frequency domain and either 1 or 2 symbols in the time domain
- ★ The DMRS occupies every third subcarrier allocated to PUCCH Format 2
- ★ Length 31 Gold sequences are used to generate the pseudo random sequence of symbols which populate the DMRS Resource Elements. The pseudo random sequence is initialised using either a scrambling identity or the Physical layer Cell Identity (PCI). The scrambling identity can be configured using *scramblingID0* within the *DMRS-UplinkConfig* information presented in Table 214

7.5.2.3 PUCCH FORMAT 3

- ★ PUCCH Format 3 occupies between 1 and 16 Resource Blocks in the frequency domain and between 4 and 14 symbols in the time domain
- ★ The DMRS occupies specific symbols which have been allocated to PUCCH Format 3. These symbols are illustrated in Figure 260
- ★ The DMRS is generated from a Zadoff-Chu sequence with a length which equals the number of subcarriers allocated to PUCCH Format 3. Cyclic shifts are applied to generate the sequences used to populate each DMRS symbol. These cyclic shifts depend upon the slot and symbol number

7.5.2.4 PUCCH FORMAT 4

- ★ PUCCH Format 4 occupies 1 Resource Block in the frequency domain and between 4 and 14 symbols in the time domain
- ★ The DMRS occupies specific symbols which have been allocated to PUCCH Format 4. These symbols are the same as those allocated to the DMRS for PUCCH Format 3 and are illustrated in Figure 260
- ★ The DMRS is generated from a Zadoff-Chu sequence of length 12. Cyclic shifts which depend upon the PUCCH Format 4 spreading factor, slot number and symbol number are applied to generate the sequences used to populate each DMRS symbol

- ★ 3GPP References: TS 38.211, TS 38.331

7.5.3 SOUNDING REFERENCE SIGNAL

★ The Sounding Reference Signal (SRS) is transmitted by the UE according to instructions provided by the Base Station. The Base Station measures the uplink propagation channel from the SRS. This UE specific measurement can then be used for:

  o uplink channel aware scheduling and link adaptation. The Base Station can use the SRS to measure the uplink propagation channel for each Resource Block within the active Bandwidth Part. The packet scheduler can then identify the best set of Resources Blocks to allocate. In addition, the uplink SINR can be measured from the SRS and this can be used as an input for link adaptation when identifying the appropriate Modulation and Coding Scheme (MCS)

  o estimation of the downlink propagation channel when channel reciprocity exists, i.e. TDD deployments. The Base Station can use this information for its downlink transmissions towards the UE. There are two general categories for downlink channel sounding using the SRS:

    ▪ the number of transmit paths at the UE equals the number of receive antenna at the UE: in this case, the SRS can be transmitted from each UE receive antenna so the Base Station can deduce the downlink propagation channel towards each antenna

    ▪ the number of transmit paths at the UE is less than the number of receive antenna at the UE: in this case, the UE must be capable of antenna switching to allow the SRS to be transmitted from each receive antenna. UE declare this capability to the Base Station to allow the SRS to be configured appropriately

  o non-codebook based transmission which involves the UE transmitting a set of SRS, where each SRS is precoded using a different set of UE generated weights. The Base Station evaluates these SRS transmissions and provides feedback regarding which set of weights should be applied when transmitting the PUSCH. Non-codebook based transmission assumes channel reciprocity so the UE is able to generate uplink precoding weights based upon downlink measurements

  o codebook based transmission which involves the UE transmitting a set of non-precoded SRS. The Base Station uses these SRS transmissions to select the antenna ports to be used for the PUSCH, and to select the appropriate Rank and precoding weights. The precoding weights are selected from a 3GPP standardised codebook. The Base Station provides feedback to the UE in terms of an SRS Resource Indicator (SRI), Rank Indicator (RI) and Transmit Precoding Matrix Indicator (TPMI). Codebook based transmission does not assume channel reciprocity so the UE is unable to generate uplink precoding weights based upon downlink measurements

  o uplink beam management for connections which do not benefit from uplink/downlink beam correspondence, i.e. the best UE transmit beam and the best UE receive beam cannot be assumed to be the same, and similarly the best Base Station receive beam and the best Base Station transmit beam cannot be assumed to be the same. SRS transmissions can be used to identify both the best UE transmit beam and the best Base Station receive beam

★ When using the SRS in combination with channel reciprocity to estimate the downlink propagation channel it should be recognised that SRS measurements do not quantify the downlink interference conditions. Thus, the SRS alone does not fully characterise the downlink radio conditions. This is particularly important towards cell edge where interference levels can be more significant. The UE must provide additional information to help characterise the downlink interference conditions, e.g. a CQI report

★ A UE can be configured to transmit the SRS from 1, 2 or 4 antenna ports. These antenna ports are numbered 1000, 1001, 1002, 1003

★ An SRS transmission can occupy 1, 2 or 4 symbols in the time domain. These symbols can be located within the last 6 symbols of a slot, i.e. symbols 8 to 13 (14 symbols per slot numbered from 0 to 13)

★ An SRS transmission can occupy up to 272 Resource Blocks in the frequency domain. An individual UE does not transmit the SRS on every subcarrier but uses a transmission comb to select a specific set of subcarriers. Transmission comb sizes of 2 and 4 are supported (illustrated in Figure 292). A transmission comb size of 2 means that an individual UE transmits on every second subcarrier. This allows two groups of UE to be frequency multiplexed with a single subcarrier offset between the two groups. A transmission comb size of 4 means that an individual UE transmits on every fourth subcarrier. This increases the frequency domain multiplexing capability but reduces the quality of the SRS measurements

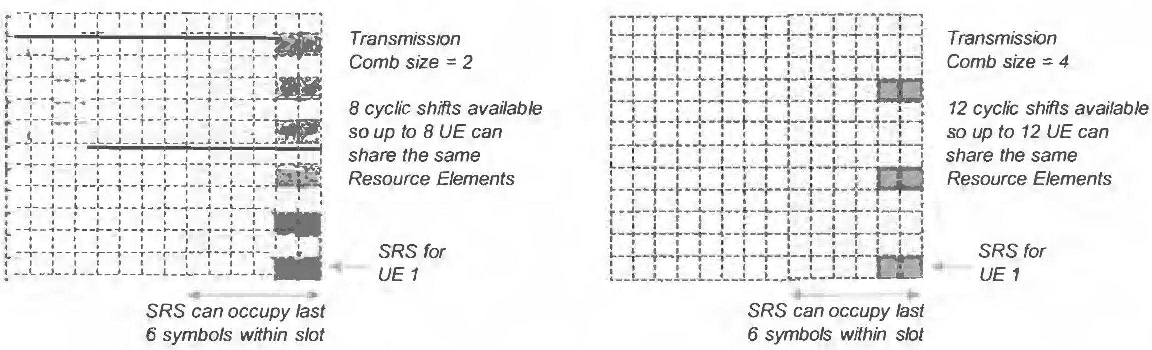


Figure 292 – Example SRS with Transmission Comb sizes of 2 and 4 (SRS duration assumed to be 2 symbols)

★ The SRS transmits a sequence with a specific cyclic shift. There are 12 cyclic shifts available when using the transmission comb size of 4, and 8 cyclic shifts available when using the transmission comb size of 2. UE sharing the same transmission comb are code multiplexed by allocating different cyclic shifts. In addition, when an individual UE transmits the SRS from multiple antenna ports then each antenna port is allocated a different cyclic shift

★ The SRS is configured using one or more SRS Resource Sets, where each set includes one or more SRS Resources. This general concept is illustrated in Figure 293. Some characteristics are configured at a set level while other characteristics are configured at a resource level. The SRS triggering mechanism is configured at a set level. This means that an SRS trigger leads to SRS transmissions for all SRS Resources within the set. The use case for the SRS Resources is also configured at a set level. This means that the SRS Resources within a set are all used for a common purpose. For example, one SRS Resource Set can be configured for non-codebook based transmission while another SRS Resource Set can be configured for downlink channel sounding

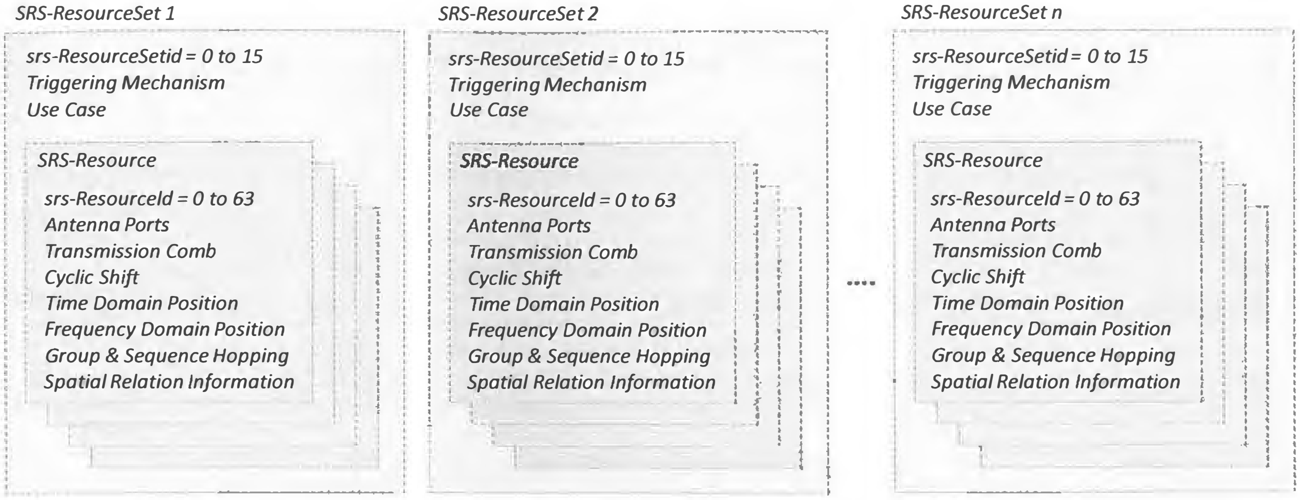


Figure 293 – SRS Resources within SRS Resource Sets

★ The parameter structure used to configure an SRS Resource Set is illustrated in Table 219. This parameter structure is configured separately for each uplink Bandwidth Part. Up to 16 SRS Resources can be linked to an SRS Resource Set, i.e. up to 16 instances of *SRS-ResourceId* belonging to *srsResourceIdList*

★ The UE capability information indicates various upper limits for the maximum number of supported SRS Resources, e.g. the maximum number of SRS Resources within a Bandwidth Part with an aperiodic trigger, and the maximum number of SRS Resources within an SRS Resource Set when the *usage* is set to *beamManagement*

SRS-ResourceSet						
srs-ResourceSetId	0 to 15					
srs-ResourceIdList	LIST (up to 16 instances)					
	SRS-ResourceId					
resourceType	CHOICE					
	aperiodic		semi-persistent		periodic	
	aperiodicSRS-Resourcetrigger	1 to 3	associatedCSI-RS	0 to 191	associatedCSI-RS	0 to 191
	csi-RS	0 to 191				
	slotOffset	1 to 32				
usage	beamManagement, codebook, nonCodebook, antennaSwitching					
alpha	0, 0.4, 0.5, 0.6, 0.7, 0.8, 0.9, 1.0					
p0	-202 to 24					
pathlossReferenceRS	CHOICE					
	ssb-Index			csi-RS-Index		
	0 to 63			0 to 191		
srs-PowerControl AdjustmentStates	sameAsFci2, separateClosedLoop					

Table 219 – Parameter structure used to configure an SRS Resource Set

★ The SRS triggering mechanism is configured using the *resourceType* information element. It can be configured as aperiodic, semi-persistent or periodic. These options are illustrated in Figure 294

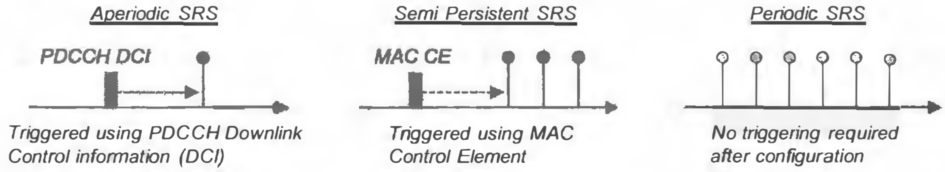


Figure 294 – Triggering mechanisms for the SRS

★ An aperiodic SRS transmission is triggered using Downlink Control Information (DCI) on the PDCCH. The following DCI Formats can include an SRS Request field: DCI Format 0_1 used for uplink resource allocations; DCI Format 1_1 used for downlink resource allocations; and DCI Format 2_3 used for UE-Group Common Signalling of SRS Transmit Power Control (TPC) commands. The SRS Request field has a length of 2 bits to provide a range from 0 to 3. The value of 0 means that an SRS transmission is not requested. The values 1, 2 and 3 can be used to address specific SRS Resource Sets, i.e. the value of the SRS Request field within the DCI must match the value of *aperiodicSRS-Resourcetrigger* within an SRS Resource Set configuration. An additional 1 bit is included within DCI Formats 0_1 and 1_1 when the UE is configured with a Supplementary Uplink to indicate whether the SRS trigger is for the Normal Uplink or the Supplementary Uplink

★ A semi-persistent SRS transmission is triggered using the MAC Control Element (CE) illustrated in Figure 295. Downlink MAC Control Elements are transmitted on the PDSCH. This MAC Control Element can be used to both activate and deactivate the transmission of an SRS Resource Set. The MAC Control Element addresses the SRS Resources using the Serving Cell, Bandwidth Part and SRS Resource Set identities. There is also a flag to indicate whether the SRS trigger is for the Normal Uplink or the Supplementary Uplink. The F_m field indicates the type of resource to be used as a reference for the spatial relationship of the m[th] SRS Resource. The single bit can indicate a resource type of either a Non-Zero Power (NZP) CSI Reference Signal or a Synchronisation Signal Block (SSB) / SRS Resource. If the latter is indicated then the first bit of the Resource ID is used to differentiate between an SSB and an SRS Resource. The Resource ID provides the identity of the resource to be used as a reference for the spatial relationship of the SRS. The Resource Serving Cell ID and Resource Bandwidth Part ID are included if the resource does not belong to the serving cell and Bandwidth Part specified at the start of the MAC Control Element

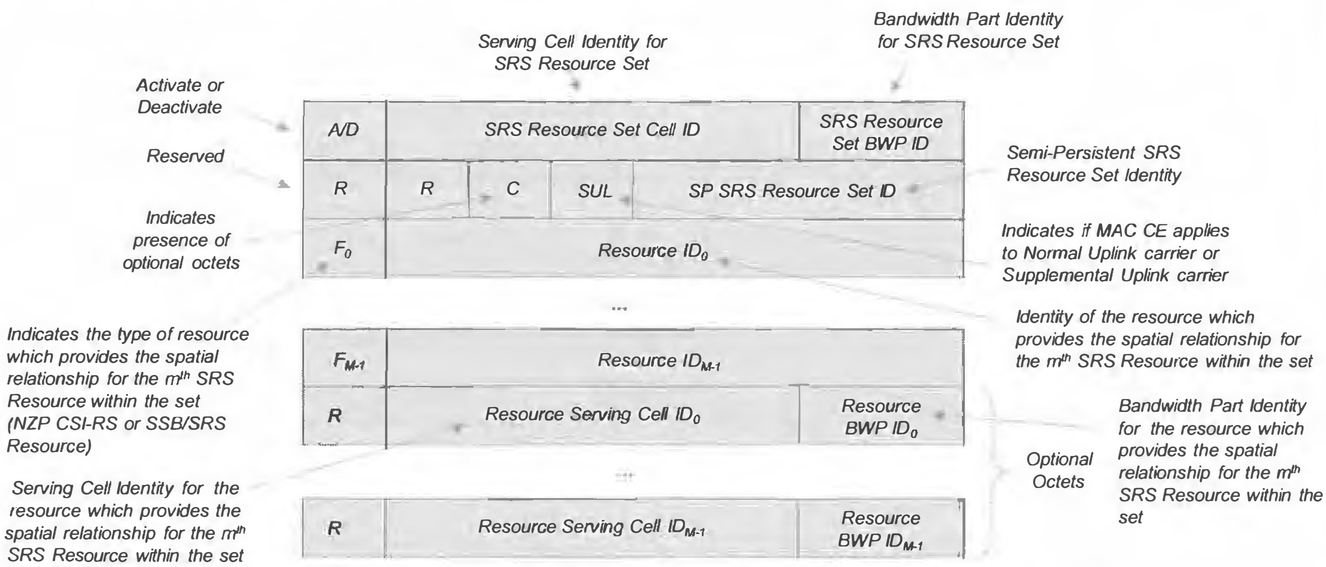


Figure 295 – MAC Control Element used to activate/deactivate Semi-Persistent SRS transmissions

★ Periodic SRS transmissions do not require an activation instruction after the UE receives the SRS Resource Set configuration. Instead, the UE starts transmitting the SRS at the appropriate time instants as soon as the configuration is received

★ Table 219 shows a *csi-RS* information element belonging to the aperiodic configuration and an *associatedCSI-RS* information element belonging to the semi-persistent and periodic configurations. These information elements are only included if the *usage* is set to non-codebook. In this case, channel reciprocity is assumed and the UE can use the CSI Reference Signal to determine the precoding weights to be applied to the SRS

★ The *alpha*, *p0*, *pathlossReferenceRS* and *srs-PowerControlAdjustmentStates* parameters are used for the SRS power control calculation. These parameters are described in section 13.3.3

★ The parameter structure used to configure an SRS Resource is illustrated in Table 220. These parameters are used to configure the resources used by the SRS transmission, i.e. the antenna port, the Transmission Comb, the time and frequency domain resources and the cyclic shift code domain resources

SRS-Resource			
srs-ResourceId			0 to 63
nrofSRS-Ports			1, 2, 4 ports
Ptrs-Portindex			0, 1
transmissionComb	CHOICE: 2	combOffset-n2	0, 1
		cyclicShift-n2	0 to 7
	CHOICE: 4	combOffset-n4	0 to 3
		cyclicShift-n4	0 to 11
resourceMapping		startPosition	0 to 5
		nrofSymbols	1, 2, 4
		repetitionFactor	1, 2, 4
freqDomainPosition			0 to 67
freqDomainShift			0 to 268
freqHopping		c-SRS	0 to 63
		b-SRS	0 to 3
		b-hop	0 to 3
groupOrSequenceHopping			Neither, groupHopping, sequenceHopping
resourceType	CHOICE: aperiodic		
	CHOICE: Semi-persistent	periodicityAndOffset	1, 2, 4, 5, 8, 10, 16, 20, 32, 40, 64, 80, 160, 320, 640, 1280, 2560
	CHOICE: periodic	periodicityAndOffset	1, 2, 4, 5, 8, 10, 16, 20, 32, 40, 64, 80, 160, 320, 640, 1280, 2560
sequenceId			BIT STRING (10)
spatialRelationInfo	servingCellId		0 to 31
	referenceSignal (CHOICE)	Ssb-Index	0 to 63
		Csi-RS-Index	0 to 191
		srs: resourceId	0 to 63
		srs: uplinkBWP	0 to 4

Table 220 – Parameter structure used to configure an SRS Resource

★ A UE is allocated a specific Zadoff-Chu sequence to transmit as the SRS. The length of this sequence is equal to the number of allocated Resource Elements. For example, if the UE transmits the SRS across 4 Resource Blocks using a Transmission Comb size of 2 then the sequence has a length of 4 × 12 / 2 = 24. The maximum sequence length is 1632 based upon an SRS transmission across 272 Resource Blocks using a Transmission Comb size of 2

★ The allocated sequence has a cyclic shift applied using the equation below, where α represents the cyclic shift and $\bar{r}_{u,v}(n)$ represents the sequence. It is not immediately obvious that α is generating a cyclic shift. However, a cyclic shift in the time domain corresponds to a series of phase shifts in the frequency domain. The sequence is mapped directly onto the set of subcarriers so corresponds to a frequency domain sequence. The combination of 'α' and 'n' provides the series of frequency domain phase shifts which generate the cyclic shift in the time domain

$$r_{u,v}^{(\alpha,\delta)}(n) = e^{j\alpha n} \times \bar{r}_{u,v}(n) \qquad 0 \leq n < \text{Length of Sequence}$$

★ 3GPP TS 38.211 specifies the cyclic shift (phase shift) using the equation shown below:

Allocated Cyclic Shift
cyclicShift-n2 or *cyclicShift-n4*

Antenna port number
1000, 1001, 1002 or 1003

$$\alpha = \frac{2\pi}{n_{SRS}^{cs,max}} \times \left[\left(n_{SRS}^{cs} + \frac{n_{SRS}^{cs,max} \times (p_i - 1000)}{N_{ap}^{SRS}} \right) mod\ n_{SRS}^{cs,max} \right]$$

Maximum number of Cyclic Shifts
8 for Transmission Comb size of 2
12 for Transmission Comb size of 4

Number of allocated antenna ports
nrofSRS-Ports

★ This equation generates values within the range: {0, 1, 2, … 5, 6, 7} × 2π/8 when using a Transmission Comb size of 2, and values within the range: {0, 1, 2, … 9, 10, 11} × 2π/12 when using a Transmission Comb size of 4. Different cyclic shifts are allocated to different antenna ports so a UE which transmits the SRS from 4 antenna ports requires 4 cyclic shifts. For example, a UE which is configured using *transmissionComb* = 4, *cyclicShift-n4* = 0 and *nrofSRS-Ports* = 4 will be allocated cyclic shifts of {0, 3, 6, 9} × 2π/12. The separation between the cyclic shifts allocated to the set of antenna ports is maximised to reduce the potential for misdetection

★ The sequence to which the cyclic shift is applied ($\bar{r}_{u,v}(n)$ in the equation above) is selected in two steps. The first step selects a group of sequences. There are 30 groups of sequences and these groups are indexed using the variable '*u*'. The second step selects a sequence from within the group. Each group includes 1 sequence of each length when the length ≤ 60, indexed as '*v*' = 0. Each group includes 2 sequences of each length when the length > 60, indexed as '*v*' = {0, 1}. This means that sequence selection is not required for shorter sequences because there is only 1 sequence within each group. Selection is between 2 sequences when the sequences are longer

★ The group is selected using the equation shown below. This equation has a dependency upon the *groupOrSequenceHopping* information element shown in Table 220. If *groupOrSequenceHopping* is set to 'Neither' or 'sequenceHopping' then $f_{gh}(n^{\mu}_{s,f}, l') = 0$ and the group index only depends upon the n^{SRS}_{ID}. If *groupOrSequenceHopping* is set to 'groupHopping' then $f_{gh}(n^{\mu}_{s,f}, l')$ generates a pseudo random result which depends upon the slot and symbol timing

Slot number within the radio frame for
subcarrier spacing configuration, µ

$$u = \left(f_{gh}\left(n^{\mu}_{s,f}, l'\right) + n^{SRS}_{ID}\right) \; mod \; 30$$

0 to *nrofSymbols* - 1　　*sequenceId*

★ The Sequence Identity (n^{SRS}_{ID}) is configured using a bit string of length 10 (as shown in Table 220). These 10 bits provide a range from 0 to 1023. Neighbouring cells should be configured with values which generate different results from the expression: (n^{SRS}_{ID}) mod 30. This ensures that neighbouring cells use different groups of sequences. One possible solution is to plan the Physical layer Cell Identities (PCI) using a mod 30 rule and then set n^{SRS}_{ID} = PCI

★ Selection of a sequence from within a group has a dependency upon the sequence length and the *groupOrSequenceHopping* information element. If the sequence length is ≤ 60 then there is only a single sequence of the appropriate length within each group and so that single sequence is always selected (*v* = 0). Similarly, if *groupOrSequenceHopping* is set to 'Neither' or 'groupHopping' then the first sequence of the appropriate length is selected (*v* = 0). Otherwise, if *groupOrSequenceHopping* is set to 'sequenceHopping' and the sequence length > 60, then sequence selection is based upon a pseudo random result which depends upon the slot and symbol timing (*v* = 0 or 1)

★ The key parameters used to configure the frequency domain position of the SRS are included within the *freqHopping* parameter structure, i.e. *c-SRS*, *b-SRS* and *b-hop* visible in Table 220. These parameters are similar to those used by LTE. A key difference is that 5G uses dedicated signalling to configure *c-SRS*, whereas LTE broadcasts *c-SRS* (known as *srs-BandwidthConfig* in LTE) within the System Information, i.e. *c-SRS* is UE specific in 5G, whereas it is cell specific in LTE. The UE specific value for *c-SRS* provides the Base Station with greater flexibility when allocating frequency domain SRS resources

★ The *c-SRS* and *b-SRS* parameters are used to identify a row and column within a look-up table specified by 3GPP TS 38.211. A subset of this look-up table is presented in Table 221 (the complete table has 64 rows). Each combination of (*c-SRS*, *b-SRS*) corresponds to a combination of ($m_{SRS,b}$, N_b)

C_{SRS}	$B_{SRS} = 0$		$B_{SRS} = 1$		$B_{SRS} = 2$		$B_{SRS} = 3$	
	$m_{SRS,0}$	N_0	$m_{SRS,1}$	N_1	$m_{SRS,2}$	N_2	$m_{SRS,3}$	N_3
0	4	1	4	1	4	1	4	1
1	8	1	4	2	4	1	4	1
2	12	1	4	3	4	1	4	1
3	16	1	4	4	4	1	4	1
…	…	…	…	…	…	…	…	…
30	128	1	64	2	32	2	4	8
31	128	1	64	2	16	4	4	4
…	…	…	…	…	…	…	…	…
60	264	1	132	2	44	3	4	11
61	272	1	136	2	68	2	4	17
62	272	1	68	4	4	17	4	1
63	272	1	16	17	8	2	4	2

Table 221 – SRS Bandwidth Configurations (indexed using *c-SRS* and *b-SRS*)

★ The $m_{SRS,b}$ parameter defines the number of Resource Blocks used for the SRS transmission. Table 221 illustrates that the allocation can range from 4 to 272 Resource Blocks. The N_b parameter is used as an input when calculating the frequency domain position of the Resource Block allocation

★ The frequency domain resource allocations associated with a specific value of *c-SRS* are organised in a nested tree structure. An example of this tree structure based upon *c-SRS* = 30 is illustrated in Figure 296. The largest resource allocation associated with *c-SRS* = 30 is 128 Resource Blocks. This could be used to complete channel sounding across an uplink Bandwidth Part which has a similar number of Resource Blocks

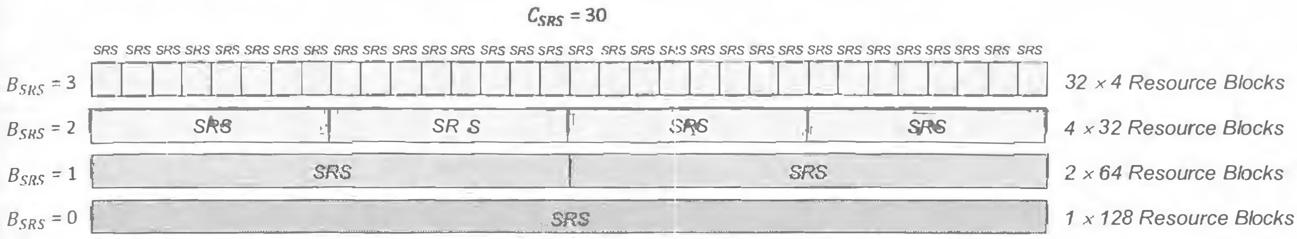


Figure 296 – Nested Tree structure of SRS transmissions with common C_{SRS}

★ Transmitting the SRS across a large bandwidth requires a relatively high UE transmit power. UE which experience a high path loss towards cell edge may not have sufficient power to allow reliable detection at the Base Station. These UE can be allocated a smaller SRS bandwidth to increase the received power density. The example illustrated in Figure 296 allows smaller allocations of 64, 32 and 4 Resource Blocks. The drawback associated with smaller bandwidths is a reduced quantity of information regarding the propagation channel, i.e. the Base Station is restricted to measuring the propagation channel across a smaller section of the uplink Bandwidth Part. If the Base Station requires knowledge of the propagation channel across the whole Bandwidth Part then multiple SRS transmissions with frequency hopping are required. For example, the UE would be required to transmit the SRS four times when using 32 Resource Blocks, or 32 times when using 4 Resource Blocks. The requirement to transmit the SRS multiple times increases delay and there is a risk that the first measurements become out-of-date before the last measurements have been completed

★ Transmitting the SRS across a smaller bandwidth provides the benefit of an increased multiplexing capacity. For example, the multiplexing capacity can be doubled is all UE transmit the SRS with a bandwidth of 64 Resource Blocks rather than 128 Resource Blocks

★ The *b-hop* parameter within the *freqHopping* parameter structure determines whether or not frequency hopping is active

- frequency hopping is inactive if *b-hop* ≥ *b-SRS*. For example, if *b-SRS* = 0 (*b-hop* is always ≥ 0) then the SRS transmission already spans the maximum bandwidth and frequency hopping is not necessary. If the UE transmits a smaller SRS bandwidth with frequency hopping disabled then the frequency domain position of the SRS is determined by the *freqDomainPosition* parameter presented in Table 220

- frequency hopping is active if *b-hop* < *b-SRS*. The extent of the frequency hopping depends upon the value of *b-hop*. Smaller values of *b-hop* lead to an increased number of frequency hopping positions. Figure 297 illustrates the increase in frequency hopping positions as the value of *b-hop* decreases when *c-SRS* = 30 and *b-SRS* = 3. The location of the frequency hopping positions depends upon the value of *freqDomainPosition*. For example, if *b-hop* = 1 then some UE can frequency hop across the left half of the bandwidth (as illustrated in Figure 297), while other UE with different *freqDomainPosition* values can frequency hop across the right half of the bandwidth

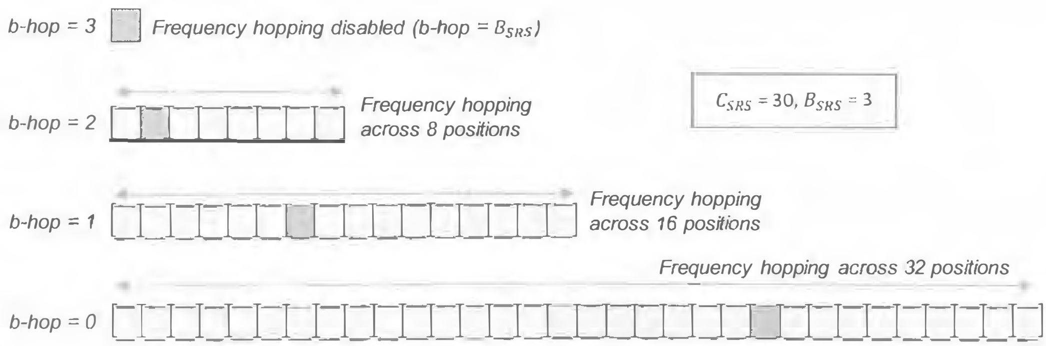


Figure 297 – Example frequency hopping positions as a function of *b-hop*

7.5.3.1 UPLINK BEAM MANAGEMENT

- In many cases, uplink beam management is not necessary because uplink/downlink beam correspondence can be assumed, i.e. the best beams in the downlink direction are also the best beams in the uplink direction. When beam correspondence is assumed, the UE completes the beam selection procedures in the downlink direction and the results are applied to both the uplink and downlink
- Within Frequency Range 2, beam correspondence is a mandatory UE capability requirement, but it uses UE capability signalling to indicate that it has been both implemented and tested for each supported operating band. The information element used to signal the beam correspondence capability is presented in Table 222

MIMO-ParametersPerBand	
beamCorrespondenceWithoutUL-BeamSweeping	supported

Table 222 – Beam correspondence UE capability information

- The SRS can be used for uplink beam management when beam correspondence is not supported. The fundamental procedure involves the UE transmitting the SRS in each beam position which allows the Base Station to select both the best UE transmit beam and the best Base Station receive beam
- The *usage* information element shown in Table 219 is set to 'beamManagement' when an SRS Resource Set has been configured for the purposes of beam management. 3GPP TS 38.214 specifies that only a single SRS Resource from within a specific SRS Resource Set can be transmitted at any given time instant when *usage* = 'beamManagement'. This effectively means that the UE transmits one beam position at a time
- If the UE is configured with multiple SRS Resource Sets with *usage* = 'beamManagement', then a single SRS Resource from each set can be transmitted simultaneously. It is expected that multiple SRS Resource Sets would be configured if the UE has multiple antenna panels. Configuring multiple Resource Sets (one for each panel) allows beam management to be completed for each panel in parallel
- Figure 298 illustrates an example of SRS Resource Sets and SRS Resources being used to support uplink beam management
  - it is assumed that the UE has 2 antenna panels and so 2 SRS Resource Sets are configured. This means that the UE will be able to transmit 2 SRS Resources simultaneously (one from each set)
  - if aperiodic SRS triggering is used then the *aperiodicSRSResourcetrigger* information element (shown in Table 219) can be configured with an equal value within each SRS Resource Set. This means that a single PDCCH DCI transmission can trigger both SRS Resource Sets
  - each antenna panel has 2 polarisations with a separate antenna port for each polarisation, so each SRS Resource has the *nrofSRS-Ports* information element (shown in Table 220) set equal to '2 ports'. This allows the UE to simultaneously transmit the SRS from both antenna ports using a single SRS Resource
  - 4 beam positions are assumed for each antenna panel so the Base Station configures 4 SRS Resources within each SRS Resource Set. Each SRS Resource is allocated a unique identity to ensure that feedback from the Base Station is not ambiguous when signalling the identity of the best beams
  - Each SRS Resource within an SRS Resource Set is configured with different timing, i.e. *resourceMapping – startPosition* (shown in Table 220) is configured differently for each SRS Resource to ensure they become active during different symbols

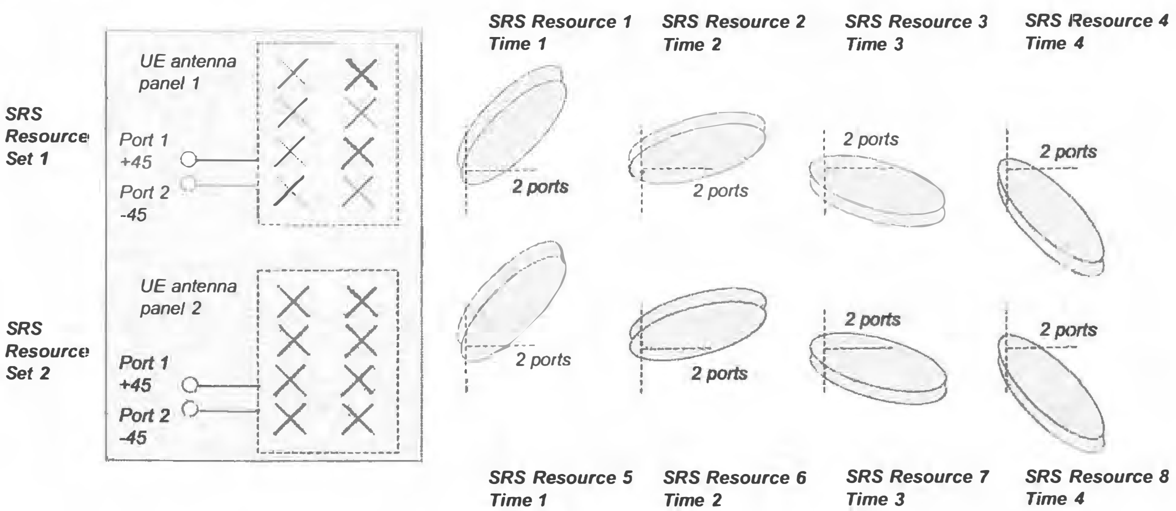


Figure 298 – SRS Resource Sets and SRS Resources for uplink Beam Management

★ Once the Base Station has identified the best UE transmit beams (one beam per antenna panel) then it must signal the identities of the relevant SRS Resources to the UE. This allows the UE to use the best beams for future transmissions. For example, if there is a third SRS Resource Set configured to support codebook based uplink transmission on the PUSCH then the *spatialRelationInfo* shown in Table 220 can be configured with the SRS Resource Identities which correspond to the best uplink beams. This means that the best uplink beams are used when determining the best Transmit Precoding Matrix Indicators (TPMI) for the PUSCH transmission

★ The Base Station also identifies the best Base Station receive beam but this information is not required by the UE so it is stored locally at the Base Station

★ If the Base Station is using analogue beamforming then it will not be able to evaluate all of the Base Station receive beams simultaneously. Instead the beams will have to be evaluated using a time multiplexed beam sweep. In this case, a single SRS transmission will not be sufficient to allow the evaluation of all Base Station receive beams. 3GPP has specified the possibility of configuring SRS repetition for this scenario. The *resourceMapping – repetitionFactor* information element (shown in Table 220) belonging to a specific SRS Resource can be used for this purpose. The Base Station can then change its receive beam with each repetition of the SRS

7.5.3.2 CHANNEL SOUNDING WITH ANTENNA SWITCHING

★ A Base Station can use the SRS in combination with channel reciprocity to deduce the downlink propagation channel. The downlink propagation channel towards each UE receive antenna can be deduced if the UE is able to transmit the SRS from each receive antenna

★ Some UE implementations may have more receive antenna than transmit paths. For example, a UE may use 4 antenna for receiving the downlink but may use only 2 of those antenna for transmitting the uplink. Some of these UE may be capable of switching the transmit paths between receive antenna. UE use the *SRS-TxSwitch* information element shown in Table 223 to inform the Base Station that transmit path switching is supported. Switching the transmit path between antenna allows the Base Station to deduce the downlink propagation channel towards each UE receive antenna

★ UE also use the *SRS-TxSwitch* information element to indicate that the number of transmit paths equals the number of receive antenna, i.e. the UE is capable of simultaneously transmitting the SRS from each antenna

SRS-TxSwitch	
supportedSRS-TxportSwitch	t1r2, t1r4, t2r4, t1r4-t2r4, tr-equal
txSwitchImpactToRx	true

Table 223 – SRS-TxSwitch UE capability information

★ Table 223 indicates that UE are able to signal their SRS transmit port switching capability as 1 transmit path switching between 2 receive antenna; 1 transmit path switching between 4 receive antenna; 2 transmit paths switching between 4 receive antenna; an equal number of transmit and receive antenna. The 't1r4-t2r4' value is applicable to an uplink MIMO capable UE which is configured to use a single uplink transmit path

★ 3GPP TS 38.214 specifies that up to two SRS Resource Sets can be configured for single transmit path switching between two receive antenna. These SRS Resource Sets are illustrated in Figure 299. 3GPP specifies that the two Resource Sets must be configured with different triggering mechanisms (different *resourceType* configurations). For example, the first Resource Set could be configured with periodic reporting so the Base Station can complete its measurements at regular intervals. The second Resource Set could be configured with aperiodic reporting so the Base Station can request additional transmissions when necessary

★ Each Resource Set includes two SRS Resources. The first SRS Resource corresponds to transmitting the SRS from the first receive antenna, while the second SRS Resource corresponds to transmitting the SRS from the second receive antenna. The two SRS resources are configured to occur in different symbols. A typical UE requires 15 µs to complete the switch between antenna. This means that there is 1 unused symbol between transmissions when using the 15, 30 or 60 kHz subcarrier spacings, or 2 unused symbols between transmissions when using the 120 kHz subcarrier spacing

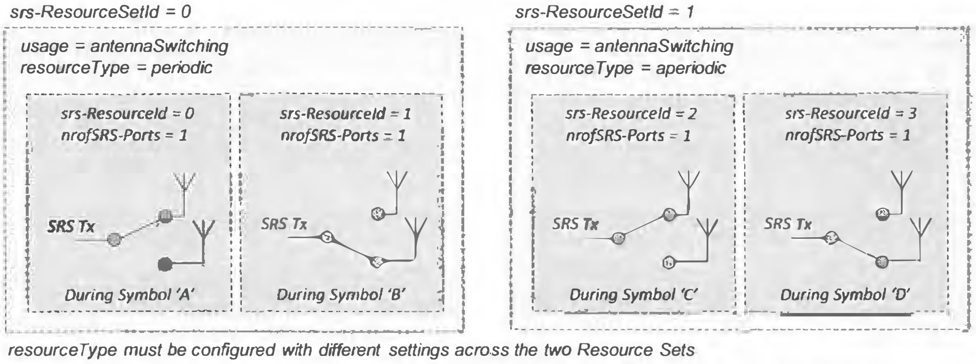


Figure 299 – SRS Antenna Switching for 1 Transmit Path & 2 Receive Paths (1T 2R)

- ★ 3GPP TS 38.214 specifies that up to two SRS Resource Sets can be configured for two transmit path switching between four receive antenna. These SRS Resource Sets are illustrated in Figure 300. Similar to the 1T 2R scenario, the two Resource Sets must be configured with different triggering mechanisms (different *resourceType* configurations)
- ★ Each Resource Set includes two SRS Resources. The first SRS Resource corresponds to transmitting the SRS from a first pair of receive antenna, while the second SRS Resource corresponds to transmitting the SRS from a second pair of receive antenna. The two SRS resources are configured to occur in different symbols. Similar to the 1T 2R scenario, a guard interval must be used to allow for the 15 μs switching delay

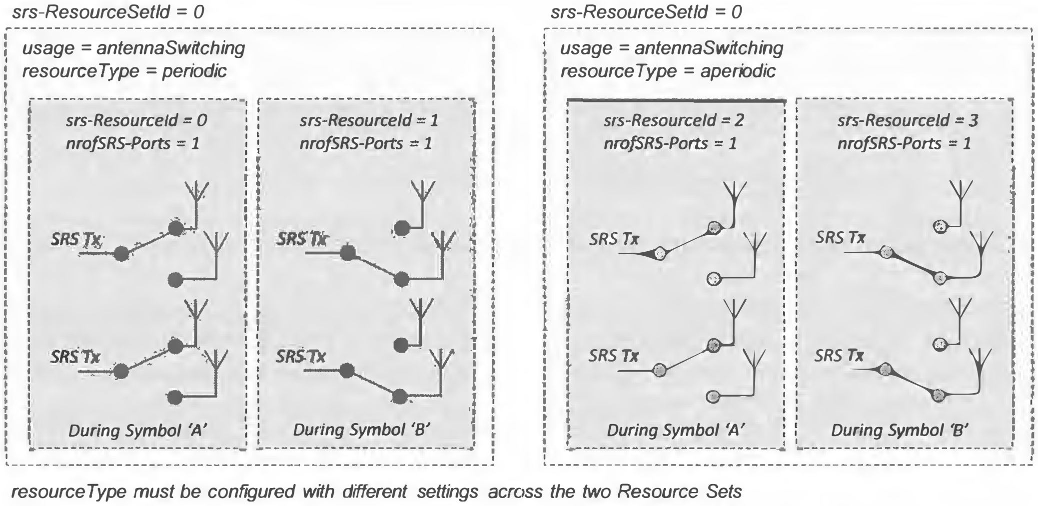


Figure 300 – SRS Antenna Switching for 2 Transmit Paths & 4 Receive Paths (2T 4R)

- ★ The case of one transmit path switching between four antenna is made more complex by the total transmit time when using aperiodic triggering. If there is 1 symbol of guard interval between each SRS transmission then 7 symbols would be required to complete the switching pattern. However, the SRS is specified to remain within the last 6 symbols of a slot. Thus, 3GPP has specified this scenario to span two slots. This requires the set of 4 SRS Resources to be distributed across 2 Resource Sets. They can be distributed such that 3 resources are in a first set while 1 resource is in a second set, or such that 2 resources are in each set. Figure 301 illustrates the case of 2 resources in each set

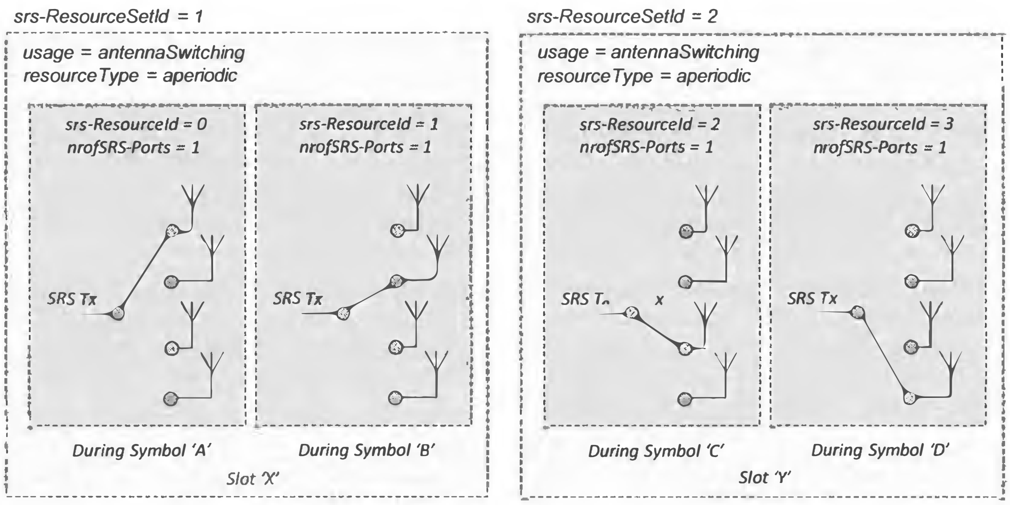


Figure 301 – Aperiodic SRS Antenna Switching for 1 Transmit Path & 4 Receive Paths (1T 4R)

7.5.3.3 CHANNEL SOUNDING WITHOUT ANTENNA SWITCHING

★ A Base Station can use the SRS in combination with channel reciprocity to deduce the downlink propagation channel. The downlink propagation channel towards each UE receive antenna can be deduced if the UE is able to transmit the SRS from each receive antenna

★ A UE uses the *SRS-TxSwitch* information element shown in Table 223 to inform the Base Station that it has an equal number of transmit paths and receive antenna, i.e. the UE is able to transmit from each antenna so antenna switching is not necessary

★ 3GPP TS 38.214 specifies that up to two SRS Resource Sets can be configured for downlink channel sounding when the number of transmit paths equals the number of receive antenna. Examples of these SRS Resource Sets are illustrated in Figure 302 for 1, 2 and 4 antenna ports

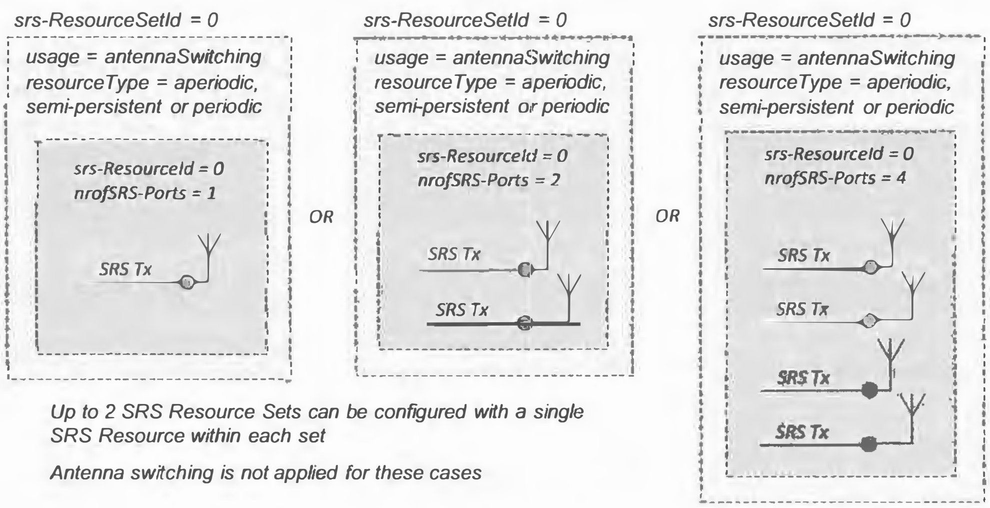


Figure 302 – Channel sounding without antenna switching

7.5.3.4 NON-CODEBOOK BASED TRANSMISSION

★ Non-Codebook based transmission assumes channel reciprocity allowing the UE to generate uplink precoding weights from the downlink CSI Reference Signals. These precoding weights are applied to a set of SRS Resources, i.e. the UE transmits precoded SRS. The Base Station provides feedback within DCI Format 0_1 when making an uplink resource allocation on the PUSCH. The feedback consists of an SRS Resource Indicator (SRI) which points towards one or more SRS Resources. Pointing towards one or more SRS Resources indicates both transmission rank and the precoding to be applied to each layer of the PUSCH

★ For example, a UE may transmit 4 precoded SRS, indexed 0 to 3. The Base Station can use the SRI within DCI Format 0_1 to indicate that the UE should transmit on the PUSCH using the precoding that was applied to SRS 0 and 3 (for example). This indicates that the UE should use rank 2 transmission because the Base Station has listed 2 SRS

★ A maximum of 1 SRS Resource Set can be configured with *usage* set to 'non-codebook'. Each SRS Resource within the Resource Set is mapped to a different antenna port. This leads to a maximum of 4 SRS Resources because there is a maximum of 4 SRS antenna ports

★ Allowing only a single SRS Resource Set means that only a single triggering mechanism can be configured. This is most likely to be aperiodic triggering due to its flexibility

★ Non-Codebook based transmission is described in section 8.2

7.5.3.5 CODEBOOK BASED TRANSMISSION

- ★ Codebook based transmission does not assume channel reciprocity so the Base Station is required to provide instruction regarding the uplink precoding weights to be applied when transmitting the PUSCH. The Base Station selects these precoding weights from a codebook standardised by 3GPP
- ★ A maximum of 1 SRS Resource Set can be configured with *usage* set to 'codebook'. The single SRS Resource Set can include a maximum of 2 SRS Resources. A UE with a single antenna panel, or 2 coherent antenna panels can be configured with a single SRS Resource. A UE with 2 non-coherent antenna panels can be configured with 2 SRS Resources, i.e. the SRS allows selection between non-coherent antenna panels. Each SRS Resource can be configured with 2 ports which corresponds to each antenna panel having 2 polarisations
- ★ The UE transmits non-precoded SRS from each non-coherent antenna panel. The Base Station provides feedback within DCI Format 0_1 when making an uplink resource allocation on the PUSCH. The feedback consists of an SRS Resource Indicator (SRI), rank and precoding information. The SRI represents a pointer towards a specific SRS Resource, i.e. a pointer towards a specific antenna panel. The rank and precoding information are jointly encoded within DCI Format 0_1, i.e. they are both included within the same data field
- ★ Allowing only a single SRS Resource Set means that only a single triggering mechanism can be configured. This is most likely to be aperiodic triggering due to its flexibility. The Base Station may decide not to trigger the SRS under certain conditions. The PUSCH Demodulation Reference Signal (DMRS) can be used instead of the SRS to help achieve peak connection throughputs. The SRS represents an overhead from the perspective of the PUSCH. Using the DMRS instead of the SRS removes that overhead and allows an increased number of Resource Elements to be allocated to the PUSCH
- ★ For example, if a UE has a single antenna panel with 2 polarisations (2 antenna ports) and is currently transmitting the PUSCH using rank 2 then the DMRS provides sufficient information regarding the propagation channel because the Base Station knows the precoding which has been applied to the DMRS by the UE. If the same UE was transmitting using rank 1 then the SRS would be required because the single DMRS would not provide information regarding both antenna ports
- ★ 3GPP TS 38.214 specifies that the number of ports configured for each SRS Resource must be equal. This requirement has been adopted to simplify the coding of information within the DCI. It prevents the bit-width of the precoding information having a dependence upon the SRI value (the bit-width depends upon the number of ports)
- ★ Codebook based transmission is described in section 8.1

7.5.4 PHASE TRACKING REFERENCE SIGNAL

★ The uplink Phase Tracking Reference Signal (PTRS) allows the Base Station to estimate and subsequently compensate for both phase noise and frequency offsets:

- o phase noise is generated by using non-ideal oscillators at both the transmitter and receiver. These oscillators do not generate completely perfect sine waves. Instead they generate sine waves which have relatively small random phase variations, i.e. phase noise is superimposed upon the sine wave. It is more difficult to manufacture high frequency oscillators with good phase noise properties. Phase noise does not have a significant impact when using frequencies below 6 GHz (Frequency Range 1) but has an increased impact when using frequencies above 6 GHz (Frequency Range 2). The use of larger subcarrier spacings in Frequency Range 2 helps to increase resilience against phase noise. Nevertheless, the PTRS is required for phase noise estimation and compensation when using Frequency Range 2

- o frequency offsets are generated by using non-ideal oscillators at both the transmitter and receiver. They are also generated by mobility, i.e. Doppler frequency offsets. Frequency offsets are relatively small shifts away from the ideal center frequency. They cause a continuous phase increase (or decrease) rather than a random phase noise. A non-ideal oscillator may generate a center frequency of '$X + \Delta$' instead of 'X'. 3GPP TS 38.104 specifies that wide area base stations must be accurate to within 0.05 parts per million (ppm), while local area base stations must be accurate to within 0.1 ppm. 3GPP TS 38.101-1 specifies that UE must be accurate to within 0.1 ppm. Doppler frequency offsets increase with mobility and operating frequency. Frequency offsets can be significant within both Frequency Range 1 and Frequency Range 2. Thus, the PTRS can be used for frequency offset estimation and compensation within both frequency ranges

★ Phase noise tends to change as a function of time but remains relatively constant as a function of frequency. This characteristic has led to the PTRS being designed to have a relatively high density in the time domain but a low density in the frequency domain, i.e. the PTRS can occupy a high percentage of symbols but a low percentage of subcarriers

★ Frequency offsets cause the modulation constellation to rotate. The rate of rotation increases as the frequency offset increases. A frequency offset can be measured by identifying the phase of the modulation constellation at two points in time and then calculating the rate of rotation between those two points. This process can be completed using 2 DMRS symbols, as illustrated in the left half of Figure 303. Alternatively, the process can be completed using a single DMRS symbol in combination with a PTRS transmission. This is illustrated in the right half of Figure 303. The latter generates a lower overhead so there is increased potential to achieve higher PUSCH throughputs

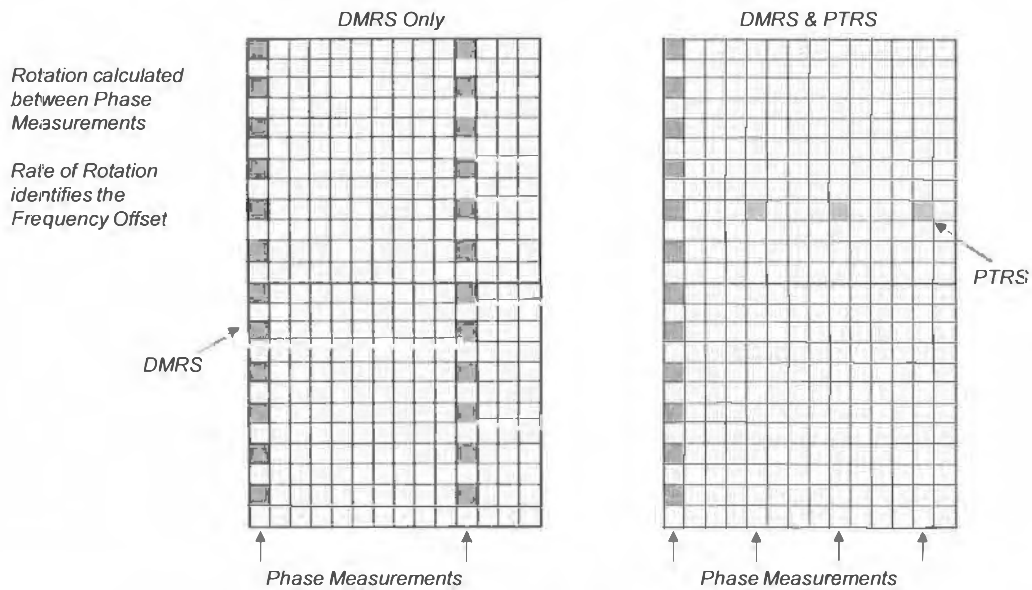


Figure 303 – Frequency Offset estimation using only DMRS and using DMRS with PTRS

★ A UE with multiple antenna panels may be designed to use a single local oscillator which is shared across antenna. In this case, there is a single source of phase noise and frequency offset so it is sufficient to transmit the PTRS using a single antenna port. A different UE with multiple antenna panels may be designed to use a separate local oscillator for each antenna. In this case, there are multiple sources of phase noise and frequency offset so it is necessary to transmit the PTRS using multiple antenna ports. The release 15 version of the specifications allows the uplink PTRS to be transmitted using 1 or 2 antenna ports

★ A UE uses the information elements presented in Table 224 to signal its capability to the Base Station. The *onePortsPTRS* information element uses 2 bits to indicate UE support for PTRS transmission within Frequency Range 1 using a single antenna port. It is mandatory for UE to support PTRS transmission within Frequency Range 2 using a single antenna port. The *twoPortsPTRS-UL* information element indicates whether or not the UE supports PTRS transmission using 2 antenna ports. This information element is specified per operating band

Information Element	Range	Comment
onePortsPTRS	2-bit Bit String	Specified for Frequency Range 1 (mandatory for Frequency Range 2)
twoPortsPTRS-UL	supported	Specified per operating band

Table 224 – UE capability information regarding number of PTRS antenna ports

★ The PTRS is configured in combination with the PUSCH DMRS. The *PTRS-UplinkConfig* parameter structure is visible within the *DMRS-UplinkConfig* parameter structure presented in Table 214 (section 7.5.1). The *PTRS-UplinkConfig* parameter structure is presented in Table 225. The set of parameters included within *PTRS-UplinkConfig* are divided into those which are applicable when Transform Precoding is disabled (CP-OFDM), and those which are applicable when Transform Precoding is enabled (DFT-S-OFDM)

PTRS-UplinkConfig		
transformPrecoderDisabled	frequencyDensity	2 instances of {1 to 276}
	timeDensity	3 instances of {0 to 29}
	maxNrofPorts	n1, n2
	resourceElementOffset	offset01, offset10, offset11
	ptrs-Power	p00, p01, p10, p11
transformPrecoderEnabled	sampleDensity	5 instances of {1 to 276}
	timeDensityTransformPrecoding	d2

Table 225 – Parameter structure used to configure the Phase Tracking Reference Signal

★ The first two parameters within the *transformPrecoderDisabled* section define the density of PTRS Resource Elements. The density in the frequency domain depends upon the number of allocated Resource Blocks, while the density in the time domain depends upon the allocated MCS

★ The *frequencyDensity* information element provides a set of two Resource Block thresholds (N_{RB0} and N_{RB1}). These two thresholds are presented in Table 226. They are used to create 3 operating regions. If the number of allocated Resource Blocks is less than the first threshold then the PTRS is not transmitted. If the number of allocated Resources Blocks is between the two thresholds then the frequency density is 2. Otherwise, the frequency density is 4

Scheduled Bandwidth	Frequency Density (K_{PTRS})
$N_{RB} < N_{RB0}$	PTRS is not used
$N_{RB0} \leq N_{RB} < N_{RB1}$	2
$N_{RB1} \leq N_{RB}$	4

Table 226 – Frequency density of the Phase Tracking Reference Signal as a function of allocated Resource Blocks

★ The PTRS overhead is larger for small Resource Block allocations so there is a point at which the benefit of including the PTRS is outweighed by the cost of the overhead. This provides the reasoning for disabling the PTRS for small Resource Block allocations

★ The *frequencyDensity* represents the frequency domain spacing between Resource Blocks allocated to the PTRS. The value of 2 means that every 2nd Resource Block includes a single PTRS subcarrier, whereas the value of 4 means that every 4th Resource Block includes a single PTRS subcarrier, i.e. the value of 2 corresponds to a higher density than the value of 4 so the density figures can be viewed as being 1/2 and 1/4. The general strategy is to use a higher density for medium resource allocations to achieve a more accurate channel estimate, and to use a lower density for larger resource allocations to minimise the overhead (for larger Resource Block allocations, there are more Resource Blocks to accommodate the PTRS so the absolute number of Resource Blocks which include the PTRS can still be relatively high)

★ If the *frequencyDensity* information element is excluded from the parameter structure, the value of K_{PTRS} is set to 2

★ The equation used to calculate the set of subcarriers allocated to the PTRS is shown below. The value of 'i' is incremented until the subcarrier number 'k' falls outside the PUSCH resource allocation. The step size between PTRS subcarriers is given by $K_{PTRS} \times 12$

Subcarrier Offset
0 to 11

0, 1, 2, ...

$$k = k_{ref}^{RE} + \left(i \times K_{PTRS} + k_{ref}^{RB}\right) \times 12$$

Resource Block Offset, 0 to 3

2 or 4 based upon number
of allocated Resource Blocks

$$k_{ref}^{RB} = \begin{cases} n_{RNTI} \bmod K_{PTRS} & \text{if } N_{RB} \bmod K_{PTRS} = 0 \\ n_{RNTI} \bmod (N_{RB} \bmod K_{PTRS}) & \text{otherwise} \end{cases}$$

★ The equation includes a subcarrier offset (k_{ref}^{RE}) and a Resource Block offset (k_{ref}^{RB}). The Resource Block offset is calculated from the RNTI which has been allocated to the UE. This effectively randomises the Resource Blocks used for the PTRS by different UE. There are two alternative calculations for k_{ref}^{RB}. These calculations ensure that the number of Resource Blocks used by the PTRS is maximised

★ The subcarrier offset (k_{ref}^{RE}) depends upon the DMRS antenna port, the DMRS Configuration Type, and the *resourceElementOffset* presented in Table 225. The dependency upon these variables is presented in Table 227. The values have been selected to ensure that the PTRS uses the same subcarriers as the DMRS. For example, antenna ports 0 and 1, with DMRS Configuration Type 1 use even numbered subcarriers for the DMRS, whereas antenna ports 2 and 3 use odd numbered subcarriers. The PTRS has not been specified to be used with the DMRS 'Double Symbol' configuration. This means that antenna ports 4 to 7 are not applicable when using Configuration Type 1, and antenna ports 6 to 11 are not applicable when using Configuration Type 2

DMRS Antenna Port	k_{ref}^{RE}							
	DMRS Configuration Type 1 *resourceElementOffset*				DMRS Configuration Type 2 *resourceElementOffset*			
	00	01	10	11	00	01	10	11
0	0	2	6	8	0	1	6	7
1	2	4	8	10	1	6	7	0
2	1	3	7	9	2	3	8	9
3	3	5	9	11	3	8	9	2
4	-	-	-	-	4	5	10	11
5	-	-	-	-	5	10	11	4

Table 227 – PTRS Subcarrier Offset as a function of the DMRS antenna port, DMRS Configuration Type and *resourceElementOffset*

★ The *timeDensity* information element provides a set of three MCS Index thresholds (*ptrs-MCS1*, *ptrs-MCS2* and *ptrs-MCS3*). These thresholds are presented in Table 228 which also includes a fourth threshold, *ptrs-MCS4*. This fourth threshold has a value which depends upon the MCS table being used. The value of *ptrs-MCS4* is set to 29 if MCS Index 28 is the highest index which has a Target Code Rate specified. The value of *ptrs-MCS4* is set to 28 if MCS Index 27 is the highest index which has a Target Code Rate specified

Scheduled MCS Index	Time Density (L_{PTRS})
I_{MCS} < *ptrs-MCS1*	PTRS is not used
ptrs-MCS1 ≤ I_{MCS} < *ptrs-MCS2*	4
ptrs-MCS2 ≤ I_{MCS} < *ptrs-MCS3*	2
ptrs-MCS3 ≤ I_{MCS} < *ptrs-MCS4*	1

Table 228 – Time density of the Phase Tracking Reference Signal as a function of MCS

★ The 4 MCS thresholds are used to create 4 operating regions. If the allocated MCS Index is less than the first threshold then the PTRS is not transmitted. Otherwise, the time density (L_{PTRS}) can have values of 4, 2 or 1 based upon the allocated MCS. The impact of phase noise becomes negligible for low MCS because the low coding rate is sufficient to protect the data (low coding rate indicates high channel coding redundancy). This provides the reasoning for allowing the PTRS to be disabled when low MCS values are allocated

★ The *timeDensity* represents the time domain spacing between symbols allocated to the PTRS. The value of 4 means that every 4th symbol can include the PTRS, while the value of 2 means that every 2nd symbol can include the PTRS, and the value of 1 means that every symbol can include the PTRS. The symbols allocated to the PTRS account for the symbols allocated to the DMRS. 3GPP TS 38.211 specifies an algorithm which avoids the PTRS being allocated the same symbols as the DMRS and also avoids the PTRS being allocated symbols immediately after the DMRS (unless the time density is 1). Figure 304 illustrates some example PTRS allocations

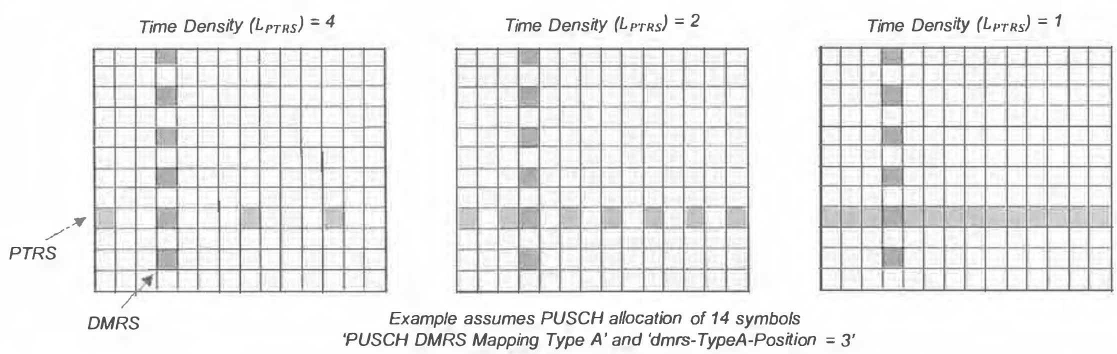


Figure 304 – Example PTRS symbols for each *timeDensity*

★ The *ptrs-Power* information element shown in Table 225 for the CP-OFDM case (Transform Precoding disabled) can be used to boost the transmit power of the PTRS relative to the transmit power of the PUSCH. The size of the boost depends upon the number of layers used by the PUSCH. The boost is larger for an increased number of layers because those layers generate additional interference towards the PTRS

★ When the PUSCH is transmitted with Transform Precoding enabled, the *transformPrecoderEnabled* section of the *PTRS-UplinkConfig* parameter structure is applicable (shown in Table 225). The PTRS is inserted prior to Transform Precoding. This is in contrast to the Demodulation Reference Signal (DMRS) which is inserted after Transform Precoding. Figure 305 illustrates the insertion of the PTRS and DMRS when generating a DFT-S-OFDM waveform

★ Inserting the PTRS prior to Transform Precoding helps to maintain the low Peak to Average Power Ratio (PAPR) associated with the DFT-S-OFDM waveform. It also allows a fixed size FFT to be used. If the PTRS were to be added after Transform Precoding, the FFT size applied to the PUSCH would have to be reduced to create space for the PTRS to be added afterwards

★ The DMRS is treated differently and is added after Transform Precoding. This simplifies the processing required to complete channel estimation. The PUSCH is not frequency multiplexed with the DMRS when Transform Precoding is applied to the PUSCH. This is not viewed as a significant drawback because the DMRS itself occupies a large percentage of the subcarriers (potentially all subcarriers when transmitting with multiple antenna ports and/or when using Multi-User MIMO). The DMRS uses a Zadoff-Chu sequence to help maintain a low PAPR

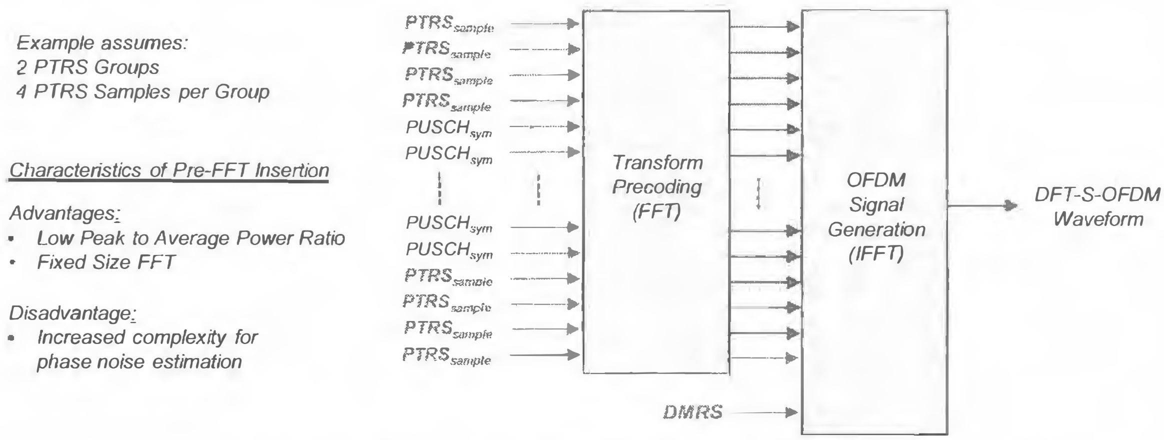


Figure 305 – Pre-FFT insertion of the PTRS with post-FFT insertion of the DMRS

★ Inserting the PTRS before Transform Precoding means that the PTRS is added in the time domain. Distributing PTRS samples amongst the set of PUSCH modulation symbols means that the PTRS is present at multiple time instants within a single DFT-S-OFDM symbol. The example illustrated in Figure 305 shows the PTRS samples positioned at each side of the PUSCH modulation symbols, i.e. at the start and end of the DFT-S-OFDM symbol. This allows the Base Station receiver to complete multiple measurements within the period of a single DFT-S-OFDM symbol

★ The *sampleDensity* information element shown in Table 225 provides a set of 5 Resource Block thresholds (N_{RB0} to N_{RB4}). These 5 thresholds are presented in Table 229. They are used to create 6 operating regions. If the number of allocated Resource Blocks is less than the first threshold then the PTRS is not transmitted. Otherwise, the number of allocated Resource Blocks determines a number of 'PTRS Groups' and a number of 'Samples per Group'. These variables define the distribution of the PTRS samples amongst the PUSCH modulation symbols

★ The PTRS samples are divided into groups and then each group has a specific position within the set of PUSCH modulation symbols. 3GPP TS 38.211 specifies the set of equations which are used to determine the position of each group. In general, the groups are distributed across the set of PUSCH modulation symbols. The number of 'Samples per Group' determines the number of PTRS samples within each group. The example illustrated in Figure 305 illustrates 2 groups with 4 samples within each group

Scheduled Bandwidth	Number of PTRS Groups	Number of Samples per Group
$N_{RB} < N_{RB0}$	PTRS is not used	
$N_{RB0} \leq N_{RB} < N_{RB1}$	2	2
$N_{RB1} \leq N_{RB} < N_{RB2}$	2	4
$N_{RB2} \leq N_{RB} < N_{RB3}$	4	2
$N_{RB3} \leq N_{RB} < N_{RB4}$	4	4
$N_{RB4} \leq N_{RB}$	8	4

Table 229 – PTRS group pattern as a function of allocated Resource Blocks

★ When Transform Precoding is used, the time density is not a function of the allocated MCS. Instead, the time density is configured directly using the *TimedensityTransformPrecoding* information element shown in Table 225. The inclusion of this information element indicates a time density of 2. The UE assumes a time density of 1 if this information element is excluded from the parameter structure. Similar to the case without Transform Precoding, the time density represents the time domain spacing between symbols allocated to the PTRS. The value of 2 means that every 2nd symbol can include the PTRS, while the value of 1 means that every symbol can include the PTRS. The symbols allocated to the PTRS account for the symbols allocated to the DMRS. 3GPP TS 38.211 specifies an algorithm which avoids the PTRS being allocated the same symbols as the DMRS and also avoids the PTRS being allocated symbols immediately after the DMRS (unless the time density is 1)

★ As part of the UE capability signalling, a UE is able to provide recommendations regarding the Resource Block and MCS thresholds presented in Table 226, Table 228 and Table 229. These recommendations allow the Base Station to configure UE specific thresholds rather than applying a common set of general thresholds across all UE. The recommendations provided by the UE are presented in Table 230. These recommendations are provided for each subcarrier spacing, i.e. the UE provides 4 instances of these recommendations to cater for the 15, 30, 60 and 120 kHz subcarrier spacings

Information Element	Range	Information Element	Range
frequencyDensity1	1 to 276	sampleDensity1	1 to 276
frequencyDensity2	1 to 276	sampleDensity2	1 to 276
timeDensity1	0 to 29	sampleDensity3	1 to 276
timeDensity2	0 to 29	sampleDensity4	1 to 276
timeDensity3	0 to 29	sampleDensity5	1 to 276

Table 230 – Content of *PTRS-DensityRecommendationUL* parameter structure

★ When Transform Precoding is disabled, the sequence used to populate the set of PTRS Resource Elements is the same as that used for the DMRS, i.e. a pseudo random sequence based upon a length-31 Gold sequence

★ When Transform Precoding is enabled, the PTRS sequence differs from the DMRS sequence because the PTRS is added before Transform Precoding whereas the DMRS is added after Transform Precoding. The DMRS uses a Zadoff-Chu sequence to help minimise the Peak to Average Power Ratio (PAPR) (a Zadoff-Chu sequence has a lower PAPR than a pseudo random sequence based upon a length-31 Gold sequence). The PTRS uses a pseudo random sequence based upon a length-31 Gold sequence because the Transform Precoding ensures that the transmitted signal has a low PAPR

★ When Transform Precoding is enabled, the pseudo random sequence generates one sample for each PTRS Group. 3GPP TS 38.211 specifies a set of spreading codes which are used to generate the complete set of samples to populate each PTRS Group. A spreading factor of 2 is used when there are 2 PTRS samples per group, while a spreading factor of 4 is used when there are 4 PTRS samples per group. The spreading code selected by the UE depends upon the RNTI and so spreading codes are effectively randomised across the population of UE

★ 3GPP References: TS 38.211, TS 38.214, TS 38.331

8 UPLINK TRANSMISSION SCHEMES

8.1 CODEBOOK BASED TRANSMISSION

★ Codebook based transmission means that the UE transmits the PUSCH using precoding weights have which been selected from a codebook standardised by 3GPP. The Base Station provides instructions on the PDCCH regarding the choice of precoding weights that the UE must apply. This means that Codebook based transmission does not rely upon channel reciprocity because the UE does not have to determine its own uplink precoding weights based upon downlink measurements

★ Codebooks are usually presented as a list of matrices where each matrix defines a set of precoding weights. The dimensions of each matrix depends upon the number of layers and the number of antenna ports. Multiple codebooks are defined to cater for the range of layers and the range of antenna ports. For example, one codebook is specified for 2 layer transmission using 2 antenna ports, and another codebook is specified for 2 layer transmission using 4 antenna ports

★ Larger codebooks provide the benefit of increased flexibility because there is a greater choice of precoding weights. However, they also create an increased signalling overhead because they require a longer bit string to signal the selected weights

★ Figure 306 illustrates an example precoding matrix for 2 layers and 4 antenna ports. The number of rows belonging to the precoding matrix is equal to the number of antenna ports, while the number of columns is equal to the number of layers. This allows matrix multiplication between the precoding matrix and a column vector which includes the input symbols from each layer. Precoding matrices are identified by their Transmitted Precoding Matrix Indicator (TPMI)

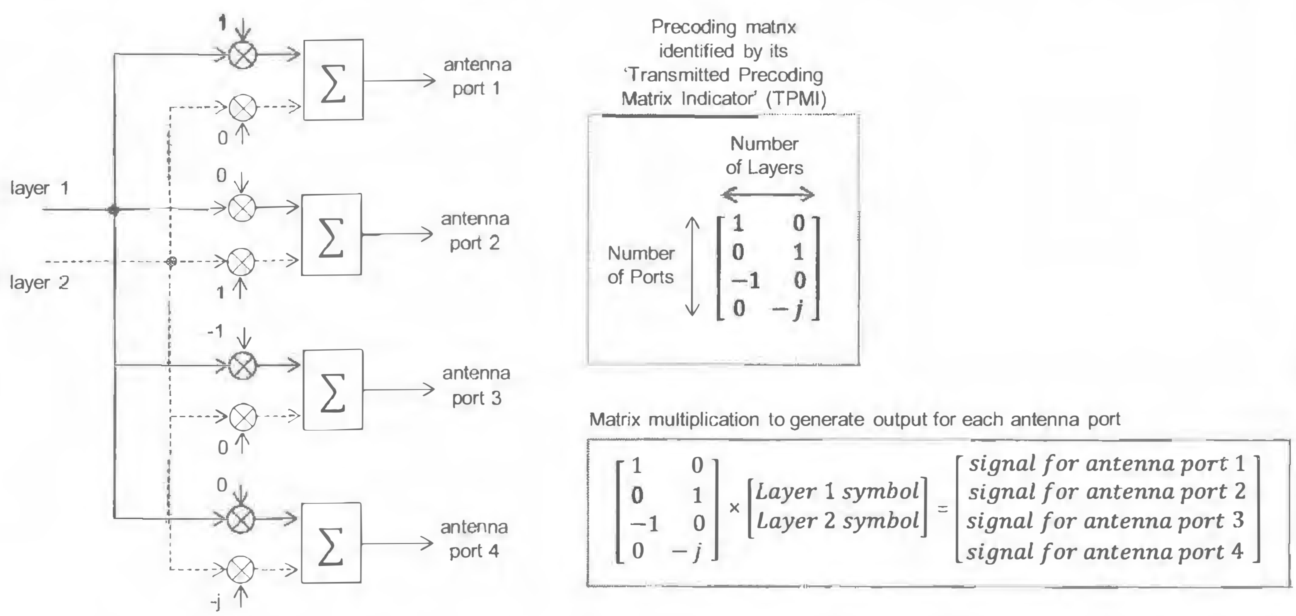


Figure 306 – Example precoding matrix for 2 layers and 4 antenna ports

★ Each precoding matrix is preceded by an amplitude scaling factor (not shown in Figure 306). This scaling factor is used to manage the total output power according to the number of layers and number of antenna ports. For example, a precoding matrix which includes 2 elements may be preceded by a scaling factor of $1 / \sqrt{2}$. This means that the power of each entry is $1 / 2$ and so the total power is unity. Similarly, a precoding matrix which includes 12 elements may be preceded by a scaling factor of $1 / 2\sqrt{3}$. This means that the power of each entry is $1 / (4 \times 3) = 1 / 12$ and so the total power is unity

★ Codebooks are carefully designed to cater for specific antenna configurations. The release 15 version of the 3GPP specifications allows for transmission using 1, 2 or 4 antenna ports. This means there can be 1, 2, 3 or 4 layers and the maximum number of weights within a precoding matrix is $4 \times 4 = 16$. Single port transmission is a special case of Codebook based transmission. It always uses a single layer and does not require a precoding matrix because there is only 1 layer to map onto 1 antenna port

★ The release 15 version of the 3GPP specifications caters for UE having 1 or 2 antenna panels, where each antenna panel can have up to 4 antenna ports. This provides a total capability of up to 8 antenna ports, whereas the specifications allow up to 4×4 MIMO which requires 4 antenna ports. UE with 2 antenna panels can switch between those panels based upon feedback from the Base Station. The end-user may be shielding one panel with a hand wrapped around the UE. In this case, the Base Station should detect the weaker signal and provide an instruction to use the other panel. Figure 307 illustrates the set of UE antenna configurations assumed by the release 15 version of the 3GPP specifications

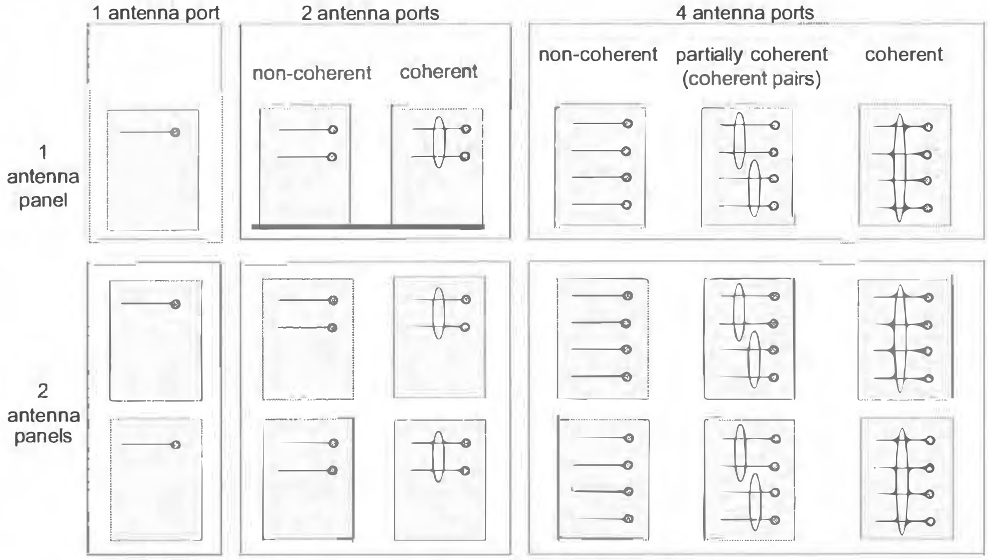


Figure 307 – Antenna port configurations assumed for Codebook based transmission

- ★ When a device has multiple antenna ports, those ports can be coherent or they can be non-coherent. The UE is able to control the relative phase of signals transmitted by coherent antenna ports. In contrast, the UE is not able to control the relative phase of signals transmitted by non-coherent antenna ports. The term 'partially coherent' is used to describe a set of antenna ports which includes some coherent ports and some non-coherent ports. Within the context of Codebook based transmission, the 'partially coherent' configuration is applicable to UE with 4 antenna ports which are grouped into pairs. The antenna ports within a specific pair are coherent but one pair is not coherent with the other pair
- ★ Figure 308 illustrates the codebook for 1 layer and 2 antenna ports. This codebook has 6 entries, where each entry is a matrix with 2 rows to match the 2 antenna ports and 1 column to match the 1 layer (the amplitude scaling factors are not shown). The first 2 entries are applicable to UE which have non-coherent antenna ports. These entries provide a simple switching function, i.e. one element within the matrix is '1' while the other element is '0'. The Base Station can use these entries to switch uplink transmission between the 2 antenna ports
- ★ All 6 entries are applicable to UE which have coherent antenna ports. The final 4 entries allow the UE to transmit the single layer using both antenna ports. The Base Station uses these entries to control the relative phase of the signals transmitted by each UE antenna port. The first antenna port transmits the single layer directly, while the second antenna port transmits the single layer with a phase shift of 0, 90, 180 or 270 degrees. The Base Station can use its knowledge of the phase shift to help combine the signals at the receiver. Transmission of the single layer using both antenna ports and a specific phase shift is not possible when the antenna ports are not coherent because the UE is unable to control the relative phase between the ports

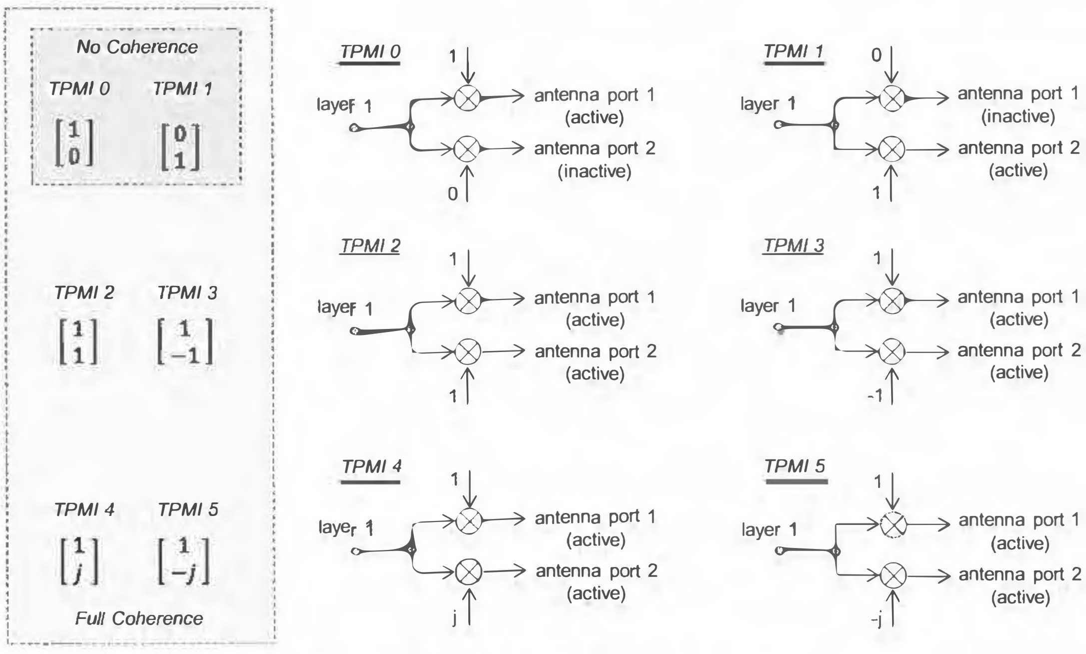


Figure 308 – Codebook for 1 layer and 2 antenna ports

★ Figure 309 illustrates the codebook for 1 layer and 4 antenna ports when Transform Precoding is disabled. This codebook has 28 entries, where each entry is a matrix with 4 rows to match the 4 antenna ports and 1 column to match the 1 layer (the amplitude scaling factors are not shown). The first 4 entries are applicable to UE which have non-coherent antenna ports. Similar to the codebook for 1 layer and 2 antenna ports, these entries provide a simple switching function, i.e. one element within the matrix is '1' while the other elements are '0'. The Base Station can use these entries to switch uplink transmission between the 4 antenna ports

★ The first 12 entries are applicable to UE which have partial coherence. TPMI 4 to 7 have non-zero values for elements 1 and 3, whereas TPMI 8 to 11 have non-zero values for elements 2 and 4. This design allows for switching between the pairs of coherent antenna ports. Antenna ports 1 and 3 are assumed to be coherent and similarly antenna ports 2 and 4 are assumed to be coherent. The first antenna port within the pair transmits the single layer directly, while the second antenna port within the pair transmits the single layer with a phase shift of 0, 90, 180 or 270 degrees, i.e. the same philosophy as the codebook presented in Figure 308 for single layer transmission with 2 coherent antenna ports. Figure 310 illustrates an example of precoding with Partial Coherence. In this example, antenna ports 1 and 3 are active while antenna ports 2 and 4 are inactive

★ All 28 entries are applicable to UE which have coherent antenna ports. The final 16 entries allow the UE to transmit the single layer using all 4 antenna ports. The Base Station uses these entries to control the relative phase of the signals transmitted by each UE antenna port. The 1st antenna port transmits the single layer directly, while the 2nd, 3rd and 4th antenna ports transmit the single layer with various combinations of phase shift

Full Coherence

Partial Coherence

No Coherence

$$\begin{array}{cccc} \text{TPMI 0} & \text{TPMI 1} & \text{TPMI 2} & \text{TPMI 3} \\ \begin{bmatrix}1\\0\\0\\0\end{bmatrix} & \begin{bmatrix}0\\1\\0\\0\end{bmatrix} & \begin{bmatrix}0\\0\\1\\0\end{bmatrix} & \begin{bmatrix}0\\0\\0\\1\end{bmatrix} \end{array}$$

$$\begin{array}{cccccccc} \text{TPMI 4} & \text{TPMI 5} & \text{TPMI 6} & \text{TPMI 7} & \text{TPMI 8} & \text{TPMI 9} & \text{TPMI 10} & \text{TPMI 11} \\ \begin{bmatrix}1\\0\\1\\0\end{bmatrix} & \begin{bmatrix}1\\0\\-1\\0\end{bmatrix} & \begin{bmatrix}1\\0\\j\\0\end{bmatrix} & \begin{bmatrix}1\\0\\-j\\0\end{bmatrix} & \begin{bmatrix}0\\1\\0\\1\end{bmatrix} & \begin{bmatrix}0\\1\\0\\-1\end{bmatrix} & \begin{bmatrix}0\\1\\0\\j\end{bmatrix} & \begin{bmatrix}0\\1\\0\\-j\end{bmatrix} \end{array}$$

$$\begin{array}{cccccccc} \text{TPMI 12} & \text{TPMI 13} & \text{TPMI 14} & \text{TPMI 15} & \text{TPMI 16} & \text{TPMI 17} & \text{TPMI 18} & \text{TPMI 19} \\ \begin{bmatrix}1\\1\\1\\1\end{bmatrix} & \begin{bmatrix}1\\1\\j\\j\end{bmatrix} & \begin{bmatrix}1\\1\\-1\\-1\end{bmatrix} & \begin{bmatrix}1\\1\\-j\\-j\end{bmatrix} & \begin{bmatrix}1\\j\\1\\j\end{bmatrix} & \begin{bmatrix}1\\j\\j\\-1\end{bmatrix} & \begin{bmatrix}1\\j\\-1\\-j\end{bmatrix} & \begin{bmatrix}1\\j\\-j\\1\end{bmatrix} \end{array}$$

$$\begin{array}{cccccccc} \text{TPMI 20} & \text{TPMI 21} & \text{TPMI 22} & \text{TPMI 23} & \text{TPMI 24} & \text{TPMI 25} & \text{TPMI 26} & \text{TPMI 27} \\ \begin{bmatrix}1\\-1\\1\\-1\end{bmatrix} & \begin{bmatrix}1\\-1\\j\\-j\end{bmatrix} & \begin{bmatrix}1\\-1\\-1\\1\end{bmatrix} & \begin{bmatrix}1\\-1\\-j\\j\end{bmatrix} & \begin{bmatrix}1\\-j\\1\\-j\end{bmatrix} & \begin{bmatrix}1\\-j\\j\\1\end{bmatrix} & \begin{bmatrix}1\\-j\\-1\\j\end{bmatrix} & \begin{bmatrix}1\\-j\\-j\\-1\end{bmatrix} \end{array}$$

Figure 309 – Codebook for 1 layer and 4 antenna ports (Transform Precoding disabled)

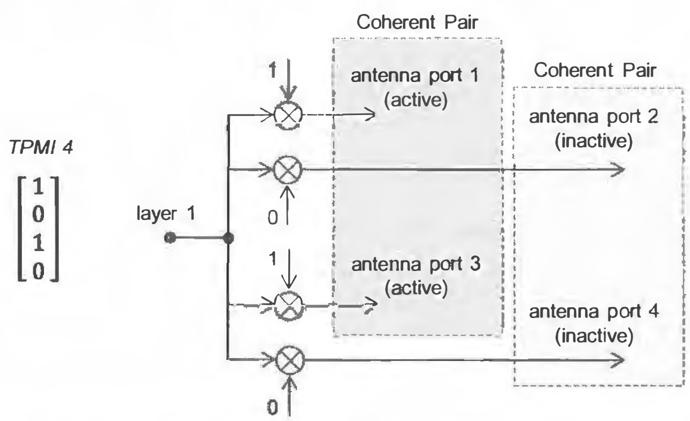


Figure 310 – Example precoding for Partial Coherence (1 layer and 4 antenna ports)

★ Figure 311 illustrates the codebook for 2 layers and 4 antenna ports. This codebook has 22 entries, where each entry is a matrix with 4 rows to match the 4 antenna ports and 2 columns to match the 2 layers. The first 6 entries are applicable to UE which have non-coherent antenna ports. These 6 entries allow the Base Station to select a specific combination of 2 antenna ports to transmit the 2 layers. Each layer is transmitted by a single antenna port without any phase shift

★ The first 14 entries are applicable to UE which have partial coherence. TPMI 6 to 13 transmit the first layer using the first pair of coherent antenna ports, and the second layer using the second pair of coherent antenna ports. Each layer is transmitted by both antenna ports belonging to the relevant coherent pair. The Base Station can control the phase shift between the transmissions belonging to each coherent pair

★ All 22 entries are applicable to UE which have coherent antenna ports. The final 8 entries allow the UE to transmit both layers from all 4 antenna ports. Each antenna port transmits the sum of the 2 layers with various combinations of phase shift. The first antenna port always transmits the sum of the 2 layers without any phase shifts

★ Figure 312 and Figure 313 illustrate the codebooks for 3 and 4 layers respectively (both are applicable to 4 antenna ports because it is not possible to transmit 3 or 4 layers using 1 or 2 antenna ports). Each codebook includes a single entry for UE which do not have any coherent antenna ports. These entries allow the UE to transmit a single layer per antenna port. The fourth antenna port is unused when there are 3 layers. Each codebook includes 2 additional entries for UE with partially coherent antenna ports. In the case of 3 layers, the 1st and 3rd antenna ports (which belong to the same coherent pair) transmit layer 1, while the 2nd and 4th antenna ports transmit layers 2 and 3 respectively. In the case of 4 layers, layers 1 and 2 are combined within the first coherent pair, while layers 3 and 4 are combined within the second coherent pair. Both codebooks include further additional entries for UE which have fully coherent antenna ports. These entries allow all layers to be transmitted by all antenna ports

Full Coherence

Partial Coherence

No Coherence

$$\text{TPMI 0}\begin{bmatrix}1&0\\0&1\\0&0\\0&0\end{bmatrix}\quad \text{TPMI 1}\begin{bmatrix}1&0\\0&0\\0&1\\0&0\end{bmatrix}\quad \text{TPMI 2}\begin{bmatrix}1&0\\0&0\\0&0\\0&1\end{bmatrix}\quad \text{TPMI 3}\begin{bmatrix}0&0\\1&0\\0&1\\0&0\end{bmatrix}\quad \text{TPMI 4}\begin{bmatrix}0&0\\1&0\\0&0\\0&1\end{bmatrix}\quad \text{TPMI 5}\begin{bmatrix}0&0\\0&0\\1&0\\0&1\end{bmatrix}$$

$$\text{TPMI 6}\begin{bmatrix}1&0\\0&1\\1&0\\0&-j\end{bmatrix}\quad \text{TPMI 7}\begin{bmatrix}1&0\\0&1\\1&0\\0&j\end{bmatrix}\quad \text{TPMI 8}\begin{bmatrix}1&0\\0&1\\-j&0\\0&1\end{bmatrix}\quad \text{TPMI 9}\begin{bmatrix}1&0\\0&1\\-j&0\\0&-1\end{bmatrix}\quad \text{TPMI 10}\begin{bmatrix}1&0\\0&1\\-1&0\\0&-j\end{bmatrix}\quad \text{TPMI 11}\begin{bmatrix}1&0\\0&1\\-1&0\\0&j\end{bmatrix}\quad \text{TPMI 12}\begin{bmatrix}1&0\\0&1\\j&0\\0&1\end{bmatrix}\quad \text{TPMI 13}\begin{bmatrix}1&0\\0&1\\j&0\\0&-1\end{bmatrix}$$

$$\text{TPMI 14}\begin{bmatrix}1&1\\1&1\\1&-1\\1&-1\end{bmatrix}\quad \text{TPMI 15}\begin{bmatrix}1&1\\1&1\\j&-j\\j&-j\end{bmatrix}\quad \text{TPMI 16}\begin{bmatrix}1&1\\j&j\\1&-1\\j&-j\end{bmatrix}\quad \text{TPMI 17}\begin{bmatrix}1&1\\j&j\\j&-j\\-1&1\end{bmatrix}\quad \text{TPMI 18}\begin{bmatrix}1&1\\-1&-1\\1&-1\\-1&1\end{bmatrix}\quad \text{TPMI 19}\begin{bmatrix}1&1\\-1&-1\\j&-j\\-j&j\end{bmatrix}\quad \text{TPMI 20}\begin{bmatrix}1&1\\-j&-j\\1&-1\\-j&j\end{bmatrix}\quad \text{TPMI 21}\begin{bmatrix}1&1\\-j&-j\\j&-j\\1&-1\end{bmatrix}$$

Figure 311 – Codebook for 2 layers and 4 antenna ports

Full Coherence

Partial Coherence

No Coherence

$$\text{TPMI 0}\begin{bmatrix}1&0&0\\0&1&0\\0&0&1\\0&0&0\end{bmatrix}\quad \text{TPMI 1}\begin{bmatrix}1&0&0\\0&1&0\\1&0&0\\0&0&1\end{bmatrix}\quad \text{TPMI 2}\begin{bmatrix}1&0&0\\0&1&0\\-1&0&0\\0&0&1\end{bmatrix}$$

$$\text{TPMI 3}\begin{bmatrix}1&1&1\\1&-1&1\\1&1&-1\\1&-1&-1\end{bmatrix}\quad \text{TPMI 4}\begin{bmatrix}1&1&1\\1&-1&1\\j&j&-j\\j&-j&-j\end{bmatrix}\quad \text{TPMI 5}\begin{bmatrix}1&1&1\\-1&1&-1\\1&1&-1\\-1&1&1\end{bmatrix}\quad \text{TPMI 6}\begin{bmatrix}1&1&1\\-1&1&-1\\j&j&-j\\-j&j&j\end{bmatrix}$$

Figure 312 – Codebook for 3 layers and 4 antenna ports

Full Coherence

Partial Coherence

No Coherence

$$\text{TPMI 0}\begin{bmatrix}1&0&0&0\\0&1&0&0\\0&0&1&0\\0&0&0&1\end{bmatrix}\quad \text{TPMI 1}\begin{bmatrix}1&1&0&0\\0&0&1&1\\1&-1&0&0\\0&0&1&1\end{bmatrix}\quad \text{TPMI 2}\begin{bmatrix}1&1&0&0\\0&0&1&0\\j&-j&0&0\\0&0&j&-j\end{bmatrix}$$

$$\text{TPMI 3}\begin{bmatrix}1&1&1&1\\1&-1&1&-1\\1&1&-1&-1\\1&-1&-1&1\end{bmatrix}\quad \text{TPMI 4}\begin{bmatrix}1&1&1&1\\1&-1&1&-1\\j&j&-j&-j\\j&-j&-j&j\end{bmatrix}$$

Figure 313 – Codebook for 4 layers and 4 antenna ports

★ Table 231 summarises the set of 7 codebooks specified by 3GPP TS 38.211. There are 2 codebooks for the 2 antenna port configuration and 5 codebooks for the 4 antenna port configuration. In the case of 4 antenna ports, there is a separate codebook to be used in combination with Transform Precoding, i.e. DFT-S-OFDM. This additional codebook has been modified to help reduce the Peak to Average Power Ratio (PAPR)

	Transform Precoding	Maximum Rank	Number of entries within each Codebook		
			codebookSubset = fullyAndPartialAndNonCoherent	*codebookSubset* = partialAndNonCoherent	*codebookSubset*= nonCoherent
2 antenna ports	enabled or disabled	1	6 entries	not applicable	2 entries
	disabled	2	3 entries	not applicable	1 entry
4 antenna ports	enabled	1	28 entries	12 entries	4 entries
	disabled	1	28 entries	12 entries	4 entries
	disabled	2	22 entries	14 entries	6 entries
	disabled	3	7 entries	3 entries	1 entry
	disabled	4	5 entries	3 entries	1 entry

Table 231 – Codebooks applicable to the PUSCH

★ The Base Station requires knowledge of the UE capability before it is able to configure the UE for Codebook based transmission. The UE uses the *FeatureSetUplinkPerCC* parameter structure shown in Table 232 to signal its maximum number of supported layers and its maximum number of resources per SRS Resource Set. The maximum number of layers equates to the number of antenna ports. The maximum number of SRS Resources equates to the number of antenna panels (a single SRS Resource with one or more antenna ports is configured for each antenna panel).

FeatureSetUplinkPerCC		
supportedSubcarrierSpacingUL	kHz15, kHz30, kHz60, kHz120, kHz240	
supportedBandwidthUL	fr1	mhz5, mhz10, mhz15, mhz20, mhz25, mhz30, mhz40, mhz50, mhz60, mhz80, mhz100
	fr2	mhz50, mhz100, mhz200, mhz400
channelBW-90mhz	supported	
mimo-CB-PUSCH	maxNumberMIMO-LayersCB-PUSCH	oneLayer, twoLayers, fourLayers
	maxNumberSRS-ResourcePerSet	1, 2
maxNumberMIMO-LayersNonCB-PUSCH	oneLayer, twoLayers, fourLayers	
supportedModulationOrderUL	bpsk-halfpi, bpsk, qpsk, qam16, qam64, qam256	
simultaneousTxSUL-NonSUL	supported	

Table 232 – *FeatureSetUplinkPerCC* parameter structure

★ The UE uses the *MIMO-ParametersPerBand* parameter structure shown in Table 233 to signal the level of coherence between its antenna ports. As described previously, the *partialNonCoherent* value is only applicable when the UE supports 4 antenna ports

MIMO-ParametersPerBand	
pusch-TransCoherence	nonCoherent, partialNonCoherent, fullCoherent

Table 233 – Antenna port coherence within the *MIMO-ParametersPerBand* parameter structure

★ Once the Base Station knows the UE capability, it can instruct the UE to use either Codebook base transmission, or non-Codebook based transmission using the *txConfig* information element within the *PUSCH-Config* parameter structure. Table 234 presents the relevant part of the *PUSCH-Config* parameter structure (the complete *PUSCH-Config* parameter structure is presented in Table 196, section 7.4)

PUSCH-Config	
txConfig	codebook, nonCodebook

Table 234 – Transmission Scheme instruction within the *MIMO-ParametersPerBand* parameter structure

★ The Base Station must also configure the UE to use an SRS Resource Set with *usage* set to 'codebook'. The parameter structure used to configure an SRS Resource Set is presented in Table 219 (section 7.5.3). A maximum of 1 SRS Resource Set can be configured with *usage* set to 'codebook'. The single SRS Resource Set includes 1 SRS Resource if the UE has 1 antenna panel, and 2 SRS Resources if the UE has 2 antenna panels. Each SRS Resource is configured with a number of antenna ports which matches the UE capability. The number of antenna ports belonging to each SRS Resource must be equal

★ Figure 314 illustrates the procedure for Codebook based transmission. The single SRS Resource Set can be configured with aperiodic, semi-persistent or periodic triggering. The Base Station uses the PDCCH to trigger an aperiodic transmission, a MAC Control Element to activate semi-persistent transmissions and RRC signalling to configure periodic transmissions. Once the SRS Resource Set has been triggered, the UE transmits the SRS from each of its antenna ports. The example illustrated in Figure 314 assumes that the UE has 2 antenna panels with 4 antenna ports belonging to each panel

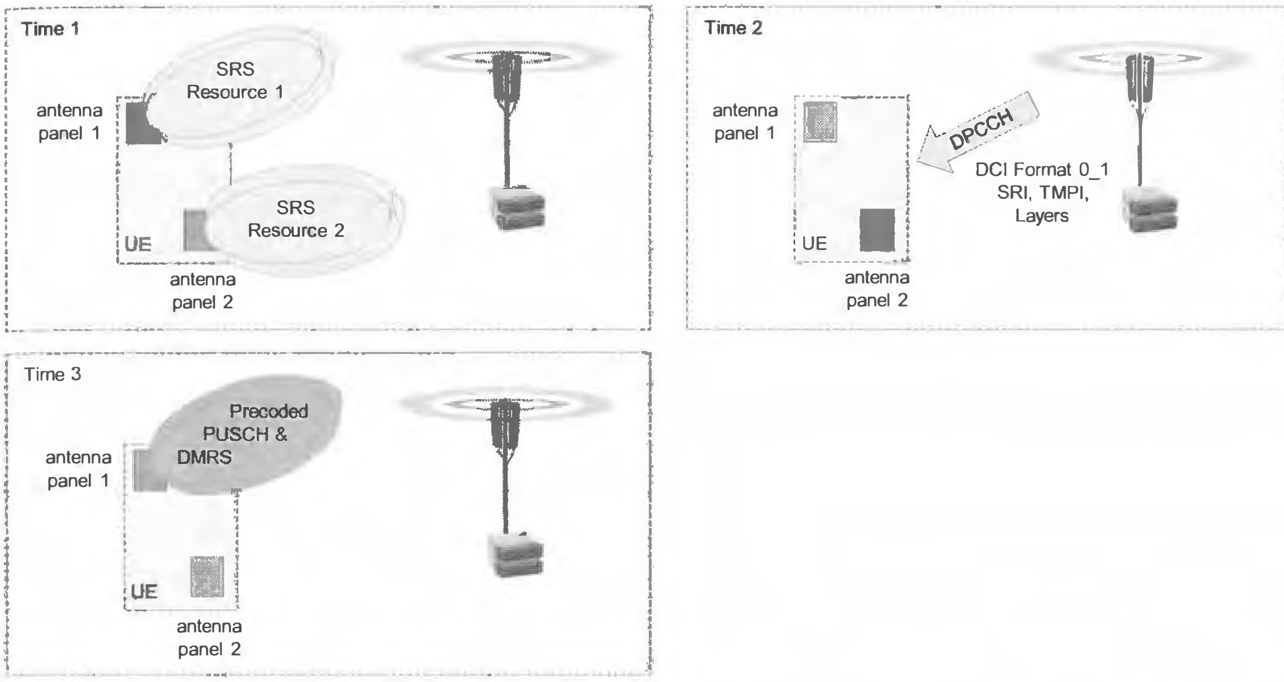


Figure 314 – Procedure for Codebook based transmission

★ The Base Station compares the SRS transmissions belonging to each SRS Resource to select an antenna panel (assuming the UE has 2 antenna panels). The Base Station then evaluates the SRS transmissions within the selected SRS Resource to determine an appropriate rank (number of layers) and precoding matrix. Both depend upon the propagation channel between the UE and the Base Station. The Base Station attempts to identify a precoding matrix which will maximise the rank and the received signal to noise ratio. The Base Station is likely to also account for the UE reported power headroom and buffer status when selecting an appropriate rank

★ The Base Station then uses Downlink Control Information (DCI) Format 0_1 to allocate the PUSCH resources. This DCI includes an SRS Resource Indicator (SRI) which instructs the UE to use a specific antenna panel. The DCI also includes a 'Precoding Information and Number of Layers' field which instructs the UE to use a specific combination of precoding matrix and number of layers. The precoding matrix is identified using its Transmitted Precoding Matrix Indicator (TPMI). The complete content of DCI Format 0_1 is presented in section 3.5.5

★ The UE is able to use the resource allocation received on the PDCCH to transmit the PUSCH while using the selected antenna panel, number of layers and precoding matrix

★ DCI Format 0_1 also includes an SRS Request field. If the SRS Resource Set has been configured to trigger aperiodically, this field can be used to request another SRS transmission, at the same time as allocating the PUSCH resources. This allows the process to repeat without the requirement for any additional signalling

★ 3GPP References: TS 38.214, TS 38.212, TS 38.331

8.2 NON-CODEBOOK BASED TRANSMISSION

★ Non-codebook based transmission means that the UE measures a downlink CSI Reference Signal to generate its own precoding weights for the PUSCH. These precoding weights are not constrained to a codebook standardised by 3GPP. Non-codebook based transmission relies upon channel reciprocity because the UE determines its uplink precoding weights based upon downlink measurements

★ The Base Station requires knowledge of the UE capability before it is able to configure the UE for non-codebook based transmission. The UE uses the *FeatureSetUplinkPerCC* parameter structure shown in Table 232 to signal its maximum number of supported layers for non-codebook based transmission (*maxNumberMIMO-LayersNonCB-PUSCH* information element)

★ Once the Base Station knows the UE capability, it can instruct the UE to use non-Codebook based transmission using the *txConfig* information element within the *PUSCH-Config* parameter structure. Table 235 presents the relevant part of the *PUSCH-Config* parameter structure (the complete *PUSCH-Config* parameter structure is presented in Table 196, section 7.4)

PUSCH-Config	
txConfig	codebook, nonCodebook

Table 235 – Transmission Scheme instruction within the *MIMO-ParametersPerBand* parameter structure

★ The Base Station must configure the UE to use an SRS Resource Set with *usage* set to 'nonCodebook'. The parameter structure used to configure an SRS Resource Set is presented in Table 219 (section 7.5.3). A maximum of 1 SRS Resource Set can be configured with *usage* set to 'nonCodebook'. The single SRS Resource Set can include up to 4 SRS Resources and each SRS Resource is configured with a single antenna port, i.e. up to 4 SRS transmissions can be associated with the SRS Resource Set

★ The UE is also configured to measure a single Non-Zero Power (NZP) Channel State Information (CSI) Reference Signal. This CSI Reference Signal is configured in combination with the SRS Resource Set presented in Table 219. In the case of semi-persistent and periodic triggering, the CSI Reference Signal is addressed using the *associatedCSI-RS* information element. In the case of aperiodic triggering, the CSI Reference Signal is addressed using the *csi-RS* information element. These information elements are only included within the parameter structure when *usage* is set to 'nonCodebook'

★ Figure 315 illustrates the procedure for non-codebook based transmission. The procedure starts with the UE measuring the downlink CSI Reference Signal. A UE with multiple antenna panels can use these downlink measurements to identify the best panel for uplink transmission. The example in Figure 315 assumes that the UE selects antenna panel 1. The UE also uses these downlink measurements to derive the precoding weights for each of the configured SRS Resources

★ Transmission of the SRS Resources is triggered by either the PDCCH for aperiodic triggering, a MAC Control Element for semi-persistent triggering or the start or a new cycle for periodic triggering. The SRS Resources are transmitted using the precoding weights derived from the CSI Reference Signal. There is one SRS Resource for each potential transmission layer, e.g. a UE which supports up to 4 layers for non-codebook based transmission will be configured to transmit 4 SRS Resources

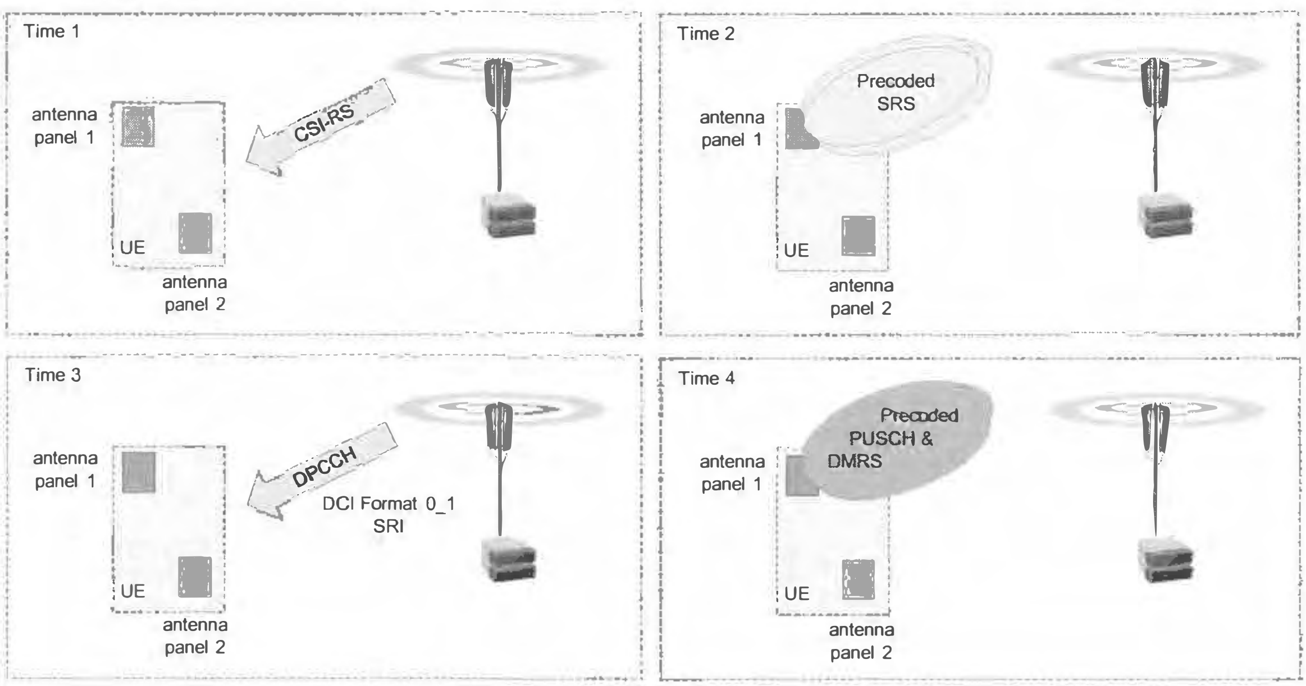


Figure 315 – Procedure for Non-Codebook based transmission

★ The Base Station uses the set of SRS transmissions to determine the number of layers for the PUSCH, and also which subset of precoded SRS should be selected to generate those layers. For example, if a UE transmits SRS Resources 1, 2, 3 and 4 then the Base Station may deduce that the radio conditions allow rank 2 transmission (2 layers) and that the precoding applied to SRS Resources 1 and 3 should be applied to the PUSCH when generating the 2 layers

★ The Base Station proceeds to allocate PUSCH resources by signalling Downlink Control Information (DCI) on the PDCCH. DCI Format 0_1 can be used to signal an SRS Resource Indicator (SRI) which identifies a specific subset of 'x' SRS Resources from the total set of 'y'. Thus, the SRI indicates both the number of layers and specific precoding weights to be applied

★ The UE uses the allocated resources to transmit both the PUSCH and its Demodulation Reference Signal (DMRS) using the specified number of layers and precoding weights

★ The procedure illustrated in Figure 315 effectively initialises non-codebook based transmission. It is not necessary for the UE to transmit the SRS in advance of every PUSCH transmission. The Base Station can assume that a single SRS Resource Set transmission remains valid for a certain period of time. This allows the Base Station to allocate further PUSCH resources without triggering the SRS

★ In addition, the DMRS can be used as a substitute for the SRS. There is a one-to-one mapping between a specific SRS Resource and a specific DMRS, i.e. the precoding applied to an SRS Resource is also applied to the corresponding DMRS. If the UE is transmitting the PUSCH and DMRS with the maximum number of layers then the DMRS provides the same information as the set of SRS Resources. However, if the transmission rank decreases so the UE is no longer transmitting the maximum number of layers, the number of DMRS will decrease and the Base Station is no longer able to track the performance of all precoding weights. In this case, the Base Station must return to using the set of SRS Resources which provide visibility of all precoding weights. Figure 316 illustrates the use of the DMRS as a substitute for the SRS Resources when transmitting with the maximum number of layers

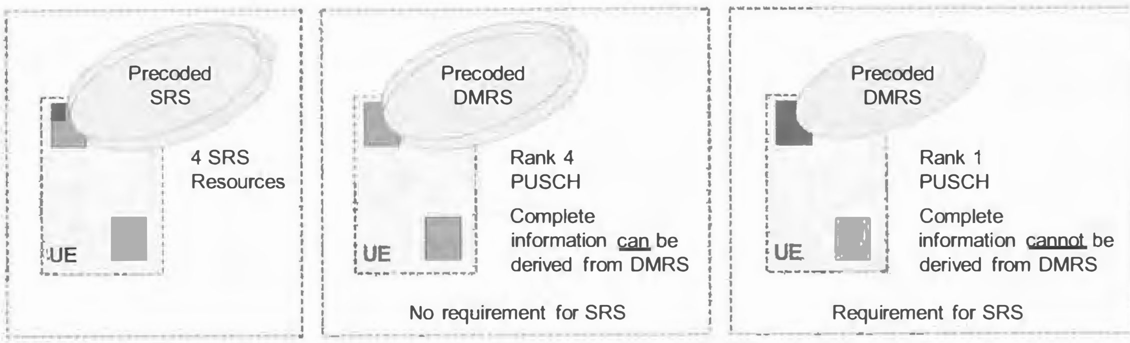


Figure 316 – Use of DMRS instead of SRS when transmitting PUSCH with maximum rank

★ 3GPP References: TS 38.214, TS 38.212, TS 38.331

9 BEAM MANAGEMENT

★ The primary objective of Beam Management is to identify and maintain the optimal beams for transmission in both the uplink and downlink directions. Beam Management can be applied to both the PDSCH and PDCCH in the downlink direction. Similarly, Beam Management can be applied to both the PUSCH and PUCCH in the uplink direction

★ The requirement for Beam Management will depend upon the deployment scenario:

  o when using Frequency Range 1, UE have multiple antenna elements but are less likely to have a beamforming capability. When using Frequency Range 2, UE are more likely to be equipped with one or more antenna panels which provide support for beamforming

  o Base Stations may be equipped with antenna which support beamforming in both Frequency Range 1 and Frequency Range 2. In general, active antenna are used to provide the beamforming capability with typically 16, 32 or 64 transceivers in Frequency Range 1 (digital beamforming), and typically 2 transceivers in Frequency Range 2 (analogue beamforming). However, some Base Stations may not be equipped with the hardware to support beamforming, or may be configured to use only a single sector beam

★ Beam Management can be performed in a hierarchical manner: initial acquisition identifies a relatively wide beam, while the subsequent beam refinement identifies a more directional and higher gain beam. It is not necessary for all physical channels to use the same beam. For example, the PDSCH could use a directional high gain beam to help maximise throughput, while the PDCCH could use a wider beam to reduce the requirement for frequent switching between beams

★ In the downlink direction, the UE can complete beam selection based upon the transmission of SS/PBCH Blocks and CSI Reference Signals. Beamforming coefficients applied to the set of SS/PBCH Blocks can be used to generate relatively wide beams for initial acquisition. In contrast, beamforming coefficients applied to the set of CSI Reference Signal resources can be used to generate more directional beams for subsequent beam refinement

★ In the uplink direction, the Base Station can complete beam selection based upon Sounding Reference Signal (SRS) transmissions. This selection procedure is not necessary if there is uplink/downlink Beam Correspondence, i.e. the beams selected for downlink transmission and reception, can also be used for uplink transmission and reception

★ The UE hardware implementation can impact the existence of Beam Correspondence. This is particularly true for Frequency Range 2 in which case separate transmit and receive antenna may be implemented to avoid transceiver switching losses. In this case, the uplink and downlink do not share the same set of antenna elements so it may be necessary to use different uplink and downlink beams, e.g. if the transmit and receive antenna elements are separated such that the angle of arrival for the receiver does not equal the angle of departure for the transmitter

★ In the case of Frequency Range 2, UE signal their support for Beam Correspondence using the *beamCorrespondenceWithoutUL-BeamSweeping* flag. This flag can be included within the *MIMO-ParametersPerBand* parameter structure shown in Table 236. Exclusion of this flag indicates that the UE does not support Beam Correspondence and requires uplink beam sweeping to identify the optimal uplink beams. In this case, the UE also includes the *uplinkBeamManagement* capability information to indicate the UE's capability in terms of SRS transmissions for Beam Management

extract from *MIMO-ParametersPerBand*		
beamCorrespondenceWithoutUL-BeamSweeping	supported	
uplinkBeamManagement	maxNumberSRS-ResourcePerSet-BM	2, 4, 8, 16
	maxNumberSRS-ResourceSet	1 to 8
beamManagementSSB-CSI-RS	maxNumberSSB-CSI-RS-ResourceOneTx	0, 8, 16, 32, 64
	maxNumberCSI-RS-Resource	0, 4, 8, 16, 32, 64
	maxNumberCSI-RS-ResourceTwoTx	0, 4, 8, 16, 32, 64
	supportedCSI-RS-Density	1, 3, 1 and 3
	maxNumberAperiodicCSI-RS-Resource	0, 1, 4, 8, 16, 32, 64

Table 236 – Extract from *MIMO-ParametersPerBand* parameter structure

★ Beam Management is also required to support mobility between beams. The preferred beam can change very rapidly when a UE is configured to use a directional beam. Seamless data transfer requires that the UE can switch between beams in a transparent manner without any throughput interruption. This requires that beam switching is managed by layers 1 and 2 rather than layer 3, i.e. mobility between beams is completed without RRC signalling

★ 3GPP TS 38.802 refers to a set of 3 Beam Management procedures: P-1 is used to complete initial downlink beam selection; P-2 is used to change the beam selection, e.g. for the purposes of beam refinement; P-3 is used to optimise the downlink UE receive beam when the UE is equipped to support beamforming

9.1 INITIAL ACQUISITION

★ A UE in RRC Idle mode establishes uplink and downlink beam pairs during the Random Access procedure. At this point the UE is already camped on a cell and is measuring the RSRP/RSRQ from the set of SS/PBCH Blocks for the purposes of cell reselection. In addition, the UE has already acquired the set of System Information Blocks (SIB) so already knows the association between the set of SS/PBCH Blocks and the set of PRACH Preambles

★ The association between the set of SS/PBCH Blocks and the set of PRACH Preambles is derived from the *RACH-ConfigCommon* parameter structure within SIB1 (Table 255 in section 13.1.1). This parameter structure includes the *ssb-perRACH-OccasionAndCB-PreamblesPerSSB* information element which provides two numerical values:

- *ssb-perRACH-Occasion* defines the number of SS/PBCH Blocks which share the same Random Access occasion, i.e. the SS/PBCH Blocks which share the same set of 64 PRACH preambles. *ssb-perRACH-Occasion* can be allocated a value from within the range: {1/8, 1/4, 1/2, 1, 2, 4, 8, 16}. For example, a value of 1/8 indicates that a single SS/PBCH Block uses PRACH preambles belonging to 8 Random Access occasions. In contrast, a value of 8 indicates that 8 SS/PBCH Blocks share the PRACH preambles belonging to a single Random Access occasion
- *CB-PreamblesPerSSB* defines the number of contention based PRACH preambles associated with each SS/PBCH Block. The range of this variable depends upon the value of *ssb-perRACH-Occasion*. For example, the upper limit is 16 when 4 SS/PBCH Blocks share a single Random Access occasion because there is a total of 64 PRACH preambles available to share

★ Figure 317 illustrates an example set of 8 SS/PBCH Blocks belonging to a specific cell. The set of SS/PBCH Blocks are time multiplexed with a maximum of 2 SS/PBCH Blocks per slot. The precise timing is dependent upon the subcarrier carrier spacing and the Frequency Range of the operating band (symbol level timings are specified in Table 56 in section 3.4). The Base Station applies a different set of beamforming coefficients to each SS/PBCH Block to generate the set of 8 beams

★ The Base Station transmits each SS/PBCH Block using a single logical antenna port (port 4000). The Base Station may apply the beamforming coefficients to a single polarisation and transmit the SS/PBCH Blocks using a single polarisation beam. Alternatively, the Base Station could apply the beamforming coefficients to both polarisations and transmit the SS/PBCH Blocks using the resultant pair of polarisation beams. In both cases, the precise transmission scheme must be transparent to the UE which expects to receive a single downlink transmission on logical antenna port 4000

★ When initiating the transition to RRC Connected mode, the UE identifies the best SS/PBCH Block and selects a contention based PRACH preamble belonging to that SS/PBCH Block. The example in Figure 317 assumes that the UE selects SS/PBCH Block 2 and contention based PRACH preamble 7. If the UE supports beamforming or has multiple antenna panels then the UE will also identify the beam and/or antenna panel used for reception of the SS/PBCH Block

★ At this point, the UE has knowledge of the downlink beam pair, i.e. the best downlink beam at the Base Station and the best downlink beam/antenna panel at the UE. At this stage, the UE assumes uplink/downlink beam correspondence so the selected downlink beam pair is also adopted as the selected uplink beam pair

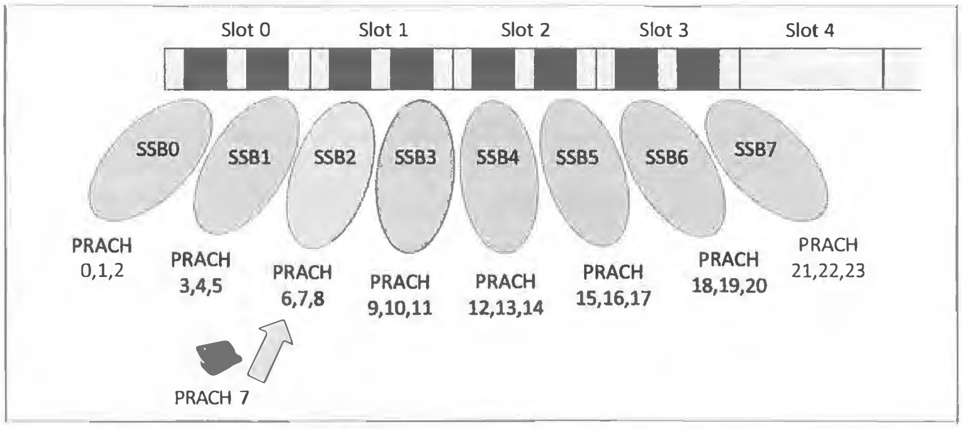


Figure 317 – Initial beam selection using SS/PBCH Blocks

★ The UE then proceeds to transmit the PRACH preamble using the appropriate Random Access occasion. Upon reception of the PRACH preamble, the Base Station can deduce the SS/PBCH Block selected by the UE and thus has knowledge of the beam to be used for subsequent downlink transmissions and uplink reception

★ Initial acquisition of the uplink and downlink beams is now complete so the remainder of the Random Access procedure can take advantage of the selected beams. The beamforming coefficients belonging to the selected SS/PBCH can be applied to the PDCCH when allocating PDSCH resources for MSG2. Similarly, the same set of beamforming coefficients can be applied to the PDSCH when transmitting MSG2

9.2 DOWNLINK BEAM REFINEMENT

★ Once a UE has entered RRC Connected mode, it is possible to initiate Beam Refinement procedures. These procedures can be used to select beams which are more directional and have higher gain. More directional beams can improve the link budget but are also likely to require more frequent switching between beams

★ The CSI Reference Signal can be used to support Beam Refinement procedures. For example, a set of 4 CSI Reference Signal resources can be associated with each SS/PBCH Block, i.e. a total of 32 CSI Reference Signal resources would be configured when using the maximum of 8 SS/PBCH Blocks in Frequency Range 1. The Base Station can apply a different set of beamforming coefficients to each CSI Reference Signal resource to generate 4 directional beams per SS/PBCH Block

★ Each set of 4 CSI Reference Signals can be time multiplexed across 4 symbols, and frequency multiplexed with the associated SS/PBCH Block. Figure 318 illustrates a set of 4 CSI Reference Signals that use the Resource Blocks above an SS/PBCH Block. This example assumes that the CSI Reference Signal resources use a density of 3 Resource Elements per Resource Block (alternatively, a density of 1 or 0.5 could be configured). It is assumed that all CSI Reference Signal resources use the same subcarriers because they are time multiplexed and there is no need for frequency co-ordination within a specific cell. Neighbouring cells can be configured to use different subcarriers to avoid interference between CSI Reference Signal transmissions. Section 16.8 discusses frequency co-ordination between neighbouring cells

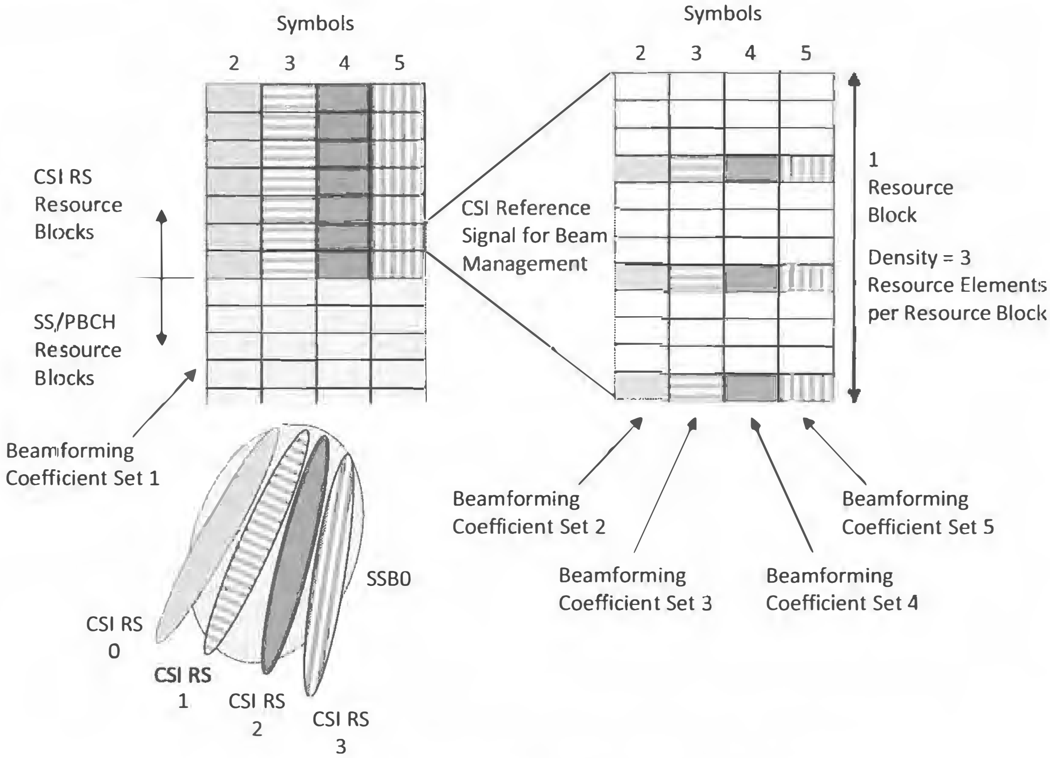


Figure 318 – Beam Refinement using CSI Reference Signals

★ The Base Station applies a different set of beamforming coefficients to each transmission: the beamforming coefficients applied to the Resource Blocks belonging to the SS/PBCH generate a relatively wide beam; the beamforming coefficients applied to the Resource Blocks belonging to each CSI Reference Signal generate 4 directional beams within the envelope of the wider SS/PBCH beam

★ The layout of the refined beams within the envelope of the wider SS/PBCH beam has a dependence upon the antenna configuration. If the antenna uses a single row of transceivers then beamforming is restricted to the azimuth direction and the set of refined beams will be arranged in a single horizontal row. If the antenna uses multiple rows of transceivers then beamforming can be completed in both the azimuth and elevation directions. This allows the refined beams to be arranged in multiple horizontal rows. Figure 319 illustrates two example refined beam layouts for these two categories of antenna configuration

★ Each CSI Reference Signal resource can be configured to use a single logical antenna port. The Base Station may apply the beamforming coefficients to a single polarisation and transmit the CSI Reference Signal using a single polarisation beam. Alternatively, the Base Station could apply the beamforming coefficients to both polarisations and transmit the CSI Reference Signal using the resultant pair of polarisation beams. In both cases, the precise transmission scheme would be transparent to the UE which would expect to receive a single downlink transmission on a single logical antenna port

★ Alternatively, the CSI Reference Signal resource can be configured to use 2 logical antenna ports. The Base Station can then transmit one port from each polarisation and the UE generates a linear average of the 2 RSRP measurements

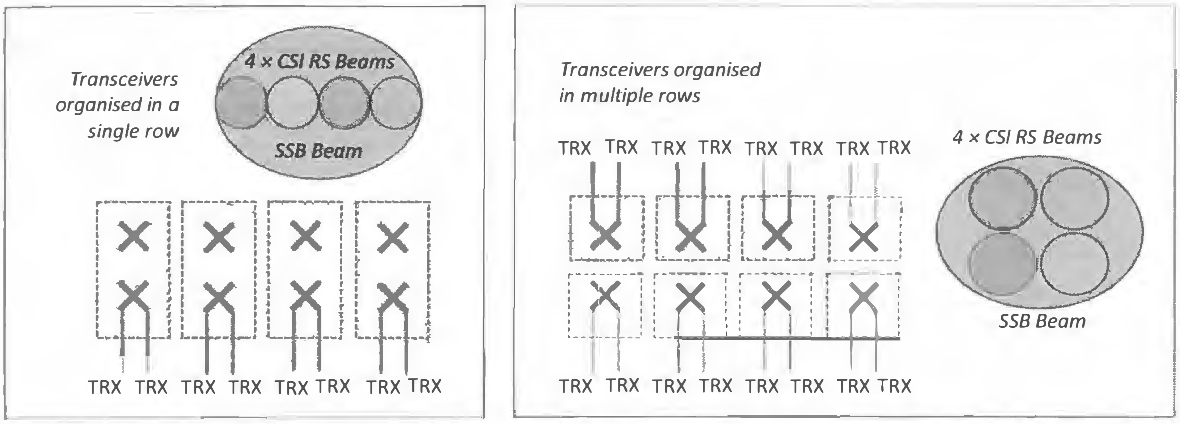


Figure 319 – Example CSI Reference Signal refined beams for different antenna layouts

★ The Base Station can instruct the UE to identify and report the best CSI Reference Signal. This is done using the CSI reporting framework which allows the Base Station to configure a CSI report with the *reportQuantity* set to 'cri-RSRP'. This means that the UE generates CSI reports which include a CSI Reference Signal Resource Indicator (CRI) to identify the strongest CSI Reference Signal, i.e. the UE identifies and reports the best downlink refined beam. The UE also reports the Layer 1 RSRP which has been measured from the strongest CSI Reference Signal

★ The refined beam can be used for both PDCCH and PDSCH transmissions. Alternatively, the Base Station may decide to use the refined beam for the PDSCH, while using the wider SS/PBCH beam for the PDCCH. This approach allows the PDSCH to benefit from the higher gain, directional beam, while the PDCCH benefits from the wider beam which is less likely to require frequent switching between beams

★ In the case of 2×2 MIMO, the two polarisations can be used to generate the two beams which transmit the 2 PDSCH logical antenna ports. In the case of higher order MIMO, it is necessary to use an increased number of beams to match the increased number of PDSCH logical antenna ports. For example, 4×4 MIMO requires the transmission of 4 PDSCH logical antenna ports. This can be done using a combination of 2 polarisations and 2 refined beams, i.e. the UE is required to report the best 2 CSI Reference Signal beams rather than only the best CSI Reference Signal beam. Rank 4 transmission will rely upon reflections and scattering to generate a downlink propagation channel which allows the UE to receive all 4 layers with sufficient quality but also with low correlation

★ Downlink beam refinement can also be used to optimise beam selection at the UE. This is primarily applicable to Frequency Range 2, in which case the UE is more likely to use one or more antenna panels to provide a beamforming capability. CSI Reference Signal repetition can be used to generate multiple transmissions of the same CSI Reference Signal beam. The UE can use these repetitions to evaluate each of its beam positions and thus identify the best beam for downlink reception, i.e. the UE completes its own beam sweep while the Base Station repeats the CSI Reference Signal transmission. The CSI Reference Signal transmissions are time multiplexed rather than frequency multiplexed because analogue beamforming is applicable to Frequency Range 2 and in this case, the UE can generate only one of its beam positions at any point in time

★ Figure 320 illustrates the concepts of downlink beam refinement at both the Base Station and UE. The Base Station does not require knowledge of the beam generated by the UE so the CSI report is configured with *reportQuantity* set to 'none'. The CSI Reference Signal is described in greater detail within section 3.7.4, whereas CSI reporting is described in greater detail within section 13.6

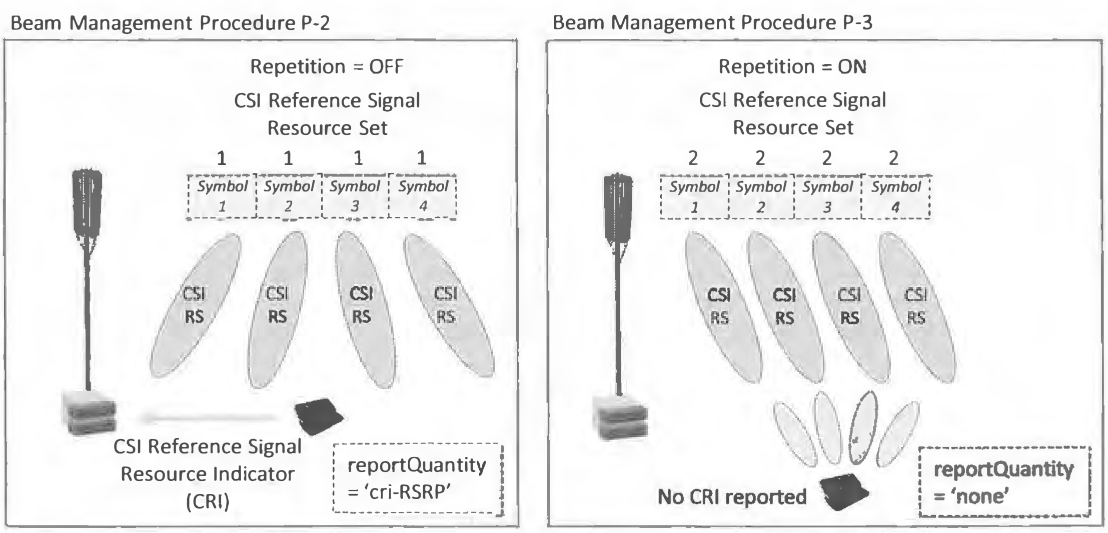


Figure 320 – Downlink beam refinement for both Base Station and UE beams

- Beam refinement based upon the CSI Reference Signal has a dependence upon the UE capability. Table 236 presents the *beamManagementSSB-CSI-RS* parameter set which belongs to the *MIMO-ParametersPerBand* UE capability information. This parameter set specifies the UE capability in terms of the number of Reference Signals supported for Beam Management. For example, the *maxNumberCSI-RS-Resource* information element specifies the maximum number of CSI Reference Signal resources supported by the UE (within the context of Beam Management). 3GPP TS 38.306 specifies that a UE must support at least 8 CSI Reference Signal resources when using an operating band within Frequency Range 1

9.3 UPLINK BEAM REFINEMENT

- Uplink beam refinement is not necessary if there is 'Beam Correspondence' between the uplink and downlink, i.e. the Base Station and UE can use the same beams for both directions
- A connection can benefit from uplink beam refinement if 'Beam Correspondence' does not exist. In contrast to downlink beam refinement which relies upon the downlink CSI Reference Signal, uplink beam refinement relies upon the uplink Sounding Reference Signal (SRS)
- The use of the SRS for uplink beam refinement is described in section 7.5.3.1. The fundamental procedure involves the UE transmitting the SRS in each beam position which allows the Base Station to select both the best UE transmit beam and the best Base Station receive beam

9.4 MOBILITY

- Both the Base Station and UE must be capable of changing beams as the radio conditions change as a function of time. Intra-cell mobility involves beam switching which requires layer 1 and layer 2 procedures. Inter-cell mobility involves a handover which requires layer 3 procedures. These two categories of mobility are illustrated in Figure 321

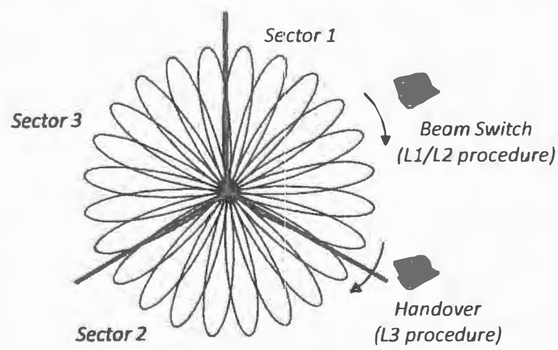


Figure 321 – Handover and Beam Switching scenarios

- Intra-cell beam switching can be both transparent and seamless from the UE perspective. The UE can be instructed to generate periodic CSI reports with the *reportQuantity* set to 'cri-RSRP' if mobility is required between CSI Reference Signal beams, or with the *reportQuantity* set to 'ssb-Index-RSRP' if mobility is required between SS/PBCH beams. Assuming the former, the UE monitors the set of CSI Reference Signal beams and periodically reports the identity of the best beam in combination with an RSRP measurement
- The Base Station can use this information to switch between beams without informing the UE. This is done by changing the set of beamforming weights which are applied to the Resource Blocks allocated to the PDCCH and PDSCH. The UE continues to receive the downlink transmissions without knowing that the beamforming weights have been changed. This basic beam switching scenario is illustrated in Figure 322
- The basic beam switching scenario can be enhanced using a set of Transmission Configuration Indicator (TCI) States to specify Quasi Co-Location (QCL) relationships between the PDCCH and a downlink Reference Signal, and between the PDSCH and a downlink Reference Signal. 3GPP introduced the concept of QCL to help the UE with its channel estimation, frequency offset estimation and synchronisation procedures. For example, if two antenna ports are categorised as being QCL in terms of Delay Spread then the UE can determine the delay spread for one antenna port and then apply the result to both antenna ports. This avoids the UE having to determine the delay spread separately for each antenna port
- A TCI State is used to define a specific QCL relationship for either the PDCCH or the PDSCH. 3GPP has specified four categories of QCL relationship which are labelled A, B C and D. These QCL categories are described in section 2.6. For example, TCI State '1' could define a QCL Type 'A' relationship between the PDSCH and CSI Reference Signal '1'. This indicates that the PDSCH and CSI Reference Signal share the same characteristics in terms of { Doppler Shift; Doppler Spread; Average Delay, Delay Spread}

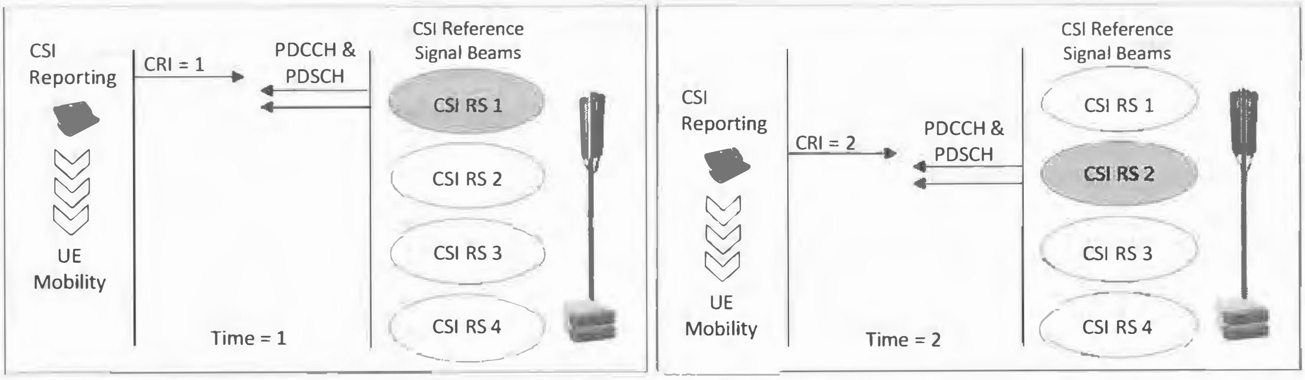


Figure 322 – Basic beam switching scenario

★ The Base Station can use RRC signalling to configure a complete set of TCI States at the start of a connection, or after a handover. Individual TCI States can then be activated using MAC Control Elements (CE) on the PDSCH and Downlink Control Information (DCI) on the PDCCH. This concept is illustrated in Figure 323

★ The 'TCI State Indication for UE-specific PDCCH' MAC Control Element is used to activate a TCI State for a specific PDCCH Control Resource Set (CORESET). This allows the UE to use information derived from the relevant CSI Reference Signal (or SS/PBCH Block) when decoding the PDCCH

★ The 'Transmission Configuration Indication' (TCI) field within DCI Format 1_1 is used to activate a TCI State for a specific PDSCH transmission. This allows the UE to use information derived from the relevant CSI Reference Signal (or SS/PBCH Block) when decoding the PDSCH

★ The RRC layer can configure up to 64 TCI States for the PDCCH and up to 128 TCI States for the PDSCH. The TCI field within DCI Format 1_1 has a length of 3 bits so it is only able to address 8 TCI States. The 'TCI States Activation/Deactivation for UE-specific PDSCH' MAC Control Element is used to select up to 8 TCI States from the total set of TCI States. These selected TCI States can then be activated by the TCI field within DCI Format 1_1

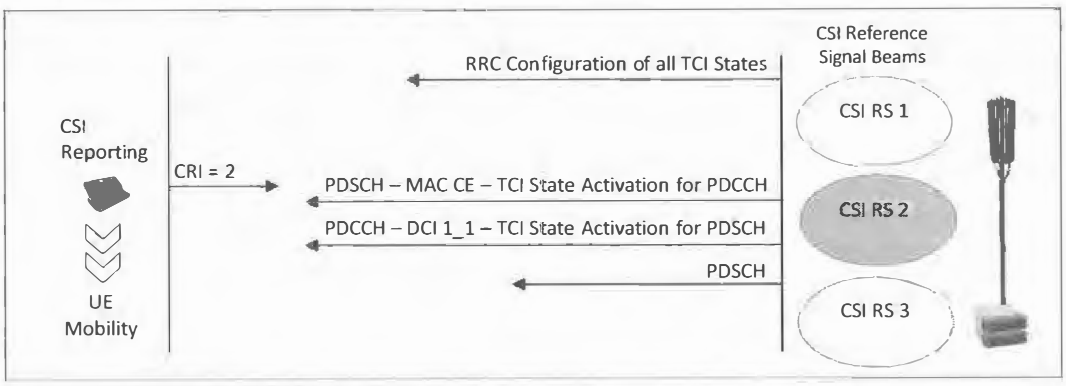


Figure 323 – Beam switching with TCI States and QCL Relationships

★ QCL Type D specifies that the PDCCH/PDSCH shares common 'Spatial Receiver Parameters' with a CSI Reference Signal or SS/PBCH Block. This category of QCL is applicable to Frequency Range 2 when UE are equipped with a beamforming capability. In this case, the QCL relationship indicates that the UE can use the same receive beam for both the PDCCH/PDSCH and the downlink Reference Signal

★ Handover procedures can be triggered using Measurement Reporting Events A3 and A5. Handovers are triggered using cell level measurements which indicate that the target cell is better than the current source cell. The derivation of cell level measurements from beam level measurements is described in section 11.1. A UE can be requested to include beam level measurement results within the Measurement Report. For example, a UE can include a series of RSRP measurements for specific SS/PBCH Blocks belonging to the target cell. This allows the handover procedure to target a specific SS/PBCH beam during the handover execution phase

★ Handovers typically take advantage of the 'contention free' Random Access procedure to help improve reliability and reduce latency. This requires the target cell to allocate one or more dedicated PRACH Preambles which are linked to one or more SS/PBCH Blocks. The UE can then identify the best SS/PBCH Block during the handover execution phase before transmitting the appropriate PRACH Preamble. Rapidly changing radio environments mean that the SS/PBCH Block which was the strongest when triggering the handover may not be the strongest when executing the handover

★ The UE can be configured with *rsrp-ThresholdSSB* within the *RACH-ConfigCommon* parameter structure. If the UE has been allocated a dedicated PRACH Preamble for an SS/PBCH Block which has an RSRP greater than this threshold then the UE initiates a 'contention free' Random Access procedure. However, if none of the SS/PBCH Blocks linked to the allocated PRACH Preambles have an RSRP greater than *rsrp-ThresholdSSB*, the UE completes a 'contention based' Random Access procedure towards the strongest SS/PBCH. These scenarios are illustrated in Figure 324

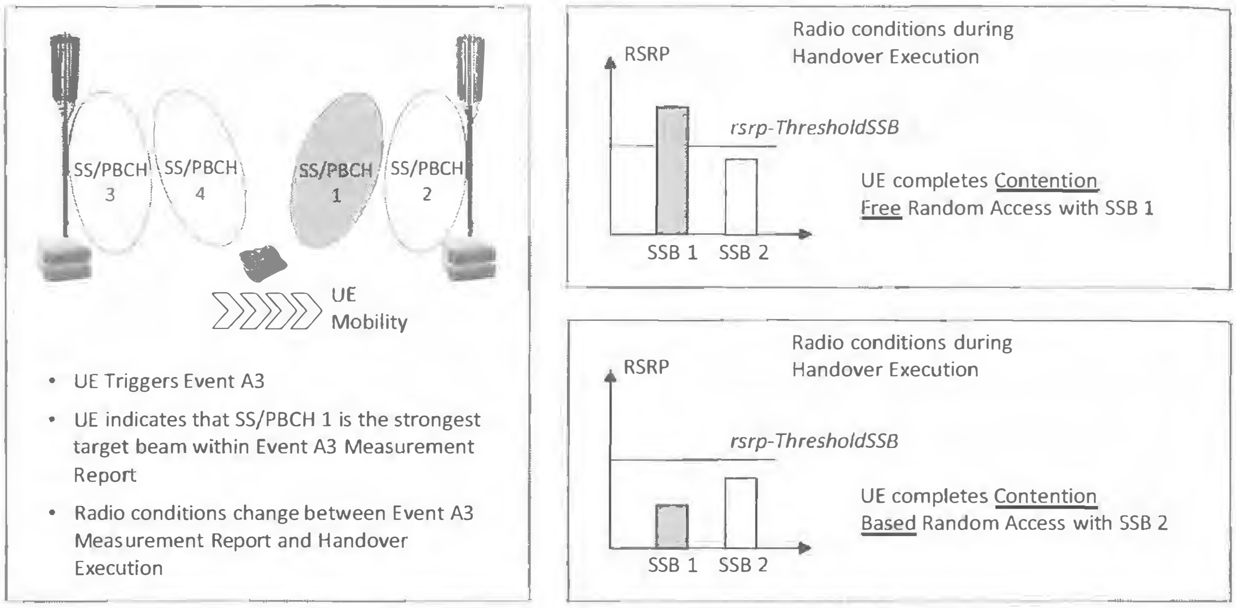


Figure 324 – Handover towards a specific Target Beam

9.5 PMI BEAM SELECTION

★ When using closed loop MIMO, a UE is instructed to select and report Precoding Matrix Indicator (PMI) values which are extracted from a specific codebook. In many cases, PMI selection corresponds to beam selection, i.e. when a UE reports a specific PMI value then the UE is indicating a preferred beam for subsequent PDSCH transmission. Thus, PMI reporting can also be viewed as a Beam Management procedure. PMI reporting and the associated beam selection procedures are described in section 13.6.3

★ Figure 325 illustrates an example where PMI reporting is completed in 2 stages, and the first stage involves 'beam group' selection, while the second stage involves 'beam selection'

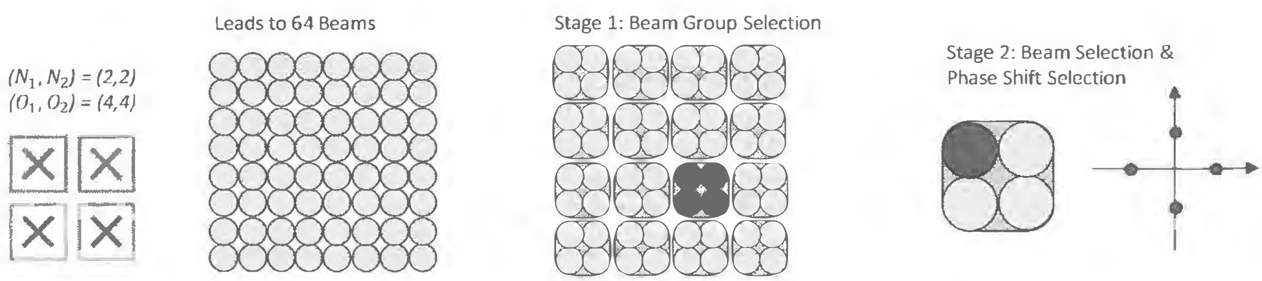


Figure 325 – Example of Beam Selection when reporting PMI for Closed Loop MIMO

9.6 BEAM FAILURE & RECOVERY

★ Under normal operating conditions, Beam Management procedures allow a UE to switch between beams as the radio conditions change over time. However, a UE can experience Beam Failure if the radio conditions suddenly change, e.g. when an end-user steps around a corner or a vehicle causes an obstruction

★ UE must be capable of detecting Beam Failure, selecting a new beam and recovering the connection with minimal delay. This is achieved by allowing these procedures to be completed using a combination of the Physical and MAC layers without any higher layer signalling, i.e. these procedures are transparent to the RRC layer. Beam Failure and Recovery are described in section 13.9.1

10 UE MEASUREMENTS

10.1 SS-RSRP

★ 'Synchronisation Signal - Reference Signal Received Power' (SS-RSRP) measurements are used for cell selection, cell reselection, power control calculations, mobility procedures and beam management. Measurements can be generated and reported at both Layer 1 and Layer 3. For example, a UE can provide SS-RSRP measurements at Layer 1 when sending Channel State Information (CSI) to the Base Station. Alternatively, a UE can provide SS-RSRP measurements at Layer 3 when sending an RRC: Measurement Report

★ SS-RSRP represents the average power received from a single Resource Element allocated to the Secondary Synchronisation Signal

- o the average is calculated using linear units, i.e. mWatts rather than dBm
- o the power measurement is based upon the energy received during the useful part of the symbol and excludes the cyclic prefix
- o when using Frequency Range 1, the reference point for the measurement is the UE antenna connector, i.e. it is assumed that the UE has a single antenna element per receive path rather than an antenna array
- o when using Frequency Range 2, the measurement is based upon the combined signal strength from all antenna elements belonging to a single receive path, i.e. it is assumed that the UE has an antenna array for each receive path

★ Measurements are filtered at Layer 1 to help remove the impact of noise and to improve measurement accuracy. This filtering is not specified explicitly by 3GPP but UE measurements must achieve the accuracy requirements defined within TS 38.133

★ Measurements are filtered at Layer 3 to remove the impact of fast fading and to help reduce short term variations in the measurement results. This filtering is specified by 3GPP within TS 38.331 and is described in section 11.2

★ Layer 1 measurements are useful for procedures which must react with minimal delay, e.g. beam management procedures which require the UE to rapidly switch between beams. Layer 3 measurements are useful for radio resource management decisions which require a longer term view of channel conditions, e.g. handover procedures should be triggered after Layer 3 filtering to reduce the risk of ping-pong between serving cells

★ 3GPP TS 38.133 specifies separate mappings between the reported and measured values for Layer 1 and Layer 3 RSRP. These mappings are presented in Table 237

★ The minimum Layer 3 value of -156 dBm has been aligned with the minimum Layer 3 value specified for LTE. The 3GPP specifications for LTE originally defined a minimum RSRP of -140 dBm but that value was decreased to -156 dBm within the release 13 version of the specifications. This reduction was introduced to cater for the coverage performance of enhanced Machine Type Communications (eMTC)

★ The maximum Layer 3 value of -31 dBm results from the use of 7 bits when signalling the RSRP, i.e. 128 entries can be defined within the mapping table. This upper limit is viewed as sufficient when compared to the upper limit of -44 dBm used by LTE. A 10 dB margin relative to LTE was proposed to account for UE receiver beamforming. The upper limit can also be verified from the perspective of the maximum input power specified for a UE. For example, a standalone UE using the 100 MHz channel bandwidth within Frequency Range 1 is specified to have a maximum input power capability of -20 dBm. If this power was received from an SS/PBCH Block then the maximum RSRP would be $-20 - 10\,LOG(20 \times 12) = -44$ dBm

Reported Value	Measured L3 SS-RSRP	Measured L1 SS-RSRP & CSI-RSRP
RSRP_0	SS-RSRP < -156	Not used
RSRP_1	-156 ≤ SS-RSRP < -155	Not used
RSRP_2	-155 ≤ SS-RSRP < -154	Not used
RSRP_3	-154 ≤ SS-RSRP < -153	Not used
...	...	...
RSRP_14	-143 ≤ SS-RSRP < -142	Not used
RSRP_15	-142 ≤ SS-RSRP < -141	Not used
RSRP_16	-141 ≤ SS-RSRP < -140	RSRP < -140
RSRP_17	-140 ≤ SS-RSRP < -139	-140 ≤ RSRP < -139
RSRP_18	-139 ≤ SS-RSRP < -138	-139 ≤ RSRP < -138
RSRP_19	-138 ≤ SS-RSRP < -137	-138 ≤ RSRP < -137
...	...	...
RSRP_110	-47 ≤ SS-RSRP < -46	-47 ≤ RSRP < -46
RSRP_111	-46 ≤ SS-RSRP < -45	-46 ≤ RSRP < -45
RSRP_112	-45 ≤ SS-RSRP < -44	-45 ≤ RSRP < -44
RSRP_113	-44 ≤ SS-RSRP < -43	-44 ≤ RSRP
RSRP_114	-43 ≤ SS-RSRP < -42	Not used
RSRP_115	-42 ≤ SS-RSRP < -41	Not used
...	...	...
RSRP_124	-33 ≤ SS-RSRP < -32	Not used
RSRP_125	-32 ≤ SS-RSRP < -31	Not used
RSRP_126	-31 ≤ SS-RSRP	Not used
RSRP_127	Infinity	Infinity

Table 237 – Mapping between measured and reported SS-RSRP and CSI-RSRP (measurements in dBm)

★ The Layer 1 RSRP has a smaller reporting range than the Layer 3 RSRP. For example, if the UE measures a Layer 1 RSRP of -150 dBm then it is reported as '< -140 dBm'. The smaller reporting range is viewed as sufficient for the purposes of Layer 1 procedures

★ A UE is configured to report Layer 1 SS-RSRP if *reportQuantity* within *CSI-ReportConfig* is set to 'ssb-Index-RSRP'. Layer 1 measurements are 'beam level' rather than 'cell level'. This means that each SS-RSRP result is linked to a specific SS/PBCH Block

- if the UE is configured to report a single RSRP value then the CSI report includes that value and the identity of the corresponding SS/PBCH Block. The RSRP value is signalled using the mapping presented in Table 237 so it requires 7 bits within the payload of the CSI report
- if the UE is configured to report multiple RSRP values then the largest measurement result is signalled using the mapping presented in Table 237. The remaining measurement results are signalled using differential values which are calculated relative to the largest result. 3GPP has specified the set of 16 differential values presented in Table 238. The use of 16 values means that each differential value occupies only 4 bits within the CSI report, rather than the 7 bits required for an absolute value. The CSI report also includes the identities of the SS/PBCH Blocks corresponding to each measurement

Reported Value	Difference between Measured RSRP and Strongest RSRP	Reported Value	Difference between Measured RSRP and Strongest RSRP
DIFFRSRP_0	0 ≥ Δ RSRP > -2	DIFFRSRP_8	-16 ≥ Δ RSRP > -18
DIFFRSRP_1	-2 ≥ Δ RSRP > -4	DIFFRSRP_9	-18 ≥ Δ RSRP > -20
DIFFRSRP_2	-4 ≥ Δ RSRP > -6	DIFFRSRP_10	-20 ≥ Δ RSRP > -22
DIFFRSRP_3	-6 ≥ Δ RSRP > -8	DIFFRSRP_11	-22 ≥ Δ RSRP > -24
DIFFRSRP_4	-8 ≥ Δ RSRP > -10	DIFFRSRP_12	-24 ≥ Δ RSRP > -26
DIFFRSRP_5	-10 ≥ Δ RSRP > -12	DIFFRSRP_13	-26 ≥ Δ RSRP > -28
DIFFRSRP_6	-12 ≥ Δ RSRP > -14	DIFFRSRP_14	-28 ≥ Δ RSRP > -30
DIFFRSRP_7	-14 ≥ Δ RSRP > -16	DIFFRSRP_15	-30 ≥ Δ RSRP

Table 238 – Mapping for differential Layer 1 RSRP reporting (differences in dB)

★ Layer 3 measurements can be either 'beam level' or 'cell level'. Both can be reported to the Base Station within an RRC: *Measurement Report* message. Layer 3 filtering is used to generate beam level results directly from the Layer 1 measurements. Cell level results are derived from the Layer 1 measurements using the rules described in section 11.1. Layer 3 filtering is subsequently applied after the cell level results have been generated

★ In the case of Layer 3 measurements, the Base Station provides the UE with an SS/PBCH Block Measurement Timing Configuration (SMTC). The SMTC defines a set of periodic time windows during which the UE should complete its measurements. Table 239 presents the information belonging to the SMTC

smtc				
periodicityAndOffset	CHOICE			
	5 subframes	offset = 0 to 4	40 subframes	offset = 0 to 39
	10 subframes	offset = 0 to 9	80 subframes	offset = 0 to 79
	20 subframes	offset = 0 to 19	160 subframes	offset = 0 to 159
duration	1, 2, 3, 4, 5 subframes			

Table 239 – SS/PBCH Block Measurement Time Configuration (SMTC)

★ The *periodicityAndOffset* is used to calculate the SFN and subframe associated with the start of each measurement window. The System Frame Numbers (SFN) which include the start of a measurement window satisfy the following condition: $SFN \bmod T = \mathrm{FLOOR}(Offset / 10)$, where $T = \mathrm{CEIL}(Periodicity / 10)$. The starting subframe is defined by *Offset* mod 10, if *Periodicity* is greater than 5 subframes. Otherwise, the starting subframes are defined by *Offset* and *Offset* + 5 (there are 2 windows per radio frame when the period is 5 ms). *duration* defines the length of the measurement window

★ A UE is permitted to use measurements from the PBCH Demodulation Reference Signal (DMRS) when generating SS-RSRP results. The DMRS and Secondary Synchronisation Signal are transmitted with equal power so results can be averaged directly. If a UE is measuring SS-RSRP for the purposes of Layer 1 reporting, then a UE can be configured to use CSI Reference Signal measurements as an additional input when generating the SS-RSRP results. CSI Reference Signals may have a different transmit power compared to the Secondary Synchronisation Signals and the PBCH DMRS. The Base Station is responsible for providing the UE with power offset information so it can be taken into account during the measurement procedure

★ 3GPP References: TS 38.215, TS 38.133, TS 38.331, TS 38.214, TS 38.212

10.2 SS-RSRQ

- 'Synchronisation Signal - Reference Signal Received Quality' (SS-RSRQ) measurements can be used for cell selection, cell reselection and mobility procedures. In contrast to RSRP measurements, RSRQ measurements are not used when reporting Channel State Information (CSI). SS-RSRQ is defined as:

$$SS\text{-}RSRQ = \frac{SS\text{-}RSRP}{(RSSI\ /\ N)}$$

where, N is the number of Resource Blocks across which the Received Signal Strength Indicator (RSSI) is measured, i.e. RSSI / N defines the RSSI per Resource Block. The RSSI represents the total received power from all sources including interference and noise. The RSRP and RSSI are both measured across the same set of Resource Blocks

- This equation is similar to the equation used by LTE. However, there are some significant differences in the measurement methods. In the case of LTE, RSRP is measured from the Cell specific Reference Signal (CRS) and the RSSI is measured from symbols which include the CRS. This means that 'RSSI / N' can never be less than the RSRP, so RSRQ is always less than 1 and is a negative number when expressed in dB
- In the case of NR, RSRP is measured from the Secondary Synchronisation Signal (SSS). In this case, it makes less sense to measure the RSSI from the same symbols as the RSRP because all subcarriers across the measurement bandwidth are fully occupied by the SSS. This means that UE in good dominance areas would always measure an RSRQ = RSRP / (12 × RSRP). 3GPP has specified the NR measurement method for RSRQ such that the RSRP and RSSI can be measured across different symbols. This means that 'RSSI / N' can be greater than or less than RSRP, so RSRQ can be greater than or less than 1, and can be either positive or negative when expressed in dB
- Figure 326 compares the two measurement methods:

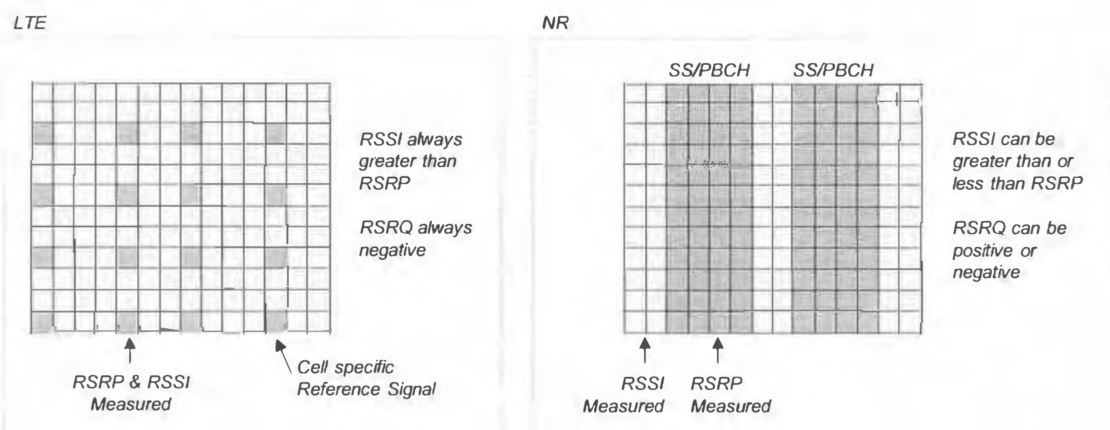


Figure 326 – Comparison between LTE and NR measurements for RSRQ

- In the case of cell selection, 3GPP does not constrain the time domain resources used to measure the RSSI. In all other cases, the time domain resources are confined to a subset of the symbols belonging to the SS/PBCH Block Measurement Time Configuration (SMTC). The SMTC was introduced within section 10.1 for the purpose of measuring SS-RSRP. This implies that the SMTC defines a time window which includes the Secondary Synchronisation Signal. The Base Station can use the *ss-RSSI-Measurement* parameter structure presented in Table 240 to configure a subset of the SMTC which excludes the SS/PBCH Block

ss-RSSI-Measurement	
measurementSlots	BIT STRING {1 to 80 bits}
endSymbol	0 to 3

Table 240 – Configuration information for SMTC and RSSI Measurements

- *measurementSlots* defines a bit string where each bit corresponds to a slot within the SMTC *duration*. For example, if the SMTC *duration* is set to 5 subframes and the subcarrier spacing is 15 kHz then the bit string will have a length of 5 bits because there are 5 slots in 5 subframes. In contrast, if the SMTC *duration* is set to 5 subframes and the subcarrier spacing is 240 kHz then the bit string will have a length of 80 bits because there are 80 slots in 5 subframes. The UE measures the RSSI during slots which correspond to a '1' within the bit string
- *endSymbol* defines the symbols within the *measurementSlots* which can be used to measure the RSSI. The value of *endSymbol* is a pointer to a row within a 3GPP standardised look-up table (Table 241). For example, *endSymbol* = '0' means that the UE can complete RSSI measurements during symbols 0 and 1, while *endSymbol* = '2' means that the UE can complete RSSI measurements during symbols 0, 1, 2, 3, 4 and 5

endSymbol	Symbol Indices
0	{0, 1}
1	{0, 1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11}
2	{0, 1, 2, 3, 4, 5}
3	{0, 1, 2, 3, 4, 5, 6, 7}

Table 241 – Symbols used for RSSI measurements within Measurement Slots

★ 3GPP has selected the symbol indices within Table 241 to ensure that RSSI measurements can be completed outside an SS/PBCH Block. For example, consider an operating band located between 3 and 6 GHz using the 15 kHz subcarrier spacing. Table 56 within section 3.4 specifies that SS/PBCH Blocks can be transmitted using 8 beams with starting symbols of {2, 8, 16, 22, 30, 36, 44, 50}. Translating these figures to represent symbols within individual slots generates {2, 8, 2, 8, 2, 8, 2, 8}, i.e. SS/PBCH Blocks always occupy symbols {2, 3, 4, 5} and {8, 9, 10, 11}. This illustrates that the UE can use symbols {0, 1} to measure the downlink RSSI without coinciding with an SS/PBCH Block

★ For the previous example, if the Base Station is configured with only 4 beams rather than the full set of 8 beams then those 4 beams could use SS/PBCH Blocks which start at {8, 22, 36, 50}. Translating these figures to represent symbols within individual slots generates {8, 8, 8, 8}, i.e. SS/PBCH Blocks always occupy symbols {8, 9, 10, 11}. This illustrates that the UE can use symbols {0, 1, 2, 3, 4, 5, 6, 7} to measure the downlink RSSI without coinciding with an SS/PBCH Block

★ *endSymbol* = '1' has been included within the table to account for downlink centric slots which have 12 symbols allocated to the downlink, 1 guard symbol and 1 uplink symbol.

★ RSRQ measurements are filtered at Layer 3 to remove the impact of fast fading and to help reduce short term variations in the measurement results. This filtering is specified by 3GPP within TS 38.331 and is described in section 11.2

★ 3GPP TS 38.133 specifies the mapping between the reported and measured SS-RSRQ. This mapping is presented in Table 242. As already explained, the measured values of RSRQ can be either positive or negative when expressed in dB

Reported Value	Measured SS-RSRQ
RSRQ_0	SS-RSRQ < -43
RSRQ_1	-43 ≤ SS-RSRQ < -42.5
RSRQ_2	-42.5 ≤ SS-RSRQ < -42
RSRQ_3	-42 ≤ SS-RSRQ < -41.5
...	...
RSRQ_124	18.5 ≤ SS-RSRQ < 19
RSRQ_125	19 ≤ SS-RSRQ < 19.5
RSRQ_126	19.5 ≤ SS-RSRQ < 20
RSRQ_127	20 ≤ SS-RSRQ

Table 242 – Mapping between measured and reported SS-RSRQ (measurements in dB)

★ When using Frequency Range 1, the reference point for the measurement is the UE antenna connector, i.e. it is assumed that the UE has a single antenna element per receive path rather than an antenna array. When using Frequency Range 2, the measurement is based upon the combined signal strength from all antenna elements belonging to a single receive path, i.e. it is assumed that the UE has an antenna array for each receive path

★ Layer 3 measurements can be either 'beam level' or 'cell level'. Both can be reported to the Base Station within an RRC: *Measurement Report* message. Beam level results are evaluated and reported after Layer 3 filtering. Cell level results are derived using the rules described in section 11.1. Layer 3 filtering is subsequently applied after the cell level results have been generated

★ 3GPP References: TS 38.215, TS 38.133, TS 38.214

10.3 SS-SINR

- 'Synchronisation Signal – Signal to Interference and Noise Ratio' (SS-SINR) measurements can be used for connected mode mobility procedures. The SS-SINR represents the ratio of the wanted signal power to the interference plus noise power. Both the wanted signal power and the interference plus noise power are measured from Resource Elements used by the Secondary Synchronisation Signal
- SS-SINR is an optional UE capability which UE must declare separately for Frequency Ranges 1 and 2. A UE uses the *ss-SINR-Meas* flag within the *MeasAndMobParametersFRX-Diff* parameter structure to signal its capability
- The time domain resources used to measure the SS-SINR are confined to the SS/PBCH Block Measurement Time Configuration (SMTC) described in section 10.1
- 3GPP TS 38.133 specifies the mapping between the reported and measured SS-SINR. This mapping is presented in Table 243. SINR values can be either positive or negative when expressed in dB

Reported Value	Measured SS-SINR
SINR_0	SS-SINR < -23
SINR_1	-23 ≤ SS-SINR < -22.5
SINR_2	-22.5 ≤ SS-SINR < -22
SINR_3	-22 ≤ SS-SINR < -1.5
…	…
SINR_124	38.5 ≤ SS-SINR < 39
SINR_125	39 ≤ SS-SINR < 39.5
SINR_126	39.5 ≤ SS-SINR< 40
SINR_127	40 ≤ SS-SINR

Table 243 – Mapping between measured and reported SS-SINR (measurements in dB)

- A UE is permitted to use measurements from the PBCH Demodulation Reference Signal (DMRS) when generating SS-SINR results. The DMRS and Secondary Synchronisation Signal are transmitted with equal power so results can be averaged directly
- When using Frequency Range 1, the reference point for the measurement is the UE antenna connector, i.e. it is assumed that the UE has a single antenna element per receive path rather than an antenna array. When using Frequency Range 2, the measurement is based upon the combined signal strength from all antenna elements belonging to a single receive path, i.e. it is assumed that the UE has an antenna array for each receive path
- 3GPP References: TS 38.215, TS 38.133, TS 38.331, TS 38.306

10.4 CSI-RSRP

- 'CSI Reference Signal Received Power' (CSI-RSRP) measurements are used for connected mode mobility, power control calculations, and beam management. Measurements can be generated and reported at both layer 1 and layer 3. For example, a UE can provide CSI-RSRP measurements at Layer 1 when sending Channel State Information (CSI) to the Base Station. Alternatively, a UE can provide CSI-RSRP measurements at Layer 3 when sending an RRC: Measurement Report
- CSI-RSRP represents the average power received from a single Resource Element allocated to the CSI Reference Signal
- Measurements are filtered at Layer 1 to help remove the impact of noise and to improve measurement accuracy. This filtering is not specified explicitly by 3GPP but UE measurements must achieve the accuracy requirements defined within TS 38.133. Measurements are filtered at Layer 3 to remove the impact of fast fading and to help reduce short term variations in the measurement results. This filtering is specified by 3GPP within TS 38.331 and is described in section 11.2
- The mappings presented in Table 237 for SS-RSRP are also applicable to CSI-RSRP, i.e. the UE reports a 7 bit value when reporting an absolute CSI-RSRP at Layer 1 or Layer 3. If the UE is configured to report multiple Layer 1 RSRP values within a CSI report then the largest measurement result is signalled using a 7 bit absolute value. The remaining results are signalled using 4 bit differential values which are calculated relative to the largest result. The differential values are signalled using the mapping presented in Table 238
- A UE is configured to report Layer 1 CSI-RSRP if *reportQuantity* within *CSI-ReportConfig* is set to 'cri-RSRP'. Each CSI-RSRP result is linked to a specific CSI-Reference Signal transmission. Measurements can use CSI Reference Signal transmissions on antenna port 3000 for Layer 3 RSRP, and measurements on both antenna ports 3000 and 3001 for Layer 1 RSRP
- 3GPP References: TS 38.215, TS 38.133, TS 38.331

10.5 CSI-RSRQ

★ 'CSI Reference Signal Received Quality' (CSI-RSRQ) measurements can be used for mobility procedures. In contrast to RSRP measurements, RSRQ measurements are not used when reporting Channel State Information (CSI). CSI-RSRQ is defined as:

$$CSI\text{-}RSRQ = \frac{CSI\text{-}RSRP}{(RSSI\ /\ N)}$$

where, N is the number of Resource Blocks across which the Received Signal Strength Indicator (RSSI) is measured, i.e. RSSI / N defines the RSSI per Resource Block. The RSSI represents the total received power from all sources including interference and noise. The RSRP and RSSI are both measured across the same set of Resource Blocks. The RSSI is measured during symbols which contain CSI Reference Signal Resource Elements

★ CSI-RSRQ measurements are based upon CSI Reference Signal transmissions on antenna port 3000

★ The mappings presented in Table 242 for SS-RSRQ are also applicable to CSI-RSRQ, i.e. the UE reports a 7 bit value when reporting an absolute CSI-RSRQ at Layer 3

★ 3GPP References: TS 38.215, TS 38.133, TS 38.331

10.6 CSI-SINR

★ 'CSI Reference Signal Signal to Interference and Noise Ratio' (CSI-SINR) measurements can be used for connected mode mobility procedures. The CSI-SINR represents the ratio of the wanted signal power to the interference plus noise power. Both the wanted signal power and the interference plus noise power are measured from Resource Elements used by the CSI Reference Signal

★ CSI-SINR is an optional UE capability which UE must declare separately for Frequency Ranges 1 and 2. A UE uses the *csi-SINR-Meas* flag within the *MeasAndMobParametersFRX-Diff* parameter structure to signal its capability

★ CSI-SINR measurements are based upon CSI Reference Signal transmissions on antenna port 3000

★ The mappings presented in Table 243 for SS-SINR are also applicable to CSI-SINR, i.e. the UE reports a 7 bit value when reporting an absolute CSI-SINR at Layer 3

★ 3GPP References: TS 38.215, TS 38.133, TS 38.331, TS 38.306

10.7 SFN AND FRAME TIMING DIFFERENCE

★ SFN and Frame Timing Difference (SFTD) measurements are important when 4G and 5G Base Stations are not time synchronised. SFTD measurements allow the UE to report the SFN and Frame Timing Difference between an E-UTRA cell and an NR cell. Knowledge of this timing difference is important for the Non-Standalone Base Station architecture when requesting a UE to complete measurements prior to Secondary Cell Addition

★ If the 4G Base Station belonging to an EN-DC Non-Standalone Base Station architecture does not know the timing of the 5G Base Station, it will not be able to configure an appropriate measurement window. This means that measurements are likely to fail because the measurement window does not coincide with the transmission of the SS/PBCH Blocks. The measurement window is defined by the SS/PBCH Block Measurement Timing Configuration (SMTC) within a set of Measurement Gaps

★ SFTD measurements are defined within the 3GPP specifications for 4G (TS 36.214). This allows an E-UTRA Primary Cell (PCell) to request measurements for an NR Primary SCG Cell (PSCell), i.e. these measurements are applicable to the EN-DC Non-Standalone Base Station architecture

★ SFTD measurements are also defined within the 3GPP specifications for 5G (TS 38.215). This allows an NR PCell to request measurements from an E-UTRA PSCell, i.e. these measurements are applicable to the NE-DC Non-Standalone Base Station architecture

★ SFTD measurements are an optional UE capability which have a dependence upon the duplexing method. For example, a UE may support SFTD measurements for FDD but not for TDD. The UE signals its capability using the information elements presented in Table 244. The *sftd-MeasPSCell* flag indicates support for measurements from a PSCell which has already been configured. The *sftd-MeasNR-Cell* flag indicates support for measurements from a candidate NR cell which has not yet been configured as a PSCell. For this latter case, the UE must be capable of completing the measurements without Measurement Gaps when the combination of E-UTRA and NR carrier frequencies is a supported EN-DC band combination

MeasAndMobParametersMRDC-XDD-Diff	
sftd-MeasPSCell	supported
sftd-MeasNR-Cell	supported

Table 244 – UE capability information for SFTD

- The SFTD measurement results reported by the UE are presented in Table 245. These results are included within an RRC *MeasurementReport*. The target cell is identified by its Physical layer Cell Identity (PCI). The SFN Offset quantifies the value of $(SFN_{PCELL} - SFN_{PSCELL})$ mod 1024. The Frame Boundary Offset quantifies the value of ROUND DOWN [$(T_{FRAME\_BOUNDARY\_PCELL} - T_{FRAME\_BOUNDARY\_PSCell}) / 5$], where the timings have units of $Ts = 1 / (15\,000 \times 2048)$, i.e. $Ts = 32.55$ ns

MeasResultCellSFTD	
physCellId	0 to 1007
sfn-OffsetResult	0 to 1023
frameBoundaryOffsetResult	-30720 to 30719
rsrp-Result	0 to 127

Table 245 – SFTD Measurement Result reported by the UE

- 3GPP References: TS 36.214, TS 38.215, TS 38.331, TS 38.306

10.8 OTHER MEASUREMENTS

- 3GPP TS 38.215 specifies 4G measurement capabilities in terms of E-UTRA RSRP, RSRQ and SINR. The RSRP and RSRQ measurements can be used for inter-system cell reselection in RRC Idle and RRC Inactive. The RSRP, RSRQ and SINR measurements can be used for inter-system handovers in RRC Connected
- 3GPP TS 38.215 also specifies Synchronisation Signal - Reference Signal Received Power per Branch (SS-RSRPB). This measurement is only applicable to Frequency Range 2 and is intended to be used during device conformance testing. It allows the UE to report an SS-RSRP result for each receive path (where a receive path is expected to be connected to an antenna array with multiple antenna elements). During conformance testing, a System Simulator (SS) can communicate with the device by encapsulating Test Mode Control (TMC) messages within RRC *DLInformationTransfer* and *ULInformationTransfer* messages. These messages are specified within 3GPP TS 38.509. The System Simulator can send an 'SS-RSRPB Report Request' to the device, which then responds with an 'SS-RSRPB Report Response'. The response message identifies the relevant SS/PBCH Block and provides measurement results for two receive paths
- Reference Signal Time Difference (RSTD) for E-UTRA measurements are specified for Location based Services. The Observed Time Difference of Arrival (OTDOA) positioning method uses RSTD measurements from the UE. The RSTD quantifies the subframe timing difference between an E-UTRA reference cell and an E-UTRA neighbouring cell. The accuracy of the positioning calculation is improved if the UE can provide RSTD measurements from an increased number of cells. RSTD measurements can be completed using the 4G Positioning Reference Signal (PRS). The PRS helps to improve the 'hearability' of neighbouring cells which can be difficult to measure as a result of them being co-channel with the reference cell, especially at locations where the reference cell signal strength is high. A UE can use the RRC *LocationMeasurementIndication* message to inform the 5G Base Station that it plans to start location based measurements which require a Measurement Gap. The *LocationMeasurementIndication* message can include timing information to help the 5G Base Station configure Measurement Gaps which coincide with the 4G Positioning Reference Signal
- Global Navigation Satellite System (GNSS) measurements are also specified for Location based Services. These measurements rely upon the UE having a receiver which is capable of receiving GNSS signals. They include:
    - UE GNSS Timing of Cell Frames for UE positioning for E-UTRAN
    - UE GNSS Code Measurements
    - UE GNSS Carrier Phase Measurements

  3GPP TS 38.305 describes the use of these measurements for network-assisted positioning services
- IEEE 802.11 WLAN RSSI measurements are also specified for Location based Services. UE are able to report both the identity of the WLAN Access Point and a corresponding RSSI measurement. The network can use this information in combination with a database of Access Point locations to determine the location of the UE
- 3GPP References: TS 38.215, TS 38.509, TS 38.305

11 MEASUREMENT REPORTING

- ★ A Base Station can use dedicated signalling to configure a UE in RRC Connected mode to perform and report measurements. Measurements can be intra-frequency, inter-frequency or inter-system
- ★ Intra and inter-frequency measurements can be based upon either SS/PBCH Blocks or CSI Reference Signal Resources. In both cases, measurements can be 'beam level' or 'cell level'. A beam level measurement is recorded from an SS/PBCH Block with a specific Block Index, or from a CSI Reference Signal Resource with a specific Resource Identity. Cell level measurements are derived from beam level measurements using the rules described in section 11.1
- ★ The definition of intra-frequency measurements depends upon the measurement resource:
  - o SS/PBCH Block intra-frequency measurements correspond to scenarios where both the serving cell and neighbouring cell use the same SS/PBCH Block center frequency and subcarrier spacing
  - o CSI Reference Signal intra-frequency measurements correspond to scenarios where the neighbouring cell is configured with a CSI Reference Signal Resource bandwidth which is confined within the bandwidth of the CSI Reference Signal Resource belonging to the serving cell, and both CSI Reference Signals use the same subcarrier spacing
- ★ Within the release 15 version of the 3GPP specifications, inter-system measurements are restricted to LTE (4G). It is not possible to configure inter-system measurements for GSM (2G), UMTS (3G) nor CDMA2000 (3G)
- ★ A measurement configuration includes: Measurement Identities, Measurement Objects, Reporting Configurations, Quantity Configurations and Measurement Gap Configurations

  Measurement Identity

  - o a Measurement Identity links a Reporting Configuration to a Measurement Object, i.e. each Measurement Identity includes a pointer towards a Reporting Configuration and a pointer towards a Measurement Object. Multiple Measurement Identities can be used to link multiple Reporting Configurations to the same Measurement Object. Alternatively, multiple Measurement Identities can be used to link a single Reporting Configuration to multiple Measurement Objects
  - o the Measurement Identity is used as a reference when the UE provides measurement results within an RRC: *Measurement Report* message, i.e. a UE provides a set of measurement results and states that they are applicable to a specific Measurement Identity. An RRC: *Measurement Report* does not explicitly indicate the Measurement Object nor the Reporting Configuration

  Measurement Object

  - o in the case of intra and inter-frequency measurements, a Measurement Object identifies the time and frequency location of the SS/PBCH Blocks and CSI Reference Signal Resources to be measured. It also specifies the corresponding subcarrier spacings. A single Measurement Object can specify both SS/PBCH Block and CSI Reference Signal information. The Reporting Configuration is responsible for selecting between these two types of measurement resource. The Measurement Object can specify a set of cell specific measurement offsets to make individual cells appear either more or less attractive. Cells can be 'Blacklisted' to exclude them from event evaluation and measurement reporting. In addition, a set of 'Whitelisted' cells can be specified. The inclusion of 'Whitelisted' cells within the Measurement Object does not necessarily mean that they will be used. The Reporting Configuration is responsible for indicating when the 'Whitelisted' cells should be used. When used, the 'Whitelisted' cells are the only cells taken into account for event evaluation and measurement reporting. The Measurement Object also includes parameters which are used when deriving cell level measurements from beam level measurements
  - o in the case of inter-system measurements, a Measurement Object identifies a specific LTE carrier and a corresponding measurement bandwidth. The Measurement Object can also specify cell specific measurement offsets to make individual cells appear either more or less attractive. Cells can be 'Blacklisted' to exclude them from event evaluation and measurement reporting

  Reporting Configurations

  - o a Reporting Configuration can specify Periodic, Event Triggered or Cell Global Identity (CGI) reporting
    - ▪ a Periodic configuration for NR reporting specifies the Reference Signal type (SS/PBCH or CSI Reference Signal), a reporting interval and a report amount. For example, a UE can be instructed to provide 4 reports based upon the SS/PBCH with an interval of 10.24 seconds between each report. Alternatively, a UE could be instructed to provide 32 reports based upon the CSI Reference Signal with an interval of 640 ms between each report. The report amount can be set to 'infinity' when a continuous stream of reports is required. The configuration also specifies the 'cell level' measurement quantities to be included within each report and the maximum number of cells to be reported. Similarly, the configuration specifies the 'beam level' measurement quantities and the maximum number of beams to be reported. The 'cell level' and 'beam level' measurement quantities can be specified as any combination of RSRP, RSRQ and SINR. There are also flags to indicate whether or not beam level measurements should be reported, and whether or not the set of 'Whitelisted' cells specified within the Measurement Object should be applied
    - ▪ a Periodic configuration for LTE reporting specifies a reporting interval and a report amount. It also specifies the reporting quantity and the maximum number of cells to report. Similar to the periodic Reporting Configuration for NR, the reporting quantity can be specified as any combination of RSRP, RSRQ and SINR
    - ▪ an Event Triggered configuration for NR reporting provides the parameters for a specific Measurement Reporting Event (Event A1, A2, A3, A4, A5, or A6). These Measurement Reporting Events are described later in this section. The Reporting

Configuration also specifies the Reference Signal type (SS/PBCH or CSI Reference Signal) used to trigger the event, the number of reports which are sent after the event has triggered and the time interval between those reports. The configuration also specifies the 'cell level' measurement quantities to be included within each report and the maximum number of cells to be reported. Similarly, the configuration specifies the 'beam level' measurement quantities and the maximum number of beams to be reported. The 'cell level' and 'beam level' measurement quantities can be specified as any combination of RSRP, RSRQ and SINR. There are also flags to indicate whether or not beam level measurements should be reported, and whether or not the set of 'Whitelisted' cells specified within the Measurement Object should be applied

- an Event Triggered configuration for LTE reporting provides the parameters for a specific Measurement Reporting Event (Event B1 or B2). The Reporting Configuration also specifies the Reference Signal type (SS/PBCH or CSI Reference Signal) used to trigger the event (applicable when using Event B2 which depends upon both NR and LTE measurements) and used for any reported NR measurements. In addition, the Reporting Configuration specifies the number of reports which are sent after the event has triggered and the time interval between those reports. Similar to the event triggered Reporting Configuration for NR, the reporting quantity can be specified as any combination of RSRP, RSRQ and SINR
- a CGI Reporting Configuration for either NR or LTE specifies the set of Physical layer Cell Identities (PCI) for which the UE is required to decode and report the Cell Global Identity (CGI). This Reporting Configuration can be used for neighbour addition and neighbour validation within the context of UE based Automatic Neighbour Relations (ANR)

★ Figure 327 illustrates an example of Measurement Identities being used to link a set of Reporting Configurations to a set of Measurement Objects. This example illustrates that multiple Reporting Configurations can be linked to the same Measurement Object, and that a single Reporting Configuration can be linked to multiple Measurement Objects

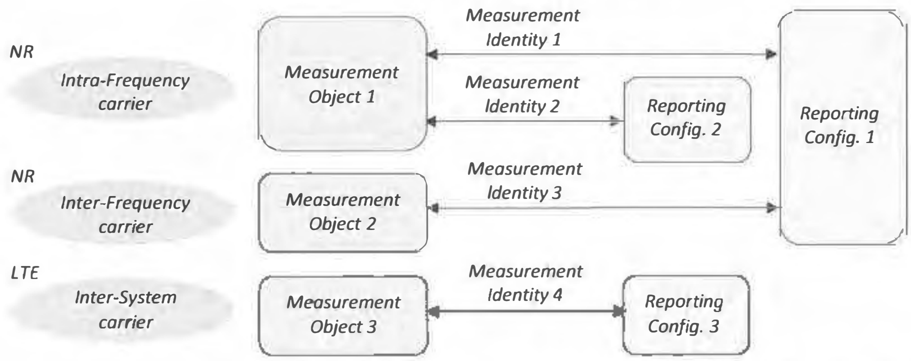


Figure 327 – Measurement Identities linking Measurement Objects to Reporting Configurations

★ Figure 328 illustrates a Measurement Identity used to link a periodic NR Reporting Configuration to an NR Measurement Object. This example illustrates that the 'Reference Signal Type' within the Reporting Configuration is used to select between the SS/PBCH Block and CSI Reference Signal information within the Measurement Object

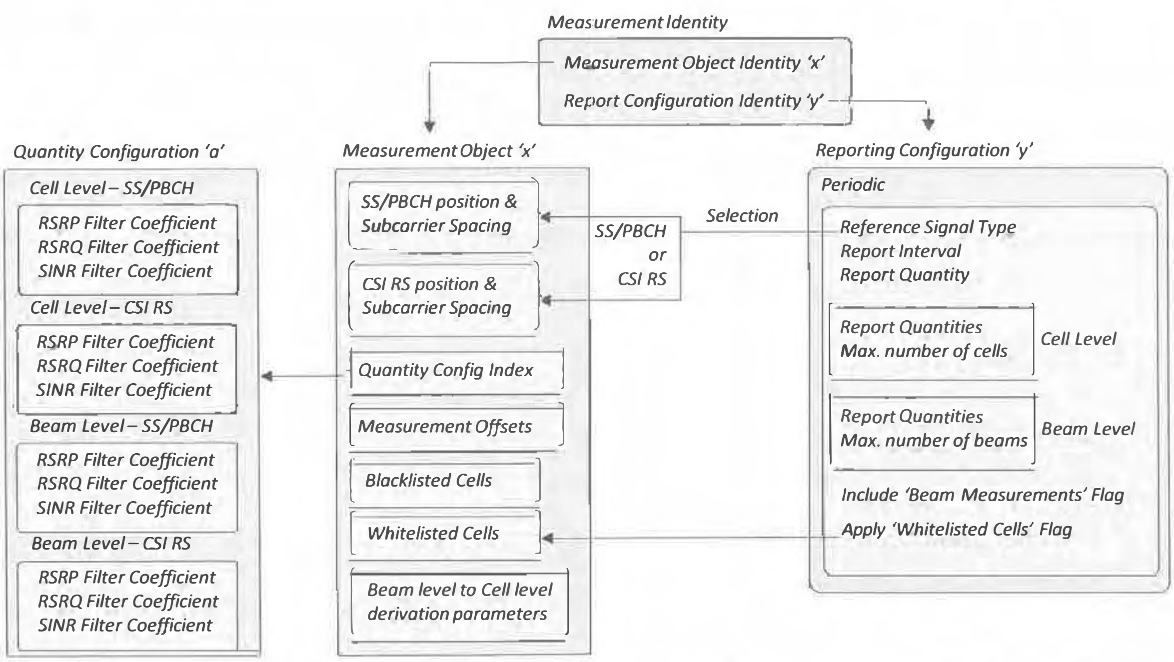


Figure 328 – Measurement Identity linking a Measurement Object for NR to a Periodic Reporting Configuration

* The example in Figure 328 also illustrates that the Measurement Object includes a pointer towards a Quantity Configuration. The Quantity Configuration specifies the set of Filter Coefficients which are to be used for Layer 3 filtering of the measurements. It is possible to configure up to 2 Quantity Configurations for NR so the pointer has a value of 1 or 2. It is only possible to configure 1 Quantity Configuration for LTE so Measurement Objects for LTE do not require this pointer

* Figure 329 illustrates a Measurement Identity being used to link an event triggered NR Reporting Configuration to an NR Measurement Object. This example illustrates that the event triggered Reporting Configuration includes the parameter set for a specific Measurement Reporting Event. In this case, the flag used to activate the Whitelisted cells is included within the parameter set for each Measurement Reporting Event. Events Al and A2 are exceptions which do not require this flag because they only depend upon the serving cell and do not require neighbour cell measurements

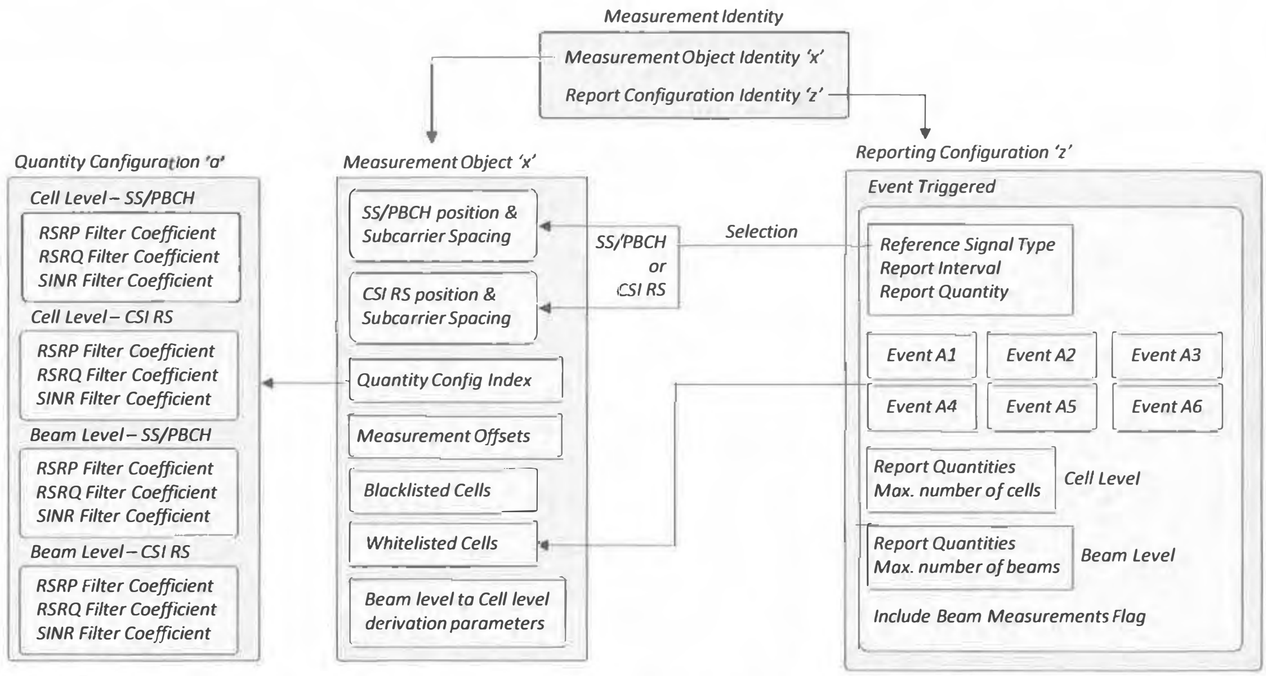


Figure 329 – Measurement Identity linking a Measurement Object for NR to an Event Triggered Reporting Configuration

<u>Quantity Configurations</u>

- the Quantity Configuration specifies the Layer 3 filtering coefficients which define the memory of the Layer 3 filtering. A large filter coefficient corresponds to a filter with a longer memory. This means that a specific measurement result impacts the output of the filter for a longer period of time (the averaging window increases). Layer 3 filtering is applied before evaluating Measurement Reporting Events (A1, A2, A3, etc) and before reporting measurements to the Base Station (in contrast, CSI reporting allows RSRP measurements to be sent at Layer 1 without Layer 3 filtering). Layer 3 filtering is described in section 11.2

- in the case of NR, it is possible to configure up to 2 Quantity Configurations. Each Quantity Configuration can specify up to 4 sets of filter coefficients to cater for Cell Level and Beam Level measurements from both SS/PBCH Blocks and CSI Reference Signal Resources. Separate filter coefficients are specified for each measurement quantity (RSRP, RSRQ and SINR).

- In the case of LTE, it is possible to configure a single Quantity Configuration which includes a single set of filter coefficients. Figure 330 illustrates the 4 sets of filter coefficients for NR and the single set for LTE

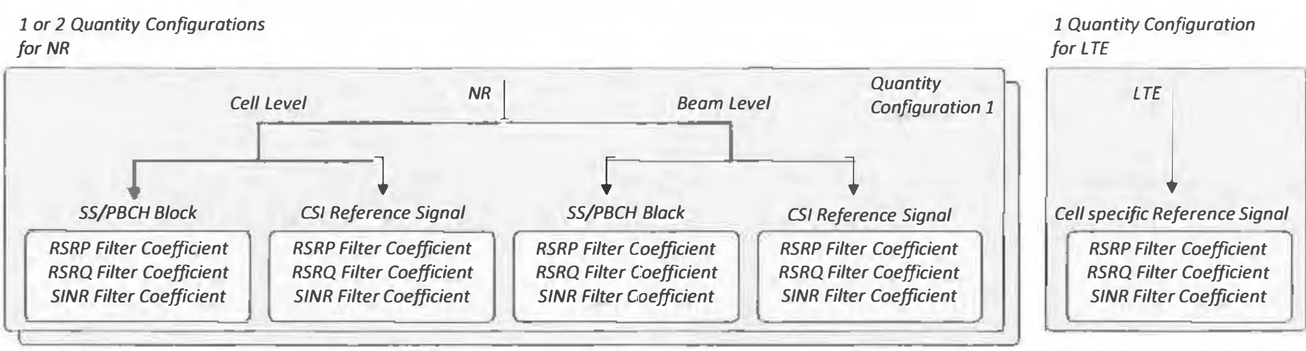


Figure 330 – Configuration of Layer 3 Filter Coefficients within Quantity Configurations

Measurement Gap Configurations

- Measurement Gaps are required if a UE is requested to perform measurements which cannot be completed while the UE is tuned to the current serving cell. Measurement Gaps impact performance because they interrupt both uplink and downlink data transfer. This means that Measurement Gaps should only be configured when necessary. Event A2 can be used as a triggering mechanism to configure Measurement Gaps. Event A2 indicates that the current serving cell has become weak so it may be necessary to complete an inter-frequency or inter-system handover
- In the case of LTE, Measurement Gaps are typically configured for inter-frequency and inter-system measurements. The measurement gaps provide sufficient time for the UE to re-tune its transceiver to the target carrier, complete the set of measurements and then re-tune its transceiver back to the original carrier. It is common to assume that each re-tuning operation requires up to 0.5 ms
- In the case of NR, Measurement Gaps may be required for intra-frequency measurements, in addition to inter-frequency and inter-system measurements. For example:
  - within Frequency Range 2 it is expected that all UE will use analogue receiver beamforming. The UE beam will normally be directed towards the serving cell, whereas neighbour cell measurements will require the beam to be directed towards the neighbouring cells. Measurement Gaps will be required while the UE redirects its beam and temporarily stops transmitting/receiving with the serving cell
  - a UE may be configured with an active Bandwidth Part which does not contain the intra-frequency SS/PBCH Block. In this case, the UE has to re-tune its transceiver to receive the intra-frequency SS/PBCH Block. This scenario is similar to re-tuning for inter-frequency measurements
- Measurement Gaps are configured using the parameter structure shown in Table 246. It is possible to configure different Measurement Gap patterns for Frequency Ranges 1 and 2 (*gapFR1* and *gapFR2*). Alternatively, a single Measurement Gap pattern can be configured for both Frequency Ranges (*gapUE*)

MeasGapConfig	
gapFR2	SetupRelease { GapConfig }
gapFR1	SetupRelease { GapConfig }
gapUE	SetupRelease { GapConfig }

GapConfig	
gapOffset	0 to 159
mgl	1.5, 3, 3.5, 4, 5.5, 6 ms
mgrp	20, 40, 80, 160 ms
mgta	0, 0.25, 0.5 ms

Table 246 – Measurement Gap Configuration

- Measurement Gaps start during radio frames and subframes which satisfy the following criteria:

SFN mod (*MGRP* / 10) = FLOOR (*gapOffset* / 10)

Subframe = *gapOffset* mod 10

where, *MGRP* is the Measurement Gap Repetition Period, and *gapOffset* can be configured with a value between 0 and MGRP – 1

- For example, when the *MGRP* is configured with a value of 40 ms and *gapOffset* is configured with a value of 35 then Measurement Gaps start during subframe 5 of SFN 3, 7, 11, 15, 19, etc
- The duration of each Measurement Gap is configured using the Measurement Gap Length (*MGL*) which can have a value between 1.5 and 6 ms
- 3GPP TS 38.133 specifies the set of 24 Gap Patterns presented in Table 247 by defining 24 combinations of *MGL* and *MGRP*. These Gap Patterns are designed to accommodate the timing of the NR and LTE transmissions to be measured. For example, when using Frequency Range 1 with a 15 kHz subcarrier spacing, a set of 8 SS/PBCH Blocks corresponding to 8 beams can be transmitted within a 5 ms time window. Adding an additional 1 ms for transceiver re-tuning leads to the 6 ms MGL. Smaller MGL can be used if fewer SS/PBCH Blocks are transmitted or if a higher subcarrier spacing is configured

Gap Pattern	MGL (ms)	MGRP (ms)
0	6	40
1	6	80
2	3	40
3	3	80
4	6	20
5	6	160
6	4	20
7	4	40

Gap Pattern	MGL (ms)	MGRP (ms)
8	4	80
9	4	160
10	3	20
11	3	160
12	5.5	20
13	5.5	40
14	5.5	80
15	5.5	160

Gap Pattern	MGL (ms)	MGRP (ms)
16	3.5	20
17	3.5	40
18	3.5	80
19	3.5	160
20	1.5	20
21	1.5	40
22	1.5	80
23	1.5	160

Table 247 – Gap Pattern Configurations

- The Measurement Gap Configuration also specifies a Measurement Gap Timing Advance (*MGTA*). The *MGTA* can be used to advance the timing of the Measurement Gap to improve the alignment between the Measurement Gaps and the SS/PBCH Block Measurement Time Configuration (SMTC). The *MGTA* allows adjustment by 0.25 or 0.5 ms whereas the *gapOffset* allows adjustment by 1 ms. Figure 450 within section 15.2 illustrates an example requirement for an *MGTA*

★ 3GPP References: TS 38.331, TS 38.133

11.1 CELL LEVEL RESULTS

★ Layer 1 measurements are recorded from specific beams which are associated with an SS/PBCH Block or a CSI Reference Signal. Cell reselection and handover procedures operate at a cell level rather than at a beam level, i.e. they involve changing the serving cell. This means it is more appropriate to use a cell level measurement rather than a beam level measurement

★ 3GPP has specified the rules for generating a cell level measurement from one or more beam level measurements within TS 38.331

★ In the case of SS/PBCH Block measurements, the derivation is based upon the following parameters:

- *nrofSS-BlocksToAverage* (value ranges from 2 to 16)
- *absThreshSS-BlocksConsolidation* (value ranges from 0 to 127)

★ These parameters can be broadcast within SIB2 and SIB4 for the purposes of cell reselection. Dedicated signalling can be used to configure them within specific Measurement Objects for the purposes of measurement reporting and handovers. The value of *absThreshSS-BlocksConsolidation* is mapped onto an RSRP or RSRQ value for cell reselection. Similarly, it is mapped onto an RSRP, RSRQ or SINR value for handovers. The look-up tables for these mappings are presented in section 0

★ If a UE is not configured with both parameters then the UE uses the measurement from the strongest beam as the cell level measurement. Similarly, if none of the beam level measurements exceed the threshold defined by *absThreshSS-BlocksConsolidation* then the measurement from the strongest beam is used as the cell level measurement

★ Otherwise, the cell level measurement is defined as the linear average of the strongest measurement results which exceed the threshold defined by *absThreshSS-BlocksConsolidation*, including a maximum of *nrofSS-BlocksToAverage* beams within the average. Examples of this derivation are illustrated in Figure 331

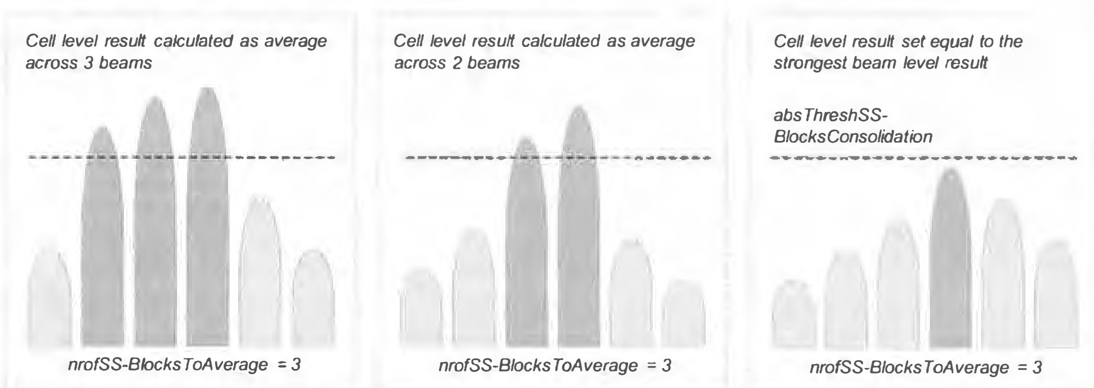


Figure 331 – Derivation of cell level results from beam level results

★ In the case of CSI Reference Signal measurements, the principles of the derivation are the same but the following parameters are used:

- *nrofCSI-RS-ResourcesToAverage* (value ranges from 2 to 16)
- *absThreshCSI-RS-Consolidation* (value ranges from 0 to 127)

★ These parameters are not broadcast within the SIB because they are not applicable to cell reselection. Dedicated signalling can be used to configure them within specific Measurement Objects for the purposes of measurement reporting and handovers

★ Figure 332 illustrates the derivation of cell level results followed by Layer 3 filtering and the subsequent evaluation of Measurement Reporting Events. Measurement Reporting Events may require cell level measurements from both the serving cell and neighbouring cells. In this case, the processing illustrated in Figure 332 is completed for each cell

★ Figure 332 also illustrates the Layer 3 filtering of beam level measurements which are then ordered to allow selection for reporting

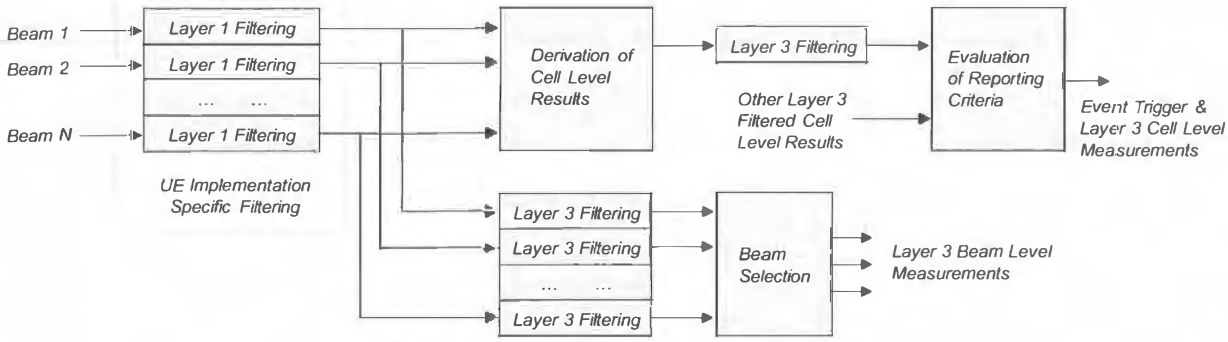


Figure 332 – Processing of beam level measurements

11.2 LAYER 3 FILTERING

★ Layer 3 filtering is applied using the equation below:

$$F_n = (1 - a) \times F_{n-1} + a \times Meas_n$$

where, F_n is the updated filtered measurement result and F_{n-1} is the previous filtered measurement result

$a = 0.5^{(k/4)}$ where k is the appropriate filter coefficient

$Meas_n$ is the latest measurement result (either cell level or beam level)

★ The filter coefficient can be configured with values of {0, 1, 2, 3, 4, 5, 6, 7, 8, 9, 11, 13, 15, 17, 19}. Filtering is not applied if the filter coefficient is set equal to 0, i.e. a = 1. A default value of 4 is assumed if the filter coefficient is not configured

★ Figure 333 illustrates the impulse response for each of the filter coefficient values assuming a new result is calculated every 200 ms. The impulse response is generated by feeding a single value of '1' into the filter. This illustrates that the filter has greater memory when using larger filter coefficients

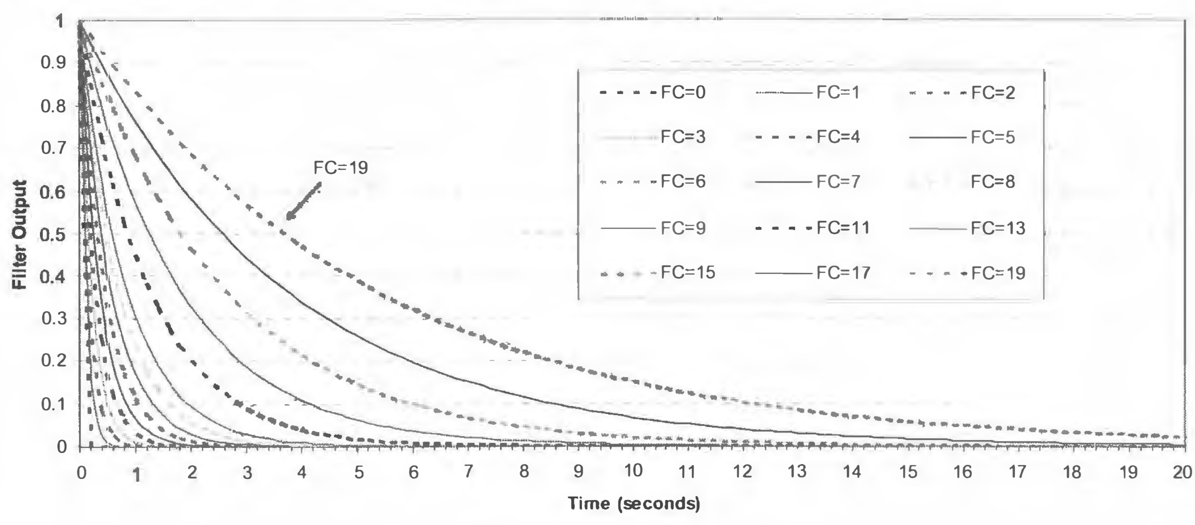


Figure 333 – Impulse response of Layer 3 filter

★ Figure 333 assumes that Layer 1 measurements are fed into the filter at a rate of once every 200 ms. The input rate impacts the memory of the filter. For example, if measurements were fed into the filter at a rate of once every 100 ms then the maximum value on the x-axis of Figure 333 would be 10 seconds rather than 20 seconds. 3GPP TS 38.331 specifies that the filter impulse response is defined by an input rate which equals one intra-frequency Layer 1 measurement period as specified by TS 38.133, assuming non-DRX operation

★ An actual implementation may use a different input rate, but in that case the implementation must also ensure that the impulse response remains unchanged relative to that specified by 3GPP

★ Filtering is applied in the same domain as the measurements, e.g. filtering is applied in dB for RSRQ and SINR measurements, and in dBm for RSRP measurements

★ 3GPP References: TS 38.331, TS 38.133

11.3 EVENT A1

- Event A1 is triggered when the serving cell becomes better than a threshold:

$$Meas_{serv} - Hyst > Threshold$$

- Event A1 is subsequently cancelled if the following condition is satisfied:

$$Meas_{serv} + Hyst < Threshold$$

- Event A1 is typically used to cancel an ongoing mobility procedure. This may be required if a UE moves towards cell edge and triggers a mobility procedure, but then subsequently moves back into good coverage before the mobility procedure has completed
- The hysteresis can be configured with a value between 0 and 15 dB, with 0.5 dB steps (signalled value between 0 and 30)
- When using RSRP, the threshold can be configured with a value between -156 and -31 dBm. The value of the threshold is signalled using the mapping presented in Table 237 (using a signalled value of between 0 and 127)
- When using RSRQ, the threshold can be configured with a value between -43 and 20 dB. The value of the threshold is signalled using the mapping presented in Table 242 (using a signalled value of between 0 and 127)
- When using SINR, the threshold can be configured with a value between -23 and 40 dB. The value of the threshold is signalled using the mapping presented in Table 243 (using a signalled value of between 0 and 127)
- A time-to-trigger can be configured from the set {0, 40, 64, 80, 100, 128, 160, 256, 320, 480, 512, 640, 1024, 1280, 2560, 5120} ms

11.4 EVENT A2

- Event A2 is triggered when the serving cell becomes worse than a threshold:

$$Meas_{serv} + Hyst < Threshold$$

- Event A2 is subsequently cancelled if the following condition is satisfied:

$$Meas_{serv} - Hyst > Threshold$$

- Event A2 is typically used to trigger a mobility procedure when a UE moves towards cell edge. Event A2 does not involve any neighbour cell measurements so it may be used to trigger a blind mobility procedure. Alternatively, it may be used to trigger a set of neighbour cell measurements which can then be used for a measurement based mobility procedure. For example, the Base Station may configure measurement gaps and inter-frequency or inter-system measurements after Event A2 has been triggered. This approach means that the UE only needs to complete the inter-frequency/inter-system measurements when coverage conditions are relatively poor and there is a high probability that a handover will be required
- The hysteresis can be configured with a value between 0 and 15 dB, with 0.5 dB steps (signalled value between 0 and 30)
- When using RSRP, the threshold can be configured with a value between -156 and -31 dBm. The value of the threshold is signalled using the mapping presented in Table 237 (using a signalled value of between 0 and 127)
- When using RSRQ, the threshold can be configured with a value between -43 and 20 dB. The value of the threshold is signalled using the mapping presented in Table 242 (using a signalled value of between 0 and 127)
- When using SINR, the threshold can be configured with a value between -23 and 40 dB. The value of the threshold is signalled using the mapping presented in Table 243 (using a signalled value of between 0 and 127)
- A time-to-trigger can be configured from the set {0, 40, 64, 80, 100, 128, 160, 256, 320, 480, 512, 640, 1024, 1280, 2560, 5120} ms

11.5 EVENT A3

- Event A3 is triggered when a neighbouring cell becomes better than a special cell by an offset (a special cell is the primary serving cell of either the Master Cell Group (MCG) or Secondary Cell Group (SCG)). The offset can be either positive or negative. The event is triggered when the following condition is satisfied:

$$Meas_{neigh} + O_{neigh,freq} + O_{neigh,cell} - Hyst > Meas_{sp} + O_{sp,freq} + O_{sp,cell} + Offset$$

- Event A3 is subsequently cancelled if the following condition is satisfied:

$$Meas_{neigh} + O_{neigh,freq} + O_{neigh,cell} + Hyst < Meas_{sp} + O_{sp,freq} + O_{sp,cell} + Offset$$

- Event A3 is typically used for intra-frequency or inter-frequency handover procedures. A UE may be configured with measurement gaps and an Event A3 for inter-frequency handover after an Event A2 has triggered. Event A3 provides a handover triggering mechanism based upon relative measurement results, e.g. it can be configured to trigger when the RSRP of a neighbouring cell is stronger than the RSRP of a special cell
- Both the neighbour and special cell can have frequency specific and cell specific offsets applied to their measurements. Each of these offsets can be configured with values between -24 and +24 dB
- The additional *Offset* added to the special cell measurement can be configured with a value between -15 and +15 dB, with 0.5 dB steps (signalled value between -30 and 30)
- The hysteresis can be configured with a value between 0 and 15 dB, with 0.5 dB steps (signalled value between 0 and 30)
- A time-to-trigger can be configured from the set {0, 40, 64, 80, 100, 128, 160, 256, 320, 480, 512, 640, 1024, 1280, 2560, 5120} ms

11.6 EVENT A4

- Event A4 is triggered when a neighbouring cell becomes better than a threshold:

$$Meas_{neigh} + O_{neigh,freq} + O_{neigh,cell} - Hyst > Threshold$$

- Event A4 is subsequently cancelled if the following condition is satisfied:

$$Meas_{neigh} + O_{neigh,freq} + O_{neigh,cell} + Hyst < Threshold$$

- Event A4 can be used for mobility procedures which do not have a dependence upon the coverage of the current serving cell. For example, load balancing procedures take the decision to move a UE away from the current serving cell due to load conditions rather than radio conditions. In this case, the UE only needs to verify that the candidate target cell provides adequate coverage
- The neighbour cell can have frequency specific and cell specific offsets applied to its measurements. Both offsets can be configured with values between -24 and +24 dB
- The hysteresis can be configured with a value between 0 and 15 dB, with 0.5 dB steps (signalled value between 0 and 30)
- When using RSRP, the threshold can be configured with a value between -156 and -31 dBm. The value of the threshold is signalled using the mapping presented in Table 237 (using a signalled value of between 0 and 127)
- When using RSRQ, the threshold can be configured with a value between -43 and 20 dB. The value of the threshold is signalled using the mapping presented in Table 242 (using a signalled value of between 0 and 127)
- When using SINR, the threshold can be configured with a value between -23 and 40 dB. The value of the threshold is signalled using the mapping presented in Table 243 (using a signalled value of between 0 and 127)
- A time-to-trigger can be configured from the set {0, 40, 64, 80, 100, 128, 160, 256, 320, 480, 512, 640, 1024, 1280, 2560, 5120} ms

11.7 EVENT A5

★ Event A5 is triggered when a special cell becomes worse than threshold1, while a neighbouring cell becomes better than threshold2. The event is triggered when both of the following conditions are satisfied:

$$Meas_{sp} + Hyst < Threshold1$$

$$Meas_{neigh} + O_{neigh,freq} + O_{neigh,cell} - Hyst > Threshold2$$

★ Event A5 is subsequently cancelled if either of the following conditions are satisfied:

$$Meas_{sp} - Hyst > Threshold1$$

$$Meas_{neigh} + O_{neigh,freq} + O_{neigh,cell} + Hyst < Threshold2$$

★ Event A5 is typically used for intra-frequency or inter-frequency handover procedures. A UE may be configured with measurement gaps and an Event A5 for inter-frequency handover after an Event A2 has triggered. Event A5 provides a handover triggering mechanism based upon absolute measurement results. It can be used to trigger a time critical handover when a current special cell becomes weak and it is necessary to change towards another cell which may not satisfy the criteria for an event A3 handover

★ The neighbour cell can have frequency specific and cell specific offsets applied to its measurements. Both offsets can be configured with a value between -24 and +24 dB

★ The hysteresis can be configured with a value between 0 and 15 dB, with 0.5 dB steps (signalled value between 0 and 30)

★ When using RSRP, the thresholds can be configured with values between -156 and -31 dBm. The value of the threshold is signalled using the mapping presented in Table 237 (using a signalled value of between 0 and 127)

★ When using RSRQ, the thresholds can be configured with values between -43 and 20 dB. The value of the threshold is signalled using the mapping presented in Table 242 (using a signalled value of between 0 and 127)

★ When using SINR, the thresholds can be configured with values between -23 and 40 dB. The value of the threshold is signalled using the mapping presented in Table 243 (using a signalled value of between 0 and 127)

★ A time-to-trigger can be configured from the set {0, 40, 64, 80, 100, 128, 160, 256, 320, 480, 512, 640, 1024, 1280, 2560, 5120} ms

11.8 EVENT A6

★ Event A6 is triggered when a neighbouring cell becomes better than a secondary cell by an offset. The offset can be either positive or negative. This measurement reporting event is applicable to Carrier Aggregation, i.e. connections which have secondary serving cells in addition to a primary serving cell

★ Event A6 is triggered when the following condition is true:

$$Meas_{neigh} + O_{neigh,cell} - Hyst > Meas_{sec} + O_{sec,cell} + Offset$$

★ Event A6 is subsequently cancelled if the following condition is satisfied:

$$Meas_{neigh} + O_{neigh,cell} + Hyst < Meas_{sec} + O_{sec,cell} + Offset$$

★ Event A6 is typically used for secondary cell swap procedures. It may be necessary to swap the secondary cell if the primary and secondary cell carriers use different antenna with different azimuths. This can lead to changes in the best secondary cell as a UE moves within the coverage of the primary serving cell

★ In this case, a frequency specific offset is not included because both the neighbour and secondary serving cell are on the same carrier, i.e. the offset would be the same for both cells and would have no impact

★ Both the neighbour and secondary serving cells can have cell specific offsets applied to their measurements. Each of these offsets can be configured with a value between -24 and +24 dB

★ The additional *Offset* added to the secondary serving cell measurement can be configured with a value between -15 and +15 dB, with 0.5 dB steps (signalled value between -30 and 30)

★ The hysteresis can be configured with a value between 0 and 15 dB, with 0.5 dB steps (signalled value between 0 and 30)

★ A time-to-trigger can be configured from the set {0, 40, 64, 80, 100, 128, 160, 256, 320, 480, 512, 640, 1024, 1280, 2560, 5120} ms

11.9 EVENT B1

★ Event B1 is triggered when a neighbouring inter-system cell becomes better than a threshold:

$$Meas_{neigh} + O_{neigh,freq} + O_{neigh,cell} - Hyst > Threshold$$

★ Event B1 is subsequently cancelled if the following condition is satisfied:

$$Meas_{neigh} + O_{neigh,freq} + O_{neigh,cell} + Hyst < Threshold$$

★ Event B1 can be used for inter-system mobility procedures which do not have a dependence upon the coverage of the current serving cell. For example, load balancing procedures take the decision to move a UE away from NR due to load conditions rather than radio conditions. In this case, the UE only needs to verify that the candidate target cell provides adequate coverage

★ The release 15 version of the 3GPP specifications only supports inter-system mobility towards LTE. This means that the neighbouring cell measurements can be based upon RSRP, RSRQ or SINR

★ The neighbouring LTE cell can have frequency specific and cell specific offsets applied to its measurements. Both offsets can be configured with a value between -24 and +24 dB

★ The hysteresis can be configured with a value between 0 and 15 dB, with 0.5 dB steps (signalled value between 0 and 30)

★ When using LTE RSRP, the threshold can be configured with a value between -140 and -44 dBm. The value of the threshold is signalled using the mapping specified in 3GPP TS 36.133 (using a signalled value of between 0 and 97)

★ When using LTE RSRQ, the threshold can be configured with a value between -19.5 and -3 dB. The value of the threshold is signalled using the mapping specified in 3GPP TS 36.133 (using a signalled value of between 0 and 34)

★ When using LTE SINR, the threshold can be configured with a value between -23 and 40 dB. The value of the threshold is signalled using the mapping specified in 3GPP TS 36.133 (using a signalled value of between 0 and 127)

★ A time-to-trigger can be configured from the set {0, 40, 64, 80, 100, 128, 160, 256, 320, 480, 512, 640, 1024, 1280, 2560, 5120} ms

11.10 EVENT B2

★ Event B2 is triggered when a primary serving cell becomes worse than threshold1, while a neighbouring inter-system cell becomes better than threshold2. The event is triggered when both of the following conditions are satisfied:

$$Meas_{pcell} + Hyst < Threshold1$$

$$Meas_{neigh} + O_{neigh,freq} + O_{neigh,cell} - Hyst > Threshold2$$

★ Event B2 is subsequently cancelled if either of the following conditions are satisfied:

$$Meas_{pcell} - Hyst > Threshold1$$

$$Meas_{neigh} + O_{neigh,freq} + O_{neigh,cell} + Hyst < Threshold2$$

★ Event B2 can be used to trigger inter-system mobility procedures when the primary serving cell becomes weak. Inter-system neighbour cell measurements are used to ensure that the target cell provides adequate coverage

★ The release 15 version of the 3GPP specifications only supports inter-system mobility towards LTE. This means that the neighbouring cell measurements can be based upon RSRP, RSRQ or SINR

★ The neighbour cell can have frequency specific and cell specific offsets applied to its measurements. Both offsets can be configured with a value between -24 and +24 dB

★ The hysteresis can be configured with a value between 0 and 15 dB, with 0.5 dB steps (signalled value between 0 and 30)

★ When using NR RSRP, threshold1 can be configured with a value between -156 and -31 dBm. When using LTE RSRP, threshold2 can be configured with a value between -140 and -44 dBm

★ When using NR RSRQ, threshold1 can be configured with a value between -43 and 20 dB. When using LTE RSRQ, threshold2 can be configured with a value between -19.5 and -3 dB

★ When using NR SINR, threshold1 can be configured with a value between -23 and 40 dB. When using LTE SINR, threshold2 can be configured with a value between -23 and 40 dB

★ A time-to-trigger can be configured from the set {0, 40, 64, 80, 100, 128, 160, 256, 320, 480, 512, 640, 1024, 1280, 2560, 5120} ms

12 IDLE MODE PROCEDURES

12.1 PLMN SELECTION

★ The UE is responsible for selecting a Public Land Mobile Network (PLMN) for subsequent cell selection. A PLMN is identified by its PLMN identity broadcast within System Information Block 1 (SIB1). A single cell can belong to multiple PLMN so SIB1 may broadcast a list of PLMN identities

★ The UE Non-Access Stratum (NAS) layer can request the UE Access Stratum (AS) layer to report available PLMN:

- o the UE scans all RF channels within its supported frequency bands
- o the UE searches for the strongest cell on each carrier and reads the system information to identity the PLMN
- o PLMN are reported to the NAS as high quality if their RSRP ≥ -110 dBm. In this case, the measured RSRP value is not reported to the NAS layer so high quality PLMN are not differentiated by their signal strengths
- o PLMN which do not satisfy the high quality criteria are reported to the NAS together with their RSRP measurement
- o UE can optimise the PLMN search procedure using stored information, e.g. carrier frequencies and cell parameters
- o the NAS layer can stop the search at any time, e.g. after finding the home PLMN

★ The NAS layer is responsible for selecting a PLMN from the list of reported PLMN. The NAS layer uses information from the USIM to help with PLMN selection:

- o International Mobile Subscriber Identity (IMSI): defines the Home PLMN (HPLMN)
- o HPLMN Selector with Access Technology: defines the priority of each technology associated with the HPLMN
- o User Controlled PLMN Selector with Access Technology: allows the end-user to prioritise the PLMN and technology
- o Operator Controlled PLMN Selector with Access Technology: allows the operator to prioritise the PLMN and access technology
- o Forbidden PLMNs: defines PLMN which the UE does not automatically attempt to access. PLMN are added to the list of Forbidden PLNM when the network rejects a Registration Request using a cause value 'PLMN not allowed' or 'Serving network not authorized'
- o Equivalent HPLMN (EHPLMN): defines a set of PLMN which are treated as equivalent to the PLMN with which the UE is registering. This list can be updated or deleted by the network during the registration procedure

★ The PLMN can be selected either automatically or manually

★ In the case of automatic selection, the UE selects the PLMN and access technology using the following order of priority:

i) HPLMN (if EHPLMN list is not available) or the highest priority EHPLMN (if EHPLMN list is available)
ii) PLMN and access technology combinations defined within the User Controlled PLMN Selector
iii) PLMN and access technology combinations defined within the Operator Controlled PLMN Selector
iv) other PLMN reported as high quality PLMN, selected in random order
v) other PLMN selected in order of decreasing signal quality

★ The UE searches all supported access technologies before selecting a PLMN when using steps iv) and v)

★ In the case of manual selection, the UE presents the end-user with the available PLMN, listing them in the following order:

i) HPLMN or Equivalent HPLMN (EHPLMN)
ii) PLMN and access technology combinations defined within the User Controlled PLMN Selector
iii) PLMN and access technology combinations defined within the Operator Controlled PLMN Selector
iv) other PLMN reported as high quality PLMN, selected in random order
v) other PLMN selected in order of decreasing signal quality

The end-user is then able to select which PLMN the UE should attempt to access

★ 3GPP references: TS 38.304, TS 23.122, TS 24.501, TS 31.102

12.2 CELL SELECTION

★ Cell selection is used to identify a cell for the UE to camp on. It is applicable after a UE is switched-on, after a UE leaves RRC Connected mode and after a UE returns to an area of coverage

★ Initial cell selection does not rely upon any stored information. The UE scans all RF channels within its supported frequency bands. Scanning is based upon the synchronisation raster described in section 2.5.2. This raster is relatively coarse to reduce the number of candidate carrier frequencies and thus reduce the delay generated by band scanning. The UE searches for one or more SS/PBCH Blocks at each candidate carrier frequency (each candidate carrier frequency has a Global Synchronisation Channel Number (GSCN)). After finding one or more SS/PBCH Blocks at a specific GSCN, the UE identifies the strongest cell and proceeds to decode the System Information. It is possible that the UE discovers a set of SS/PBCH Blocks which do not have any associated System Information. In that case, the PBCH can provide information which directs the UE towards another set of SS/PBCH Blocks. This information is extracted from the subcarrier offset (k_{SSB}) described in section 6.1

★ A UE is permitted to use stored information to support the cell selection procedure. This can include carrier frequencies which the UE has previously camped on. It can also include cell parameters from previously received measurement control information or previously detected cells. In the case of cell selection after leaving RRC Connected mode, the Base Station can use the *RRCRelease* message to direct the UE towards a specific carrier. A UE uses the initial cell selection procedure if cell selection based upon stored information is unsuccessful

★ A UE attempts to camp on a 'suitable' cell during the cell selection procedure. If the UE fails to camp on a 'suitable' cell then the UE will attempt to camp on an 'acceptable' cell. When camped on a 'suitable' cell, the UE can register with the network and access its normal set of services. When camped on an 'acceptable' cell, the UE is restricted to limited services, i.e. emergency calls and reception of Public Warning System (PWS) notifications

★ A 'suitable' cell is defined as a cell which:

- o is not barred
- o belongs to the PLMN selected by the NAS layer, the registered PLMN or an Equivalent PLMN
- o belongs to at least one Tracking Area which is not forbidden
- o satisfies the cell selection criteria

★ The Master Information Block (MIB) uses the *cellBarred* flag to indicate whether or not the cell is barred. If the cell is barred then the UE is not permitted to camp on that cell and the UE has to wait 300 seconds before re-checking the MIB to determine whether or not the cell remains barred. If a cell is barred, the *intraFreqReselection* flag within the MIB indicates whether or not the UE is permitted to camp on another cell belonging to the same carrier frequency

★ SIB1 is known as the 'Remaining Minimum System Information' (RMSI). It provides a list of PLMN Identities and specifies a Tracking Area Code for each PLMN. It also provides the set of parameters which define the cell selection criteria

★ 3GPP TS 38.304 specifies the cell selection criteria ('S' criteria) as:

$$Srxlev > 0 \qquad \text{AND} \qquad Squal > 0$$

$$where, \quad Srxlev = Qrxlevmeas - (Qrxlevmin + Qrxlevminoffset) - Pcompensation - Qoffset_{temp}$$

$$Squal = Qqualmeas - (Qqualmin + Qqualminoffset) - Qoffset_{temp}$$

★ *Qrxlevmeas* is the SS-RSRP measured by the UE. In the case of cell selection, 3GPP does not specify the rules for deriving a cell level measurement from a set of beam level measurements. Instead, this derivation is left to the UE implementation. Figure 334 illustrates some example solutions for deriving the cell level measurement from a set of beam level measurements. The first example assumes that the cell level measurement is based upon only the strongest beam. In this case, cell selection is effectively completed using beam level measurements rather than cell level measurements. The second example assumes that the cell level measurement is derived from the 'x' strongest beams, whereas the third example assumes that the cell level measurement is derived from all beams which exceed a specific threshold

★ *Qrxlevmin* defines the minimum RSRP threshold for the cell. It is broadcast by SIB1 and can be configured with a value between -140 and -44 dBm, using a step size of 2 dBm. Its value defines the Idle Mode coverage area of the cell. A high value will restrict the coverage area, whereas a low value may lead to failed connection setup attempts at cell edge. An initial value can be based upon the maximum allowed path loss calculated from a set of uplink and downlink link budgets. Subsequent field trials can be used for optimisation

★ *Qrxlevminoffset* is included within the 'S' criteria when a UE is completing a periodic search for a higher priority PLMN while camped on a visited PLMN. The value of *Qrxlevminoffset* is always positive so the cell selection criteria becomes more stringent. The objective of using this offset is to help reduce the potential for ping-pong

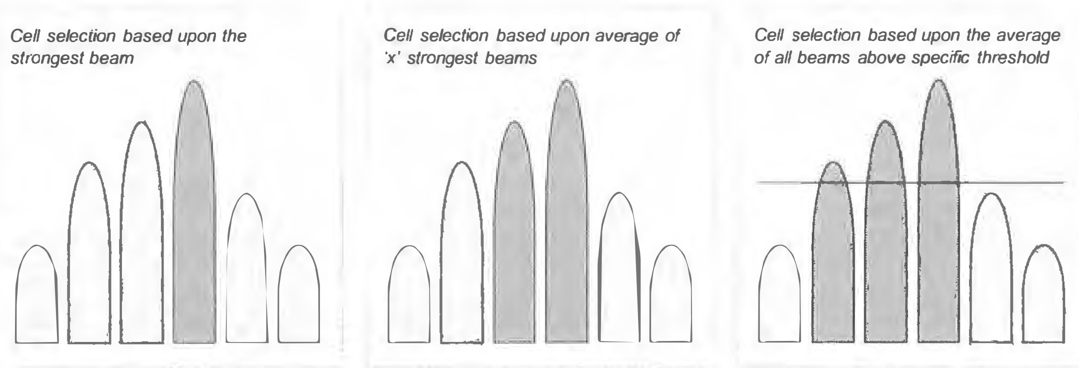


Figure 334 – Examples of deriving a cell level measurement from a set of beam level measurements

★ *Pcompensation* is used to adjust the value of *Qrxlevmin* according to the UE transmit power capability. In a simple deployment scenario, *Pcompensation* = MAX(P_{EMAX1} – $P_{POWERCLASS}$, 0), where P_{EMAX1} is the maximum allowed uplink transmit power within the cell (broadcast within SIB1), and $P_{POWERCLASS}$ is the maximum transmit power capability of the UE. It is assumed that the value of *Qrxlevmin* has been configured based upon a UE transmit power equal to P_{EMAX1}. UE which have a transmit power capability less than P_{EMAX1} may not be able to establish a connection at cell edge. In that case, *Pcompensation* is used to make the 'S' criteria more stringent to avoid those UE camping on the cell at locations where they cannot establish a connection

★ In a more complex deployment scenario, SIB1 can broadcast multiple maximum UE transmit powers. The primary maximum UE transmit power is 'P_{EMAX1}' which is used for the simple deployment scenario and is included within the *frequencyInfoUL* section of SIB1. Additional maximum UE transmit powers can be broadcast within an instance of *nr-NS-PmaxList*. Each additional maximum UE transmit power is linked to an additional spectrum emissions requirement, i.e. the UE is permitted to use another maximum transmit power if it is able to achieve the specified spectrum emissions requirement. The UE selects the first pair of values within the list which are supported and sets 'P_{EMAX2}' equal to the corresponding additional maximum UE transmit power. The UE then calculates *Pcompensation* = MAX(P_{EMAX1} – $P_{POWERCLASS}$, 0) – MIN(P_{EMAX2}, $P_{POWERCLASS}$) + MIN(P_{EMAX1}, $P_{POWERCLASS}$). This more complex deployment scenario can lead to a negative value for *Pcompensation* which increases the cell range. For example, if $P_{POWERCLASS}$ = 23 dBm, while P_{EMAX1} = 15 dBm and P_{EMAX2} = 18 dBm, then *Pcompensation* = MAX(15 – 23, 0) – MIN(18, 23) + MIN(15, 23) = 0 – 18 + 15 = -3 dB, i.e. the 'S' criteria is relaxed by 3 dB and the UE is permitted to camp on the cell outside the normal *Qrxlevmin*

★ $Qoffset_{temp}$ is defined by the value of *connEstFailOffset* within the *connEstFailureControl* section of SIB1. This temporary offset is applied if the UE experiences repetitive connection setup failures caused by T300 expiring, i.e. the UE does not receive an *RRCSetup* nor *RRCReject* message after sending an *RRCSetupRequest*. The temporary offset is applied for a period of time '*T*' if T300 expires for '*N*' consecutive connection setup attempts, where '*T*' = *connEstFailOffsetValidity* and '*N*' = *connEstFailCount*. The temporary offset makes the 'S' criteria more stringent so the UE is more likely to start searching for another cell

★ *Qqualmeas* is the SS-RSRQ measured by the UE. Similar to *Qrxlevmeas*, the UE is responsible for deriving a cell level measurement from the set of beam level measurements (assuming the UE detects multiple beams)

★ *Qqualmin* defines the minimum RSRQ threshold for the cell. It can be configured with a value between -43 and -12 dB, using a step size of 1 dB. A high value will restrict the coverage area, whereas a low value may lead to failed connection setup attempts. *Qqualmin* is optional within SIB1 so it is not mandatory to use an RSRQ threshold during cell selection. The UE assumes a value of negative infinity for *Qqualmin* if it is excluded from SIB1, i.e. ensuring that the UE always passes the *Squal* part of the 'S' criteria.

★ *Qqualminoffset* is included within the 'S' criteria when a UE is completing a periodic search for a higher priority PLMN while camped on a visited PLMN. The value of *Qqualminoffset* is always positive so the cell selection criteria becomes more stringent. The objective of using this offset is to help reduce the potential for ping-pong

★ 3GPP reference: TS 38.304, TS 38.331

12.3 CELL RESELECTION

★ Cell reselection is the mobility solution for UE in the RRC Idle and RRC Inactive states

★ In the case of RRC Idle, a UE can complete cell reselections without informing the network, as long as the UE remains within a registered Tracking Area. The UE is responsible for acquiring SIB1 after each cell reselection to determine whether or not the UE remains located within a registered Tracking Area. The UE completes a NAS: Registration procedure with the AMF after moving into an unregistered Tracking Area

★ In the case of RRC Inactive, a UE can complete cell reselections without informing the network, as long as the UE remains within the allocated RAN Notification Area (RNA). A Base Station allocates a RAN Notification Area when moving a UE from RRC Connected to RRC Inactive (using the *RRCRelease* message). The UE is responsible for acquiring SIB1 after each cell reselection to determine whether or not the UE remains located within the allocated RAN Notification Area. The UE completes an RRC: Resume procedure with cause value '*rna-Update*' after moving outside the allocated RAN Notification Area

12.3.1 ABSOLUTE PRIORITIES

★ Absolute Priorities influence the network layer selected by a UE during cell reselection, i.e. Absolute Priorities are used to differentiate network layers, rather than cells belonging to the same layer

★ In general, Absolute Priorities can be allocated to network layers belonging to GSM, UMTS, CDMA2000, LTE and NR. For example, the LTE system can broadcast priorities for these network layers within SIB6 (UMTS), SIB7 (GSM), SIB8 (CDMA2000), SIB3/SIB5 (LTE) and SIB24 (NR)

★ The release 15 version of NR is restricted to supporting intra-frequency and inter-frequency cell reselection within the NR network, and inter-system cell reselection towards LTE.

★ Absolute Priorities are broadcast within the following NR system information:

- o SIB2 - absolute priority for the current NR carrier
- o SIB4 - absolute priorities for inter-frequency NR carriers
- o SIB5 - absolute priorities for inter-system LTE carriers

★ Absolute Priorities can also be signalled directly to individual UE within an *RRCRelease* message, i.e. when UE are moving to RRC Idle or RRC Inactive. These priorities do not need to be consistent with those broadcast within the SIB. For example, the SIB may prioritise an NR carrier while the *RRCRelease* message may prioritise an LTE carrier. The priorities within the *RRCRelease* message can be used for load balancing purposes. For example, 'x' percent of UE can be allocated a first set of priorities which move those UE to carrier 1, while 'y' percent of UE can be allocated a second set of priorities which move those UE to carrier 2

★ Timer T320 is provided in combination with the Absolute Priorities within an *RRCRelease* message. T320 can be configured with values ranging from 5 minutes to 3 hours. A UE discards the priorities provided by the *RRCRelease* message when T320 expires. These priorities are also discarded when the UE enters RRC Connected mode. In this case, the UE relies upon receiving another set of priorities within the next *RRCRelease* message, or reverting to using the priorities within the System Information

★ The value and current state of T320 is carried across technologies so T320 will continue running if a UE completes a cell reselection from NR to LTE. Similarly, if the UE receives a set of Absolute Priorities and a value for T320 within an *RRCConnectionRelease* message on LTE, then the value of T320 and the set of priorities can be carried across to NR. In the case of UMTS, the equivalent timer is known as T322

★ NR allows Absolute Priorities to be configured using the pair of information elements presented in Table 248. These information elements allow up to 40 priority levels to be configured, ranging from 0 to 7.8. Integer values are configured by excluding the second information element. Earlier versions of legacy technologies were limited to using the set of 8 integer priorities. The concept of sub-priority was introduced within the release 13 version of the 3GPP specifications to cater for the increasing number of layers within live network deployments

CellReselectionPriority	0 to 7
CellReselectionSubPriority	0.2, 0.4, 0.6, 0.8

Table 248 – Configuration of Absolute Priority

★ Inter-frequency layers belonging to NR can be configured with equal priorities but inter-system layers belonging to different technologies are not permitted to use the same priority

★ 3GPP references: TS 38.304, TS 38.331

12.3.2 TRIGGERING MEASUREMENTS

- Measurement rules are intended to reduce the quantity of neighbour cell measurements completed by a UE. This is done by triggering measurements only when necessary. Reducing the quantity of measurements helps to increase the UE battery life
- A UE does not have to complete intra-frequency neighbouring cell measurements if both of the following conditions are satisfied:

$$Srxlev > S_{IntraSearchP} \quad \text{AND} \quad Squal > S_{IntraSearchQ}$$

- A UE has to complete intra-frequency neighbouring cell measurements if either condition is not satisfied.
- These conditions mean that the UE does not have to complete intra-frequency measurements when the coverage conditions are relatively good. *SintrasearchP* and *SintrasearchQ* are both broadcast by SIB2. It is not mandatory to broadcast a value for *SintrasearchQ*. A default value of 0 dB is assumed if *SintrasearchQ* is excluded from SIB2. The default value means that *Squal* is always greater than *SintrasearchQ*
- *SintrasearchP* can be configured with a value between 0 and 62 dB, using a step size of 2 dB. In contrast, *SintrasearchQ* can be configured with a value between 0 and 31 dB, using a step size of 1 dB
- A UE always completes measurements for cell reselection towards a higher priority inter-frequency or inter-system layer
- A UE does not have to complete measurements for cell reselection towards an equal or lower priority inter-frequency layer if both of the following conditions are satisfied. Similarly, A UE does not have to complete measurements for cell reselection towards a lower priority inter-system layer if both of the following conditions are satisfied:

$$Srxlev > S_{nonIntraSearchP} \quad \text{AND} \quad Squal > S_{nonIntraSearchQ}$$

- A UE has to complete inter-frequency/inter-system measurements if either condition is not satisfied
- *SnonintrasearchP* and *SnonintrasearchQ* are both broadcast by SIB2. Both information elements are optional. A default value of infinity is assumed for *SnonintrasearchP* if it is excluded, whereas a default value of 0 dB is assumed for *SnonintrasearchQ* if it is excluded. This means that measurements are always required if *SnonintrasearchP* is excluded from SIB2 (assuming equal or lower priority inter-frequency layers or lower priority inter-system layers exist)
- *SnonintrasearchP* can be configured with a value between 0 and 62 dB, using a step size of 2 dB. In contrast, *SnonintrasearchQ* can be configured with a value between 0 and 31 dB, using a step size of 1 dB
- Figure 335 illustrates the general concept of triggering neighbour cell measurements based upon *Srxlev*. Ignoring the impact of offsets and *Pcompensaton*, *Srxlev* is 0 dB when the measured RSRP is equal to *Qrxlevmin* (the equation for *Srxlev* is presented in section 12.2). The value of *Srxlev* increases as the measured RSRP increases relative to *Qrxlevmin*

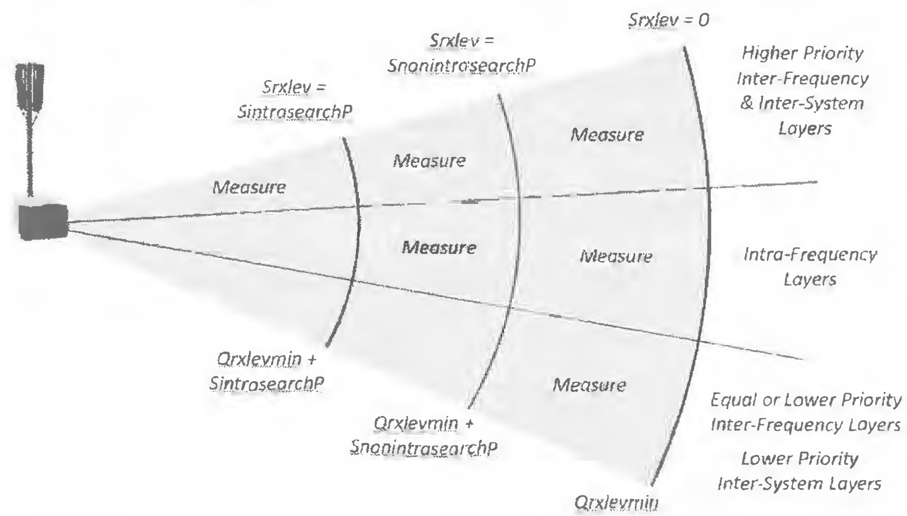


Figure 335 – Triggering of measurements based upon Srxlev

- The equivalent figure for *Squal* is the same but *Qrxlevmin* is replaced by *Qqualmin* and *SintrasearchP/SnonintrasearchP* are replaced by *SintrasearchQ/SnonintrasearchQ*
- 3GPP references: TS 38.304, TS 38.331

12.3.3 MOBILITY STATES

- Mobility states are used to scale the time-to-trigger used for cell reselection (*Treselection*). The scaling factor reduces the time-to-trigger for high mobility states to allow cell reselection to complete more rapidly
- In addition, mobility states are used to scale the hysteresis applied to serving cell measurements when ranking intra-frequency and equal priority inter-frequency neighbours. The scaling factor reduces the hysteresis for high mobility states to allow cell reselection to complete more rapidly
- 3GPP TS 38.304 specifies normal, medium and high mobility states. The high and medium mobility states are applicable if the optional *speedStateReselectionPars* parameter set is broadcast by SIB2. This parameter set is presented in Table 249

speedStateReselectionPars		
mobilityStateParameters	t-Evaluation	30, 60, 120, 180, 240 s
	t-HystNormal	30, 60, 120, 180, 240 s
	n-CellChangeMedium	1 to 16
	n-CellChangeHigh	1 to 16
q-HystSF	sf-Medium	-6, -4, -2, 0 dB
	sf-High	-6, -4, -2, 0 dB

Table 249 – Speed state reselection parameters within SIB2

- A UE has normal mobility by default.
- A UE detects high mobility if the number of cell reselections during a time window '*t-Evaluation*' is greater than '*n-CellChangeHigh*'
- A UE detects medium mobility if the number of cell reselections during a time window '*t-Evaluation*' is greater than or equal to '*n-CellChangeMedium*' but less than or equal to '*n-CellChangeHigh*'
- A UE returns from the high or medium mobility states to the normal mobility state if the criteria for neither medium nor high mobility are detected during a time period '*t-HystNormal*'
- A UE excludes ping-pongs between two cells when counting the number of cell reselections
- If a UE is in the high or medium mobility state then speed dependent scaling rules are applied
- If high mobility is detected
  - '*sf-High*' from '*q-HystSF*' in SIB2 is added to the serving cell value for *Qhyst* (applicable to intra-frequency and equal priority inter-frequency cell reselection)
  - '*t-ReselectionNR*' (SIB2) is multiplied by '*sf-High*' from '*t-ReselectionNR-SF*' (SIB2) for intra-frequency cell reselection
  - '*t-ReselectionNR*' (SIB4) is multiplied by '*sf-High*' from '*t-ReselectionNR-SF*' (SIB4) for inter-frequency cell reselection
  - '*t-ReselectionEUTRA*' (SIB4) is multiplied by '*sf-High*' from '*t-ReselectionEUTRA-SF*' (SIB5) for inter-system cell reselection
- The same rules are applied for medium mobility but '*sf-High*' is replaced by '*sf-Medium*'
- '*sf-high*' and '*sf-medium*' for '*Qhyst*' can be configured with values of -6, -4, -2 and 0 dB, i.e. they tend to decrease the value of *Qhyst* to make cell reselection faster for UE with increased mobility
- '*sf-high*' and '*sf-medium*' for '*Treselection*' can be configured with values of 0.25, 0.5, 0.75 and 1.0, i.e. they tend to decrease *Treselection* to make cell reselection faster for UE with increased mobility
- When *Treselection* is scaled, the result is rounded up to the nearest second
- 3GPP references: TS 38.304, TS 38.331

12.3.4 RESELECTION

INTRA-FREQUENCY AND EQUAL PRIORITY INTER-FREQUENCY

★ Ranking is applicable to intra-frequency cell reselection and equal priority inter-frequency cell reselection. It is not applicable to inter-system cell reselection because inter-system layers cannot be allocated an equal priority

★ The UE ranks all cells which satisfy the cell selection 'S' criteria presented in section 12.2. Ranking is completed using the 'R' criteria:

$$Rs = Qmeas,s + Qhyst - Qoffset_{temp,s}$$ (calculated for the serving cell)

$$Rn = Qmeas,n - Qoffset - Qoffset_{temp,n}$$ (calculated for the neighbouring cell)

★ Ranking is always completed using RSRP measurements. *Rs* and *Rn* are calculated using 'cell level' measurements rather than 'beam level' measurements. The derivation of 'cell level' measurements from 'beam level' measurements is described in section 11.1

★ *Qhyst* is broadcast within SIB2. In the case of intra-frequency neighbouring cells, *Qoffset* is defined by *q-OffsetCell* broadcast within SIB3. In the case of inter-frequency neighbouring cells, *Qoffset* is defined as the sum of *q-OffsetCell* and *q-OffsetFreq* broadcast within SIB4. Offsets which are excluded from the SIB are assumed to have a value of 0 dB

★ Cell specific offsets for intra-frequency cell reselection should be applied with care because they can lead to a UE camping on a cell which is not the 'normal' best server. In this case, the UE is likely to generate increased levels up uplink interference towards the 'normal' best server and may experience increased levels of downlink interference from the 'normal' best server

★ $Qoffset_{temp}$ is defined by the value of *connEstFailOffset* within the *connEstFailureControl* section of SIB1. This temporary offset is applied if the UE experiences repetitive connection setup failures caused by T300 expiring, i.e. the UE does not receive an *RRCSetup* nor *RRCReject* message after sending an *RRCSetupRequest*. The temporary offset is applied for a period of time '*T*' if T300 expires for '*N*' consecutive connection setup attempts, where '*T*' = *connEstFailOffsetValidity* and '*N*' = *connEstFailCount*. The temporary offset reduces the cell ranking so makes the cell less attractive

★ $Qoffset_{temp,s}$ is applied if the UE has had connection setup attempt failures on the serving cell, whereas $Qoffset_{temp,n}$ is applied if the UE has previously had setup attempt failures on the neighbouring cell and the *connEstFailOffsetValidity* timer is still running

★ If *rangeToBestCell* is not broadcast by SIB2 then cell reselection is completed if a neighbouring cell is ranked higher than the current serving cell during a time period defined by *Treselection*, and if more than 1 second has passed since the UE camped on the current serving cell. *Treselection* for intra-frequency cells is broadcast in SIB2, whereas *Treselection* for inter-frequency cells is broadcast in SIB4

★ If *rangeToBestCell* is broadcast by SIB2 then the cell reselection procedure accounts for both the ranking and the 'beam level' measurements. This principle is illustrated in Figure 336. The UE identifies the highest ranked cell and then defines a threshold which is *rangeToBestCell* below the ranking of that highest ranked cell. Any cells which have a ranking below that threshold are then excluded. For the remaining cells, the UE counts the number of beams which exceed *absThreshSS-BlocksConsolidation*. The cell with the highest count is then categorised as the best cell. Cell reselection is completed if a neighbouring cell has been categorised as the best cell during a time period defined by *Treselection*, and if more than 1 second has passed since the UE camped on the current serving cell. For the example illustrated in Figure 336, cell 2 is categorised as the best cell because its ranking is greater than the *rangeToBestCell* threshold and it has 2 beams which exceed *absThreshSS-BlocksConsolidation*

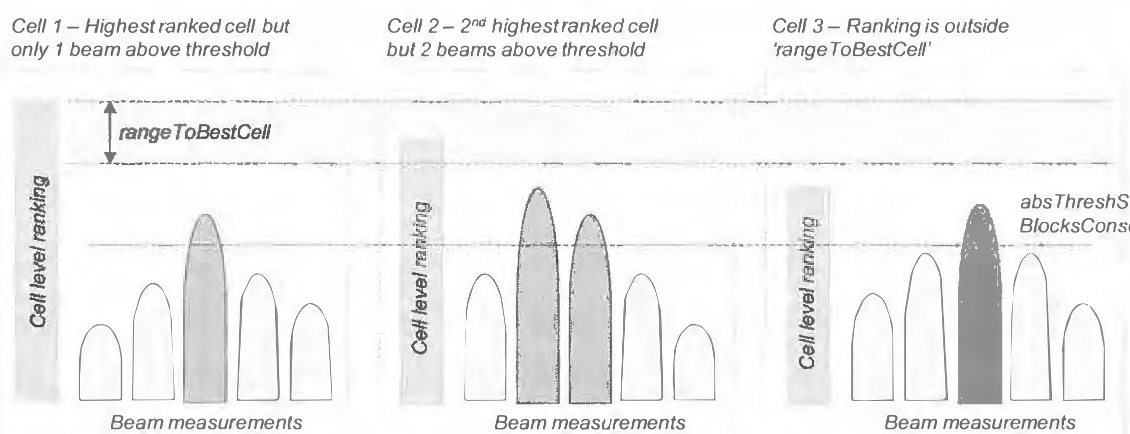


Figure 336 – Ranking of cells when *rangeToBestCell* is broadcast by SIB2

HIGHER PRIORITY INTER-FREQUENCY & INTER-SYSTEM

★ Cell reselection towards a higher priority layer can be based upon either RSRP measurements or RSRQ measurements. If *threshServingLowQ* is broadcast by SIB2 then the procedure is based upon RSRQ measurements. In that case, the UE moves to the higher priority layer if the following condition is satisfied for the target cell:

$$Squal_{target} > Thresh_{X,HighQ}$$

★ $Squal_{target}$ is calculated according to the cell selection 'S' criteria presented in section 12.2

★ SIB4 broadcasts $Thresh_{X,HighQ}$ for inter-frequency neighbours, whereas SIB5 broadcasts $Thresh_{X,HighQ}$ for LTE inter-system neighbours. The value of $Thresh_{X,HighQ}$ can range from 0 to 31 dB, with a step size of 1 dB. Ignoring the impact of any offsets, $Thresh_{X,HighQ}$ defines a margin relative to *Qqualmin*, as shown in Figure 337

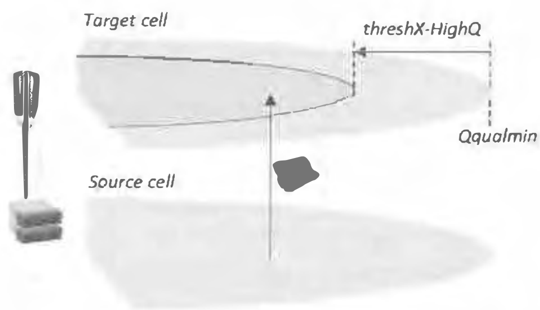


Figure 337 – *threshX-HighQ* criteria for cell reselection towards a higher priority layer

★ If *threshServingLowQ* is not broadcast by SIB2 then the cell reselection procedure is based upon RSRP measurements. In that case, the UE moves to the higher priority layer if the following condition is satisfied for the target cell:

$$Srxlev_{target} > Thresh_{X,HighP}$$

★ $Srxlev_{target}$ is calculated according to the cell selection 'S' criteria presented in section 12.2

★ SIB4 broadcasts $Thresh_{X,HighP}$ for inter-frequency neighbours, whereas SIB5 broadcasts $Thresh_{X,HighP}$ for LTE inter-system neighbours. The value of $Thresh_{X,HighP}$ can range from 0 to 62 dB, with a step size of 2 dB. Ignoring the impact of any offsets and *Pcompensation*, $Thresh_{X,HighP}$ defines a margin relative to *Qrxlevmin*. Figure 337 is applicable if *Qqualmin* is swapped with *Qrxlevmin* and $Thresh_{X,HighQ}$ is swapped with $Thresh_{X,HighP}$

★ Cell reselection is completed if a target neighbouring cell satisfies the criteria during a time period defined by *Treselection*, and if more than 1 second has passed since the UE camped on the current serving cell. The value of *Treselection* is obtained from SIB4 when completing inter-frequency cell reselection, and from SIB5 when completing inter-system cell reselection

LOWER PRIORITY INTER-FREQUENCY & INTER-SYSTEM

★ Cell reselection towards a lower priority layer can be based upon either RSRP measurements or RSRQ measurements. If *threshServingLowQ* is broadcast by SIB2 then the procedure is based upon RSRQ measurements. In that case, the UE moves to the lower priority layer if both of the following conditions are satisfied:

$Squal_{source} < Thresh_{Serving,LowQ}$ (checked for the serving cell)

$Squal_{target} > Thresh_{X,LowQ}$ (checked for the neighbouring cell)

★ $Squal_{source}$ and $Squal_{target}$ are calculated according to the cell selection 'S' criteria presented in section 12.2

★ SIB4 broadcasts $Thresh_{X,LowQ}$ for inter-frequency neighbours, whereas SIB5 broadcasts $Thresh_{X,LowQ}$ for LTE inter-system neighbours. The values of both $Thresh_{Serving,LowQ}$ and $Thresh_{X,LowQ}$ can range from 0 to 31 dB, with a step size of 1 dB. Ignoring the impact of any offsets, these thresholds define margins relative to *Qqualmin*, as shown in Figure 338

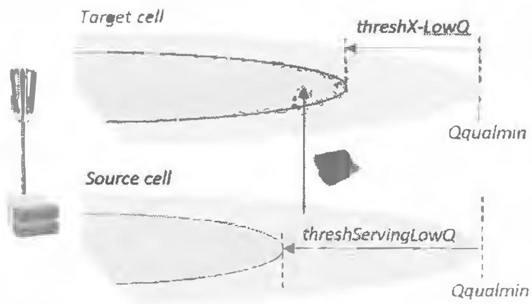


Figure 338 – *threshX-LowQ* and *threshServingLowQ* criteria for cell reselection towards a lower priority layer

★ If *threshServingLowQ* is not broadcast by SIB2 then the cell reselection procedure is based upon RSRP measurements. In that case, the UE moves to the lower priority layer if both of the following conditions are satisfied:

$Srxlev_{source} < Thresh_{Serving,LowP}$	(checked for the serving cell)
$Srxlev_{target} > Thresh_{X,LowP}$	(checked for the neighbouring cell)

★ $Srxlev_{source}$ and $Srxlev_{target}$ are calculated according to the cell selection 'S' criteria presented in section 12.2

★ SIB2 broadcasts $Thresh_{Serving,LowP}$, whereas SIB4 broadcasts $Thresh_{X,LowP}$ for inter-frequency neighbours and SIB5 broadcasts $Thresh_{X,LowP}$ for LTE inter-system neighbours. The value of both $Thresh_{Serving,LowP}$ and $Thresh_{X,LowP}$ can range from 0 to 62 dB, with a step size of 2 dB

★ Cell reselection is completed if the source and target neighbouring cell satisfy the criteria during a time period defined by *Treselection*, and if more than 1 second has passed since the UE camped on the current serving cell. The value of *Treselection* is obtained from SIB4 when completing inter-frequency cell reselection, and from SIB5 when completing inter-system cell reselection

★ 3GPP references: TS 38.304, TS 38.331

12.4 PAGING

12.4.1 PROCEDURE

★ This section describes the 5G paging procedure which is applicable to Base Station architectures which allow the UE to camp on the 5G system in RRC Idle. For example, this section is applicable to the Standalone Base Station architecture 'option 2' which is based upon a 5G Base Station connected to the 5G Core Network. The 5G paging procedure is not applicable to Non-Standalone Base Station architecture 'option 3' which is based upon a 4G anchor Base Station providing control plane connectivity to the 4G Core Network. In that case, the UE camps on the 4G system in RRC Idle mode and the 4G paging procedure is applicable. The 4G and 5G paging procedures are very similar but there are some important differences, e.g. the 5G paging procedure does not allow a UE to be addressed using its IMSI

★ UE listen for paging messages while in RRC Idle and RRC Inactive. Paging messages allow the network to initiate mobile terminated connections. The Core Network is responsible for RRC Idle paging procedures, whereas the serving Base Station is responsible for RRC Inactive paging procedures. An additional category of paging is applicable to UE in RRC Connected, RRC Idle and RRC Inactive. This additional category is applicable when there is a requirement to notify UE of a change to the System Information or an incoming ETWS/CMAS message. In these cases, the paging procedure does not use NGAP nor RRC Paging messages. Instead, the paging procedure uses only the payload of the PDCCH. Downlink Control Information (DCI) Format 1_0 can include a 'Short Message' when the CRC bits are scrambled using the P-RNTI. This 'Short Message' can be used to indicate that System Information has been updated and needs to be re-acquired or there is an incoming ETWS/CMAS message

★ For a UE in RRC Idle, the AMF maintains a record of the UE location in terms of its registered Tracking Area(s). The UE triggers a NAS Registration procedure with cause value 'mobility registration updating' if it moves outside the registered Tracking Area(s). The UE does not update the network while moving within the registered Tracking Area(s). In general, this means that paging messages must be broadcast by all Base Stations belonging to the registered Tracking Area(s). This tends to generate a relatively high paging load, especially for large Tracking Areas which capture a large number of UE

★ Specific Core Network implementations may make certain assumptions regarding the UE location. For example, if a UE releases its connection from a specific Base Station and then a paging procedure is triggered 30 seconds later, there is a high probability that the UE has remained within the coverage of the same Base Station. In this case, the AMF may send the paging message to only that single Base Station rather than all Base Stations within the registered Tracking Area(s). If the paging attempt is unsuccessful then the AMF can re-send the paging message using the full set of Base Stations. This type of solution reduces paging load at the cost of increased delay for UE which have moved to a different Base Station

★ Figure 339 illustrates an AMF completing the paging procedure for a UE in RRC Idle. The UE uses Discontinuous Reception (DRX) to help conserve UE battery life while in RRC Idle, i.e. the UE receiver enters a sleep mode between periodic Paging Occasions. At each Paging Occasion, the UE scans for a PDCCH transmission which has its CRC scrambled by the P-RNTI. All UE share a common P-RNTI value of 'FFFE'. Downlink Control Information (DCI) Format 1_0 is always used when allocating PDSCH resources for a Paging message. The UE determines its Paging Occasions using a combination of information broadcast in SIB1 and its allocated 5G-S-TMSI. Paging Occasions are described in the next section

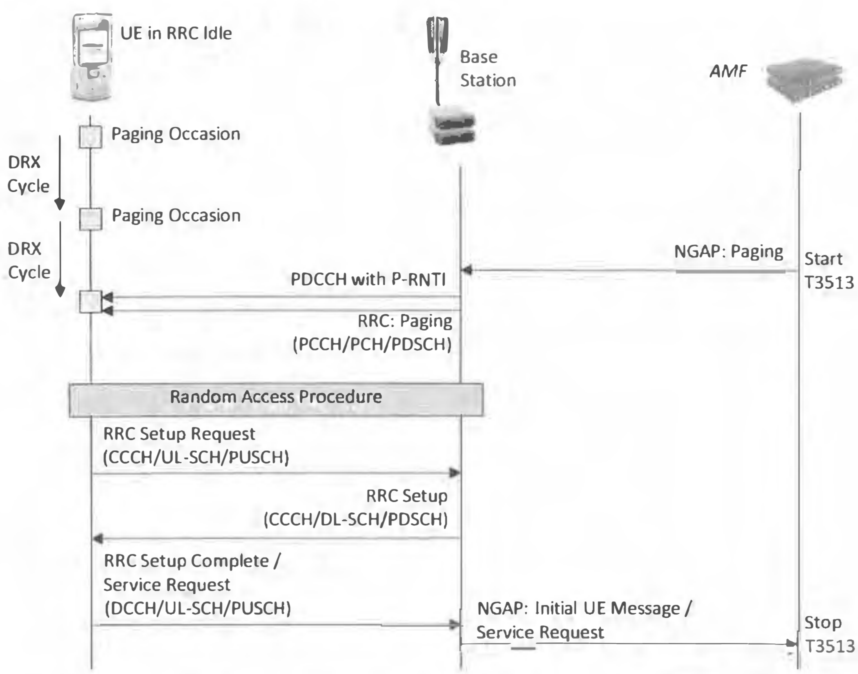


Figure 339 – Paging procedure initiated by the Core Network for a UE in RRC Idle

★ The AMF is responsible for providing 'UE Reachability' services for other Network Functions. For example, an SMS Function (SMSF) may have received an SMS addressed to a UE which is registered with the AMF. In that case, the SMSF requests the AMF to initiate the paging procedure before forwarding the SMS for delivery. Alternatively, a User Plane Function (UPF) may have received downlink data which is addressed to a UE currently in RRC Idle. In that case, the UPF notifies the SMF that downlink data has arrived, and the SMF requests the AMF to initiate the Paging procedure. The UPF can subsequently forward the downlink data to the Base Station once the UE has entered RRC Connected and the Base Station has setup a GTP-U tunnel with the UPF

★ The AMF starts the T3513 timer when sending the NGAP: *Paging* message to a Base Station. This timer serves as a supervision timer for the Paging procedure. The AMF assumes that the paging procedure has failed if T3513 expires before receiving a response from the UE. This may trigger the AMF to initiate a re-transmission of the Paging message

★ The NGAP: *Paging* message is presented in Table 250. Only the 'UE Paging Identity' and 'TAI List for Paging' fields are mandatory so the remaining fields may be excluded from the message

NGAP: Paging				
UE Paging Identity	5G-S-TMSI	AMF Set Identity & AMF Pointer & 5G-TMSI		
Paging DRX	32, 64, 128, 256			
TAI List for Paging	SEQUENCE {1 to 16 instances}			
	Tracking Area Identity	PLMN Id & Tracking Area Code (TAC)		
Paging Priority	1, 2, 3, 4, 5, 6, 7, 8			
UE Radio Capability for Paging	Capability for NR	List of Supported NR Bands	SEQUENCE {1 to 1024 instances}	
			1 to 1024	
	Capability for E-UTRA	List of Supported E-UTRA Bands	SEQUENCE {1 to 64 instances}	
			1 to 256	
Assistance Data for Paging	Recommended Cells	SEQUENCE {1 to 16 instances}		
		NG-RAN CGI	CHOICE	
			NR CGI	*E-UTRA CGI*
		Time Stayed in Cell	0 to 4095 seconds	
	Paging Attempt Information	Paging Attempt Count	1 to 16	
		Intended Number of Paging Attempts	1 to 16	
		Next Paging Area Scope	Same, changed	
Paging Origin	non-3PP			

Table 250 – NGAP: Paging message

★ The Base Station uses the 'UE Paging Identity' to address the UE within the RRC: *Paging* message. This identity corresponds to a 5G-S-TMSI which is a concatenation of the AMF Set Identity (10 bits), the AMF Pointer (6 bits) and the 5G-TMSI (32 bits). The 10 Least Significant Bits (LSB) of the 5G-TMSI are used to determine the Paging Frames and Paging Occasions for the UE. The AMF is responsible for ensuring that the population of UE are allocated 5G-TMSI values which evenly distribute the UE across the set of Paging Frames and Paging Occasions. The 5G-S-TMSI is used instead of the IMSI when addressing the UE because it is a temporary identity. The use of a temporary identity helps to improve security by avoiding exposure of the permanent UE identity. In contrast, the S1AP: *Paging* message used by 4G allows the UE to be addressed by either its IMSI or S-TMSI

★ The 'Paging DRX' field can be included to ensure that the Base Station determines the correct DRX pattern being used by the UE. The Base Station broadcasts the Default DRX cycle duration within SIB1. The Base Station also provides this Default DRX cycle duration to the AMF during the NG interface setup procedure. The AMF may negotiate a UE specific DRX cycle during the NAS Registration procedure. This negotiation is transparent to the Base Station so the Base Station may not know the DRX cycle being used by the UE

★ The AMF can also use the 'Core Network Assistance Information' parameter structure to provide the Base Station with information regarding a UE specific DRX cycle. This parameter structure can be included within an NGAP: *Initial Context Setup Request*, *UE Context Modification Request*, *Handover Request* or *Path Switch Request Acknowledge* message

★ The 'Tracking Area Identity (TAI) List' is included to ensure that the Base Station broadcasts the RRC: *Paging* message using the appropriate cells. In many cases, all cells belonging to a Base Station will belong to the same Tracking Area. However, there are also deployment scenarios where the cells will belong to different Tracking Areas. For example, a Base Station which is shared between operators may have one set of cells belonging to a first Tracking Area for the first operator, and another set of cells belonging to a second Tracking Area for the second operator

★ The 'Paging Priority' can be included to prioritise specific Paging messages at the Base Station. The priority can be configured with a value from 1 to 8, where '1' represents the highest priority. The AMF deduces a priority level from the Allocation and Retention Priority (ARP) indicated by the SMF when requesting the AMF to page the UE. Specific services are likely to have high ARP priorities, e.g. Mission Critical Services (MCS) and Multimedia Priority Services (MPS)

- The 'UE Radio Capability for Paging' provides the Base Station with information regarding the operating bands supported by the UE. This can be used to reduce the number of cells which broadcast the RRC: *Paging* message, i.e. there is no need to broadcast a Paging message on a carrier which the UE does not support. This parameter structure allows both 5G and 4G operating bands to be listed. The 4G operating bands are applicable when the 5G Core Network is connected to a next generation eNode B (ng-eNode B), i.e. a Base Station which supports the 4G air-interface

- The 'Assistance Data for Paging' can be used to provide a list of recommended cells. This list can include cells which the UE has previously visited, and it can also include cells which the UE has not previously visited. In the case of previously visited cells, the AMF specifies the time that the UE spent in each cell. If the time is greater than 4095 seconds then the AMF signals a value of 4095 seconds. The Base Station can use this information when selecting the cells to broadcast the RRC: Paging message. The AMF derives the set of recommended cells from information previously received from the Base Station. A Base Station can provide the AMF with information regarding recommended cells and RAN nodes for paging within the NGAP: *UE Context Release Complete* message. The AMF stores this information for any subsequent paging procedures

- The 'Assistance Data for Paging' can also be used to provide the Base Station with information regarding the re-transmission of NGAP: *Paging* messages. The AMF can specify the current paging attempt count and the total number of attempts which are planned. The AMF can also specify whether or not it plans to change the scope of the geographic paging area on the next paging attempt. The Base Station can use this information to help define its own paging strategy. For example, if the AMF is approaching its final paging attempt then the Base Station can increase the priority of the paging procedure and potentially broadcast the RRC: *Paging* message across an increased number of cells

- The 'Paging Origin' flag is included when the paging procedure has been triggered for a PDU Session which is associated with a non-3GPP access technology. The UE uses the 3GPP access network to respond by sending a NAS: *Service Request* message. This message indicates whether or not the PDU Session can be re-activated using the 3GPP access technology

- Once the Base Station has received the NGAP: *Paging* message then it determines an appropriate Paging Frame and Paging Occasion for the RRC: *Paging* message to be scheduled across the air-interface. The Base Station uses Downlink Control Information (DCI) Format 1_0 to allocate PDSCH resources for the RRC: *Paging* message. The CRC bits are scrambled using the P-RNTI to indicate that the PDSCH resource allocation is applicable to a paging procedure. The content of DCI Format 1_0 is presented in section 3.5.6

- Table 251 presents the content of an RRC: Paging message. A single message can include up to 32 paging records, and each paging record can address a single UE

RRC: Paging				
Paging Record List	SEQUENCE {1 to 32 instances}			
	PagingRecord	ue-Identity	CHOICE	
			ng-5G-S-TMSI	*fullI-RNTI*
			BIT STRING {48 bits}	BIT STRING {40 bits}
		accessType	non3GPP	

Table 251 – RRC: Paging message

- The RRC: Paging message allows the UE to be addressed using either its 5G-S-TMSI or its 'full' I-RNTI. The I-RNTI is applicable to UE which are paged from RRC Inactive. The Base Station allocates an I-RNTI when moving a UE from RRC Connected to RRC Inactive

- The UE initiates the random access procedure after receiving an RRC: *Paging* message. The *RRC Setup Request* message is sent as MSG3 using a cause value of 'mt-Access'. A NAS: *Service Request* message is included within the *RRC Setup Complete* message. The Base Station forwards this NAS message to the AMF to complete the Paging procedure

- For a UE in RRC Inactive, the serving Base Station maintains a record of the UE location in terms of its allocated RAN Notification Area (RNA). The UE triggers an RRC Resume procedure with cause value 'rna-Update' if it moves outside the allocated RNA. The UE does not update the network while moving within the allocated RNA. In general, this means that paging messages must be broadcast by all Base Stations belonging to the allocated RNA

- In the case of RRC Inactive, the UE specific NG-C connection towards the AMF and the UE specific NG-U connection towards the UPF are maintained. This means that the AMF can continue to forward NAS messages towards the serving Base Station and the UPF can continue to forward downlink data towards the serving Base Station. The serving Base Station is responsible for paging the UE to allow reception of the downlink NAS message or downlink data

- Figure 340 illustrates an example based upon the serving Base Station receiving downlink data from the UPF. The serving Base Station is reliant upon having an Xn connection towards each of the Base Stations within the RNA. The serving Base Station can then forward an XnAP: *RAN Paging* message to each Base Station. The XnAP: *RAN Paging* message is presented in Table 252 (alternatively, all cells within the RNA may belong to a single Base Station using the CU/DU Split architecture. In this case, it is not necessary to rely upon Xn connectivity)

- The 'UE Identity Index Value' is set equal to '5G-S-TMSI mod 1024', i.e. a value from 0 to 1023 which occupies 10 bits. This value allows the target Base Station to determine the Paging Frames and Paging Occasions without having to transfer the full 5G-S-TMSI across the Xn interface

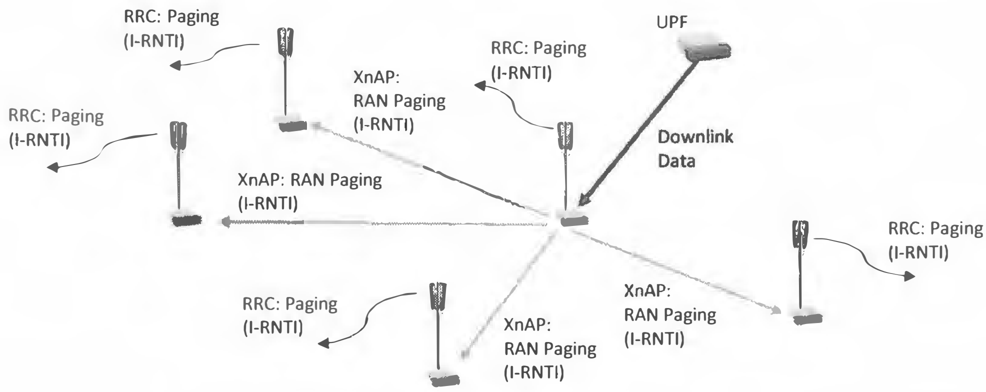


Figure 340 – Distribution of Paging message for UE which is RRC Inactive

<table>
<tr><th colspan="7">XnAP: RAN Paging</th></tr>
<tr><td>UE Identity Index Value</td><td colspan="6">BIT STRING {10 bits}</td></tr>
<tr><td>UE RAN Paging Identity</td><td colspan="2">Full I-RNTI</td><td colspan="4">BIT STRING {40 bits}</td></tr>
<tr><td>Paging DRX</td><td colspan="6">32, 64, 128, 256</td></tr>
<tr><td rowspan="7">RAN Paging Area</td><td colspan="2">PLMN Identity</td><td colspan="4">BIT STRING {24 bits}</td></tr>
<tr><td colspan="6">CHOICE</td></tr>
<tr><td colspan="3">Cell List</td><td colspan="3">RAN Area Identity List</td></tr>
<tr><td colspan="3">SEQUENCE {1 to 32 instances}</td><td colspan="3">SEQUENCE {1 to 16 instances}</td></tr>
<tr><td rowspan="3">NG-RAN Cell Identity</td><td colspan="2">CHOICE</td><td rowspan="3">RAN Area Id</td><td>TAC</td><td>BIT STRING {24 bits}</td></tr>
<tr><td>NR Cell Id</td><td>E-UTRA Cell Id</td><td rowspan="2">RANAC</td><td rowspan="2">0 to 255</td></tr>
<tr><td>BIT STRING {36 bits}</td><td>BIT STRING {28 bits}</td></tr>
<tr><td>Paging Priority</td><td colspan="6">1, 2, 3, 4, 5, 6, 7, 8</td></tr>
<tr><td rowspan="3">Assistance Data for RAN Paging</td><td rowspan="3" colspan="2">RAN Paging Attempt Information</td><td colspan="3">Paging Attempt Count</td><td>1 to 16</td></tr>
<tr><td colspan="3">Intended Number of Paging Attempts</td><td>1 to 16</td></tr>
<tr><td colspan="3">Next Paging Area Scope</td><td>Same, changed</td></tr>
</table>

Table 252 – XnAP: RAN Paging message

★ The 'UE RAN Paging Identity' is the full I-RNTI which was allocated to the UE within the *RRCRelease* message when moving the UE to RRC Inactive. This identity is used to address the UE within the RRC: *Paging* message

★ The 'Paging DRX' specifies the DRX cycle used by the UE. This value allows the target Base Station to identify the appropriate Paging Frames and Paging Occasions

★ The 'RAN Paging Area' allows the target Base Station to identify the cells which are required to broadcast the RRC: *Paging* message. The set of cells can be specified explicitly using up to 32 Cell Global Identities (CGI). Alternatively, they can be specified using up to 16 RAN Area Identities. The use of RAN Area Identities relies upon each cell being configured with both a Tracking Area Code (TAC) and RAN Area Code (RANAC)

★ The 'Paging Priority' can be included to prioritise specific Paging messages at the target Base Station. The priority can be configured with a value from 1 to 8, where '1' represents the highest priority. If the paging procedure has been triggered by the reception of a downlink NAS message from the AMF, then a 'RAN Paging Priority' may have been included within the NGAP: *Downlink NAS Transport* message

★ The 'Assistance Data for RAN Paging' can be used to provide the target Base Station with information regarding the re-transmission of XnAP: *RAN Paging* messages. The serving Base Station can specify the current paging attempt count and the total number of attempts which are planned. The serving Base Station can also specify whether or not it plans to change the scope of the geographic paging area on the next paging attempt

★ Figure 341 illustrates the paging procedure used to notify UE of a change to the System Information or an incoming ETWS/CMAS message. This procedure is applicable to UE in RRC Connected, RRC Idle and RRC Inactive. In this case, the paging procedure does not use NGAP, XnAP nor RRC Paging messages. Instead, the paging procedure uses only the payload of the PDCCH. Downlink Control Information (DCI) Format 1_0 can include a 'Short Message' when the CRC bits are scrambled using the P-RNTI. This 'Short Message' can be used to indicate that System Information has been updated and needs to be re-acquired or there is an incoming ETWS/CMAS message

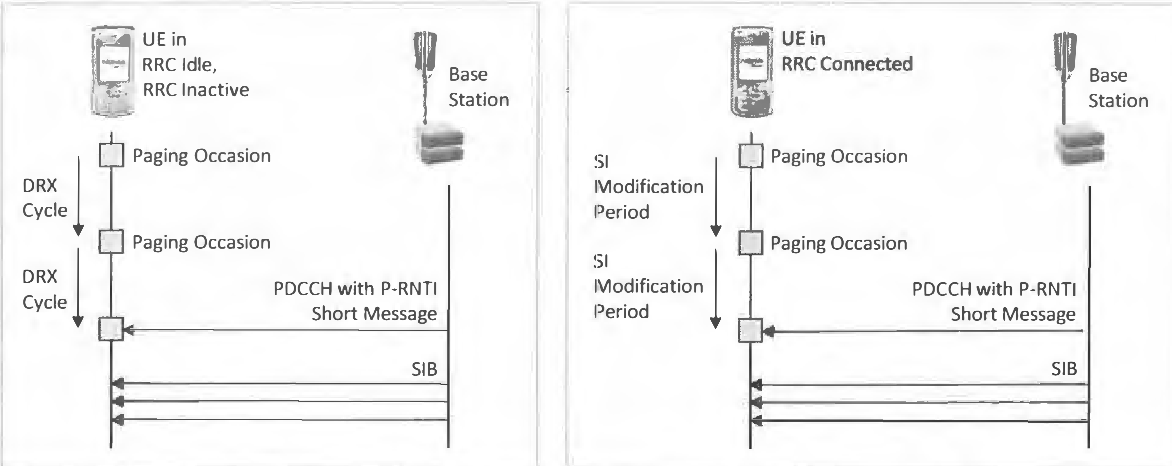


Figure 341 – Paging procedure for System Information update or ETWS/CMAS notification

★ UE in RRC Idle or RRC Inactive monitor the PDCCH once per DRX cycle during the UE's Paging Occasion. UE in RRC Connected monitor the PDCCH once per System Information Modification Period during any Paging Occasion (assuming the UE has been configured with a Common Search Space to monitor paging within the active Bandwidth Part)

★ If the UE is paged with a System Information change notification then the UE re-acquires the System Information from the start of the next Modification Period. If the UE is paged with an ETWS/CMAS notification then the UE immediately re-acquires SIB1 and checks for scheduling information which is applicable to SIB6/SIB7 for ETWS, and SIB 8 for CMAS. The UE then proceeds to acquire the relevant Public Warning System (PWS) SIB

★ Base Stations which use multiple beams to provide coverage across the cell area are required to broadcast paging messages across all beams. For example, a Base Station which uses 8 beams to provide coverage will be required to transmit each paging message 8 times. This means that Paging Occasions must allow sufficient time for UE to scan all beams

★ 3GPP references: TS 38.304, TS 38.331, TS 38.413, TS 38.212, TS 38.423

12.4.2 OCCASIONS

★ UE in RRC Idle and RRC Inactive use Discontinuous Reception (DRX) to help reduce power consumption. A DRX cycle includes a relatively long period during which the UE transceiver can switch to a sleep mode, and a relatively short period during which the UE transceiver switches to an active mode. The UE uses the active mode to check for paging messages and to complete any measurements necessary for cell reselection

★ A UE monitors one Paging Occasion (PO) per DRX cycle. The population of UE can be divided into groups such that each group of UE monitors a different Paging Occasion. This helps to distribute the load generated by the paging procedure

★ A UE has to identify its Paging Frames (PF) before identifying its Paging Occasions (PO). Paging Frames are defined by the SFN which satisfy the equation:

$$(SFN + PF_{offset}) \bmod T = (T / N) \times (UE_{ID} \bmod N)$$

where, SFN identifies the Paging Frame (PF)
PF_{offset} is a time domain offset in terms of Radio Frames
T is the DRX Cycle duration in Radio Frames
N is the total number of Paging Frames during each DRX Cycle
UE_{ID} is '5G-S-TMSI mod 1024'

★ The DRX Cycle (T) is defined as the default Paging Cycle broadcast by SIB1 unless a UE specific value has been configured. If a UE specific value has been configured, the DRX Cycle is the minimum of the default Paging Cycle and the UE specific Paging Cycle. The Base Station can specify a UE specific Paging Cycle within the *RRCRelease* message when moving a UE to RRC Inactive. Alternatively, the UE and AMF can negotiate a UE specific Paging Cycle during the Registration procedure, i.e. the UE can suggest a Paging Cycle within the NAS: *Registration Request* message, while the AMF can confirm the value within the NAS *Registration Accept* message. The DRX cycle can have values of 32, 64, 128 or 256 radio frames

★ Figure 342 illustrates an example of a DRX cycle which has a duration of 32 Radio Frames. This means that each UE checks for paging messages once every 320 ms. Long DRX cycles help to conserve UE battery life but they also increase the average latency for mobile terminated connections

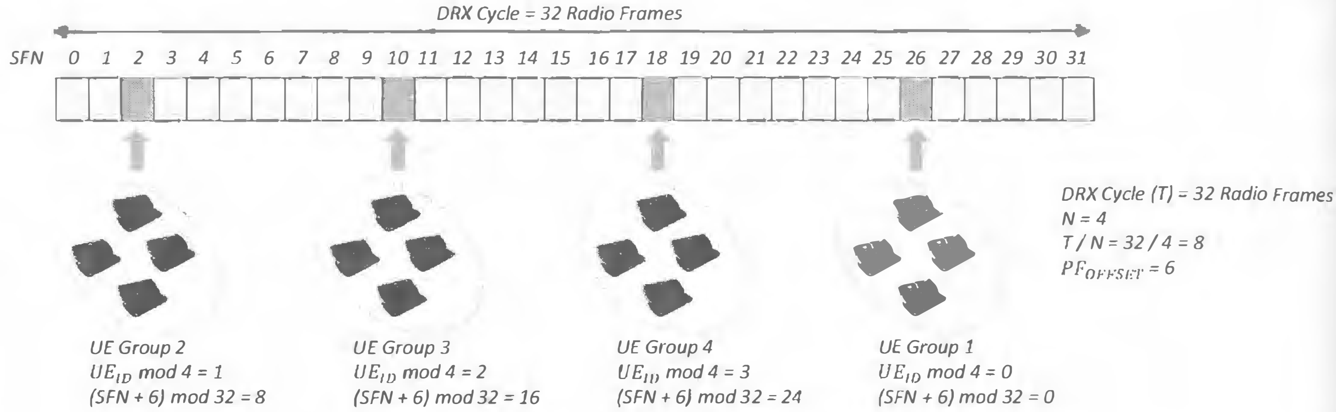


Figure 342 – Example of Paging Frames within a DRX Cycle

★ The example illustrated in Figure 342 is based upon 4 Paging Frames per DRX cycle, i.e. $N = 4$. This means that the population of UE is divided into 4 groups and each group is linked to a specific Paging Frame within each DRX cycle. A UE uses its 5G-S-TMSI to identify its group. The UE first calculates UE_{ID} = '*5G-S-TMSI mod 1024*', and then calculates the group identity as 'UE_{ID} *mod N*'. The AMF is responsible for allocating 5G-S-TMSI values which lead to an even distribution of UE across the groups. For example, if there are 4 groups and the AMF allocates 4 UE with 5G-S-TMSI values of 4, 8, 12 and 16 then all 4 UE will belong to the same group. In contrast, if the AMF allocates 5G-S-TMSI values of 1, 2, 3 and 4 then the 4 UE will belong to different groups

★ PF_{offset} defines a time domain offset which can have a value within the range from 0 to X, where 'X' is the number of Radio Frames between the Paging Frames belonging to each group. The example illustrated in Figure 342 has 7 Radio Frames between the Paging Frames belonging to each group, so PF_{offset} can be configured with values between 0 and 7

★ A UE has to monitor the PDCCH during each Paging Occasion. This means that each Paging Occasion must be linked to a specific Search Space within which the PDCCH can be transmitted. PDCCH transmissions for paging can share the same Search Space as PDCCH transmissions for SIB1. In the case of Multiplexing Pattern 3 (described in section 3.5.3), the Search Space for SIB1 is frequency multiplexed with the SS/PBCH Block. This means that a UE could check for paging messages and complete SS/PBCH Block measurements for cell reselection within a single and relatively short time window. An example of this general concept is illustrated in Figure 343. There is an argument for this type of approach when using beam sweeping because it means that the transmission of SS/PBCH Blocks, SIB1 and Paging messages can be managed using a single sweep

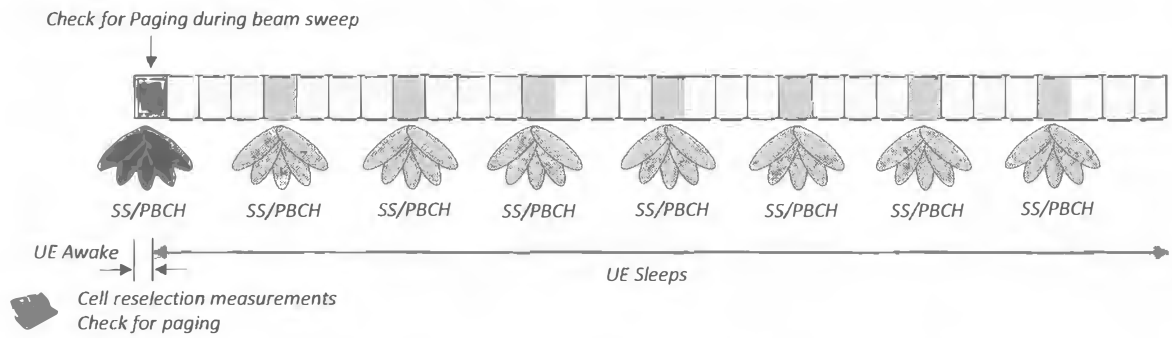


Figure 343 – A UE checking for paging messages and measuring an SS/PBCH Block during a DRX active period

★ When using either Multiplexing Pattern 2 or 3 for the Search Space belonging to SIB1, the period of the Search Space is equal to the period of the SS/PBCH Blocks. This means that the period of the SS/PBCH Blocks can impact the maximum number of Paging Frames per DRX cycle, i.e. increasing the SS/PBCH Block period can reduce the number of potential Paging Frames per DRX cycle. Figure 344 illustrates this dependency when assuming a DRX cycle of 320 ms and a range of SS/PBCH Block periods

★ The example at the top of Figure 344 is based upon an SS/PBCH Block period of 160 ms. This means that there are 2 SS/PBCH Blocks per beam within each DRX cycle, i.e. there are 2 Search Spaces for SIB1 within each DRX cycle. If these Search Spaces are shared with PDCCH transmissions for paging then there can be a maximum of 2 Paging Frames per DRX cycle. Similarly, if the SS/PBCH Block period is 80 ms, there can be a maximum of 4 Paging Frames per DRX cycle. Cells used for initial access will have an SS/PBCH Block period of 20 ms or less so the number of Paging Frames per DRX cycle can be relatively high. SS/PBCH Block periods of 5 and 10 ms allow every radio frame to be used as a Paging Frame

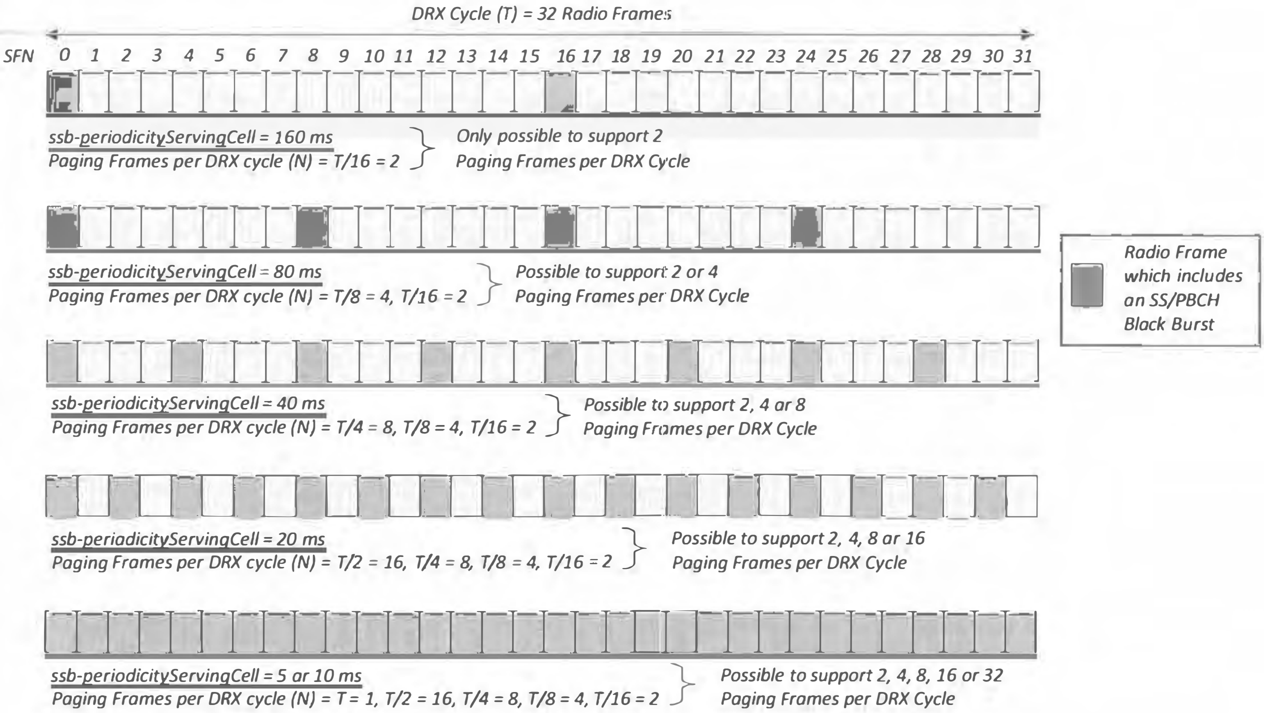


Figure 344 – Dependency of Paging Frames per DRX Cycle when using SS/PBCH – Type 0 CSS Multiplexing Patterns 2 or 3

★ Multiplexing Pattern 1 for the Search Space belonging to SIB1 (described in section 3.5.3) is based upon time multiplexing, i.e. the Search Space is time multiplexed with the SS/PBCH Blocks. In this case, the Search Space has a fixed period of 20 ms. This means that the number of Paging Frames per DRX cycle can be configured as T/2, T/4, T/8 or T/16 (similar to the 20 ms SS/PBCH Block period example in Figure 344)

★ Alternatively, the Search Space for paging can be configured separately, meaning that paging does not share the Search Space used by SIB1. In this case, the period of the Search Space can be configured specifically to match the period between Paging Frames. The Search Space used for paging is configured using the *pagingSearchSpace* information element within the *PDCCH-ConfigCommon* parameter structure belonging to SIB1. If this Search Space set to '0' then it means that Paging and SIB1 share the same Search Space. Otherwise, if *pagingSearchSpace* has a value > 0 then paging and SIB1 do not share the same Search Space

★ After identifying the set of Paging Frames, a UE must proceed to identify its Paging Occasion (PO). A Paging Occasion index is calculated using the following expression:

$$i\_s = FLOOR\ (UE_{ID}\ /\ N)\ mod\ Ns$$

where, UE_{ID} is '5G-S-TMSI mod 1024'
N is the total number of Paging Frames during each DRX Cycle
Ns is the number of Paging Occasions per Paging Frame

★ A single Paging Occasion includes PDCCH monitoring occasions for all beams. For example, if a UE calculates that it should use Paging Occasion '1' for a cell which is configured with 8 beams then that single Paging Occasion includes a PDCCH monitoring occasion for each of the 8 beams. This allows the UE to receive its paging message from any of the beams, i.e. the paging message transmission is repeated by each beam

★ The value of Ns is restricted to being '1' or '2' when paging and SIB1 share the same Search Space. Most scenarios would use $Ns = 1$ so there would be a single Paging Occasion associated with each Paging Frame. If the SS/PBCH Block period is 5 ms then there can be 2 Paging Occasions per Paging Frame. In this case, Ns can be set to '2' such that half of the UE within the paging group use the first Paging Occasion ($i\_s = 0$) while the other half use the second Paging Occasion ($i\_s = 1$)

★ The value of Ns can be set to '1', '2' or '4' when paging and SIB1 do not share the same Search Space, i.e. there can be up to 4 Paging Occasions per Paging Frame. In this case, the Search Space must be configured to ensure that there are sufficient PDCCH monitoring occasions to match the number of Paging Occasions

★ The parameters required to calculate the Paging Frame and Paging Occasion are broadcast using the *PCCH-Config* parameter structure within SIB1 (with the exception of the *5G-S-TMSI* which is allocated by the AMF during the Registration procedure). The *PCCH-Config* parameter structure is presented in Table 253

PCCH-Config					
defaultPagingCycle	32, 64, 128, 256 radio frames				
nAndPagingFrameOffset	CHOICE				
	oneT	*halfT*	*quarterT*	*oneEighthT*	*oneSixteenthT*
	-	0,1	0 to 3	0 to 7	0 to 15
ns	four, two, one				
firstPDCCH-MonitoringOccasionOfPO	CHOICE				
	sCS15KHZoneT	SEQUENCE {1 to 4 instances}			
		0 to 139			
	sCS30KHZoneT-SCS15KHZhalfT	SEQUENCE {1 to 4 instances}			
		0 to 279			
	sCS60KHZoneT-SCS30KHZhalfT-SCS15KHZquarterT	SEQUENCE {1 to 4 instances}			
		0 to 559			
	sCS120KHZoneT-SCS60KHZhalfT-SCS30KHZquarterT-SCS15KHZoneEighthT	SEQUENCE {1 to 4 instances}			
		0 to 1119			
	sCS120KHZhalfT-SCS60KHZquarterT-SCS30KHZoneEighthT-SCS15KHZoneSixteenthT	SEQUENCE {1 to 4 instances}			
		0 to 2239			
	sCS120KHZquarterT-SCS60KHZoneEighthT-SCS30KHZoneSixteenthT	SEQUENCE {1 to 4 instances}			
		0 to 4479			
	sCS120KHZoneEighthT-SCS60KHZoneSixteenthT	SEQUENCE {1 to 4 instances}			
		0 to 8959			
	sCS120KHZoneSixteenthT	SEQUENCE {1 to 4 instances}			
		0 to 17919			

Table 253 – PCCH-Config parameter structure

★ The value of *nAndPagingFrameOffset* defines the number of Paging Frames per DRX cycle (N), i.e. the number of paging groups. For example, if the DRX cycle (T) has a duration of 32 Radio Frames while *nAndPagingFrameOffset* has been set to 'oneEighthT' then there are 32/8 = 4 Paging Frames per DRX cycle, i.e. the population of UE is divided into 4 groups. If the DRX cycle (T) has a duration of 256 Radio Frames while *nAndPagingFrameOffset* has been set to 'oneT' then there are 256/1 = 256 Paging Frames per DRX cycle, i.e. the population of UE is divided into 256 groups. *nAndPagingFrameOffset* also defines the value of PF_{offset}

★ The value of *Ns* used to calculate the Paging Occasion is configured using the '*ns*' information element

★ The *firstPDCCH-MonitoringOccasionOfPO* information element can be used to specify the first PDCCH monitoring occasion associated with a specific Paging Occasion. This information element is not necessary when paging shares a Search Space with SIB1

★ *firstPDCCH-MonitoringOccasionOfPO* can provide a sequence of up to 4 values which correspond to having up to 4 Paging Occasions. The range of *firstPDCCH-MonitoringOccasionOfPO* depends upon both the subcarrier spacing and the period between Paging Frames. For example, when using a 15 kHz subcarrier spacing there are 140 symbols per Radio Frame, so there are 140 symbols per Paging Frame when there is 1 Paging Frame per Radio Frame, i.e. potentially 140 PDCCH monitoring occasions. When using the 120 kHz subcarrier spacing there are 1120 symbols per Radio Frame, so there are 1120 × 16 = 17920 symbols per Paging Frame when there is 1 Paging Frame per 16 Radio Frames

★ 3GPP references: TS 38.304, TS 38.331, TS 38.213

13 PHYSICAL AND MAC LAYER PROCEDURES

13.1 RANDOM ACCESS

★ There are 2 categories of the Random Access procedure:
  - o Contention Based Random Access (CBRA)
  - o Contention Free Random Access (CFRA)

★ The 'Contention Based' procedure allows the UE to select a random access preamble from a pool of preambles shared with other UE. This means that the UE risks selecting the same preamble as another UE and subsequently experiencing contention. The 'Contention Free' procedure requires the Base Station to allocate a dedicated random access preamble. This removes the possibility of the UE experiencing contention. Both categories of procedure are illustrated at a high level in Figure 345

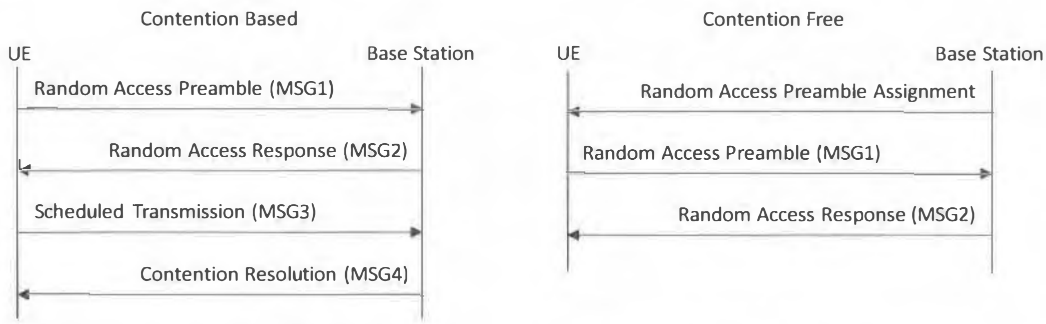


Figure 345 – Contention Based and Contention Free Random Access procedures

★ If multiple UE select the same preamble for the 'Contention Based' procedure, those UE will decode the same content from the Random Access Response (MSG2). The Random Access Response provides the uplink resource allocation for MSG3, so each UE which decoded the same MSG2 content will transmit MSG3 using the same set of Resource Blocks and symbols. The Base Station will decode one of those MSG3 and will then complete Contention Resolution. If MSG3 included a CCCH message then Contention Resolution is based upon a MAC Control Element within MSG4. If MSG3 included a DCCH message or DTCH data then Contention Resolution is achieved by addressing the UE on the PDCCH by its C-RNTI. Contention Resolution allows the group of UE which transmitted the same preamble to deduce which MSG3 was decoded by the Base Station and thus deduce which UE has successfully completed the Random Access procedure. The remaining UE continue the procedure with another preamble transmission

★ In the case of the 'Contention Free' procedure, the UE is provided with a dedicated preamble using either RRC signalling or Layer 1 signalling, i.e. the allocated preamble can be specified within an RRC message or within Downlink Control Information (DCI) on the PDCCH

★ Table 254 presents a list of procedures which rely upon Random Access. All of these procedures can use Contention Based Random Access, while only a subset can use Contention Free Random Access (Contention Free Random Access requires the Base Station to have an opportunity to allocate a dedicated preamble)

	Contention Based	Contention Free
Initial Access from RRC Idle mode	✓	-
Transition from RRC Inactive to RRC Connected	✓	-
RRC Connection Re-establishment	✓	-
Handover	✓	✓
Downlink Data arrival while UE is Out-of-Sync (PDCCH Order)	✓	✓
Uplink Data arrival while UE is Out-of-Sync	✓	-
Uplink Data arrival for UE without PUCCH resource allocation	✓	-
On-Demand System Information	✓ (MSG3 based)	✓ (MSG1 based)
Beam Failure Recovery	✓	✓
Scheduling Request Failure	✓	-
Synchronous Reconfiguration	✓	✓
Establishing Time Alignment during SCell Addition	✓	✓

Table 254 – Procedures which use Random Access

★ UE making the transition from RRC Idle to RRC Connected use MSG3 to send the *RRCSetupRequest*. Similarly, UE making the transition from RRC Inactive to RRC Connected use MSG3 to send the *RRCResumeRequest* (or *RRCResumeRequest1*). In both cases, the Contention Based procedure is used and the UE is responsible for selecting a PRACH preamble from the pool or preambles

★ UE completing the RRC Connection Re-establishment procedure use MSG3 to send the *RRCReestablishmentRequest*. This procedure also relies upon Contention Based Random Access

★ The handover procedure can use either Contention Based or Contention Free Random Access. In the case of Contention Free Random Access, the Base Station provides the UE with a specific PRACH preamble using the *RACH-ConfigDedicated* parameter structure within the *RRCReconfiguration* message. In the case of Contention Based Random Access, the Base Station excludes the PRACH preamble allocation. The *RRCReconfiguration* message acts as the handover command. The UE uses MSG3 to send the *RRCReconfigurationComplete* message which acts as the acknowledgement to indicate handover completion. The Contention Free Random Access procedure is preferred for handovers due to its increased reliability and lower latency

★ A 'PDCCH Order' is used to trigger the Random Access procedure when downlink data arrives for a UE which has lost uplink synchronisation while in RRC Connected mode, i.e. Timing Advance Commands have not been used to maintain uplink synchronisation and the *TimeAlignmentTimer* has expired. The Random Access Procedure is used to re-synchronise the UE prior to forwarding the downlink data. A 'PDCCH Order' is signalled using DCI Format 1_0 (presented in section 3.5.6). A 'PDCCH Order' can trigger either the Contention Based or the Contention Free Random Access procedure by excluding or including a PRACH preamble index within the DCI. A 'PDCCH Order' does not require an RRC message to be transferred for MSG3. Instead a C-RNTI MAC Control Element is included within MSG3. This C-RNTI is used for Contention Resolution when using Contention Based Random Access

★ A UE uses the Contention Based Random Access procedure if uplink data arrives while the UE has lost uplink synchronisation in RRC Connected mode. Similar to the downlink scenario, the Random Access procedure is used to re-synchronise the UE prior to transferring the data. The UE is not required to send an RRC message within MSG3 but sends a C-RNTI MAC Control Element which is subsequently used for Contention Resolution

★ A UE is typically allocated a set of PUCCH resources to send Scheduling Requests. If a UE has not been allocated any PUCCH resources then it can use the Contention Based Random Access procedure to obtain an uplink resource allocation, i.e. MSG3. The UE is not required to send an RRC message within MSG3 but sends a C-RNTI MAC Control Element instead. If the UE requires additional uplink resource allocations, MSG3 may also include a Buffer Status Report (BSR) MAC Control Element

★ On-demand System Information can be requested using either MSG1 or MSG3. Figure 235 (section 6) illustrates the Random Access procedure being used for this purpose

  o *si-RequestConfig* is included within SIB1 if the Base Station supports 'On-demand' SIB requests using MSG1. In this case, the UE transmits a specific PRACH preamble to request a specific SIB, or a specific set of SIB. This procedure only requires MSG1 and MSG2 so corresponds to the Contention Free Random Access procedure. After receiving MSG2, the UE scans the PDCCH for System Information resource allocations

  o the Base Station relies upon 'On-demand' SIB requests using MSG3 if *si-RequestConfig* is excluded from SIB1 while at least one SIB has *si-BroadcastStatus* set to 'notBroadcasting'. In this case, MSG3 is used to transmit the *RRCSystemInfoRequest*. This procedure requires the UE to select a PRACH preamble from the normal pool of preambles so the procedure is Contention Based and requires the Base Station to return MSG4 for contention resolution

★ Beam Failure Recovery uses the Random Access procedure to allow rapid recovery without the requirement for RRC signalling. In the case of the Contention Free procedure, the Base Station provides the UE with a PRACH preamble index for each beam available for recovery. This allows the Base Station to identify the beam which has been selected by the UE. The beam used for recovery can be either an SS/PBCH beam or a CSI Reference Signal beam. In the case of the Contention Based procedure, the UE selects a PRACH preamble which corresponds to the SS/PBCH beam targeted for recovery

★ A UE reverts to using the Contention Based Random Access procedure if a Base Station does not provide an uplink resource allocation after the UE has sent a series of Scheduling Requests on the PUCCH. The upper limit for the number of Scheduling Request attempts is defined by *sr-TransMax*. In this case, the Random Access procedure is used as an alternative mechanism for requesting uplink resources

★ The Base Station can instruct a UE to complete a synchronous reconfiguration by including the *reconfigurationWithSync* parameter structure within an *RRCReconfiguration* message. This triggers the UE to complete a Random Access procedure which then allows both the UE and Base Station to subsequently apply the new configuration at the same time. The Base Station can specify a specific PRACH preamble within the *reconfigurationWithSync* parameter structure for the Contention Free Random Access procedure

★ The Random Access procedure can be used to initialise Timing Advance when adding a Secondary Cell which belongs to a new Timing Advance Group (TAG). This may be applicable if the new Secondary Cell is not co-sited with the existing serving cells so experiences a different propagation delay. The Random Access procedure allows the Base Station to initialise the Timing Advance for the new Secondary Cell. The UE subsequently maintains Timing Advance for each Timing Advance Group. Similar to the synchronous reconfiguration procedure, the Base Station can specify a specific PRACH preamble within the *reconfigurationWithSync* parameter structure for the Contention Free Random Access procedure

13.1.1 CONTENTION BASED

★ The UE requires knowledge of the available PRACH preambles and PRACH occasions before it can initiate the Contention Based Random Access Procedure. The Base Station uses the *RACH-ConfigCommon* parameter structure shown in Table 255 to provide this information either within SIB1 or using dedicated signalling. The parameters within *RACH-ConfigCommon* will be referenced throughout the remainder of this section

RACH-ConfigCommon		
rach-ConfigGeneric	prach-ConfigurationIndex	0 to 255
	msg1-FDM	1, 2, 4, 8
	msg1-FrequencyStart	0 to 274
	zeroCorrelationZoneConfig	0 to 15
	preambleReceivedTargetPower	-202 to -60, step 2 dBm
	preambleTransMax	3, 4, 5, 6, 7, 8, 10, 20, 50, 100, 200
	powerRampingStep	0, 2, 4, 6 dB
	ra-ResponseWindow	1, 2, 4, 8, 10, 20, 40, 80 slots
totalNumberOfRA-Preambles	1 to 63	
ssb-perRACH-OccasionAnd CB-PreamblesPerSSB	CHOICE	
	oneEighth	4, 8, 12, 16, 20, 24, 28, 32, 36, 40, 44, 48, 52, 56, 60, 64
	oneFourth	4, 8, 12, 16, 20, 24, 28, 32, 36, 40, 44, 48, 52, 56, 60, 64
	oneHalf	4, 8, 12, 16, 20, 24, 28, 32, 36, 40, 44, 48, 52, 56, 60, 64
	one	4, 8, 12, 16, 20, 24, 28, 32, 36, 40, 44, 48, 52, 56, 60, 64
	two	4, 8, 12, 16, 20, 24, 28, 32
	four	1 to 16
	eight	1 to 8
	sixteen	1 to 4
groupBconfigured	ra-Msg3SizeGroupA	56, 72, 144, 208, 256, 282, 480, 640, 800, 1000 bits
	messagePowerOffsetGroupB	-infinity, 0, 5, 8, 10, 12, 15, 18 dB
	numberOfRA-PreamblesGroupA	1 to 64
ra-ContentionResolutionTimer	8, 16, 24, 32, 40, 48, 56, 64 subframes	
rsrp-ThresholdSSB	0 to 127	
rsrp-ThresholdSSB-SUL	0 to 127	
prach-RootSequenceIndex	CHOICE	
	l839	0 to 837
	l139	0 to 137
msg1-SubcarrierSpacing	15, 30, 60, 120 kHz	
restrictedSetConfig	unrestrictedSet, restrictedSetTypeA, restrictedSetTypeB	
msg3-transformPrecoder	enabled	

Table 255 – *RACH-ConfigCommon* parameter set

★ A UE starts by identifying the PRACH Preambles which belong to the pool for Contention Based Random Access. The UE already knows that every PRACH occasion offers a maximum of 64 preambles, numbered from 0 to 63. The *totalNumberOfRA-Preambles* quantifies the total number of preambles per PRACH occasion which are available for both the Contention Based and Contention Free Random Access procedures (excluding preambles which have been reserved, e.g. preambles which have been reserved for on-demand System Information requests). This parameter has a range from 0 to 63 so it is used when less than 64 preambles are available. Excluding this parameter from *RACH-ConfigCommon* indicates that all 64 preambles are available

★ *ssb-perRACH-OccasionAndCB-PreamblesPerSSB* allows the UE to quantify the number of Contention Based PRACH preambles associated with each SS/PBCH beam. This parameter can be divided into two parts with *ssb-perRACH-Occasion* defining the number of SS/PBCH beams sharing the same PRACH occasion, i.e. sharing the same set of 64 preambles. Figure 346 illustrates examples with 1 beam per PRACH occasion, 1/2 beam per PRACH occasion and 2 beams per PRACH occasion. This relationship determines the total number of preambles available to each beam. *CB-PreamblesPerSSB* defines the number of Contention Based preambles per PRACH occasion which are available to a specific beam

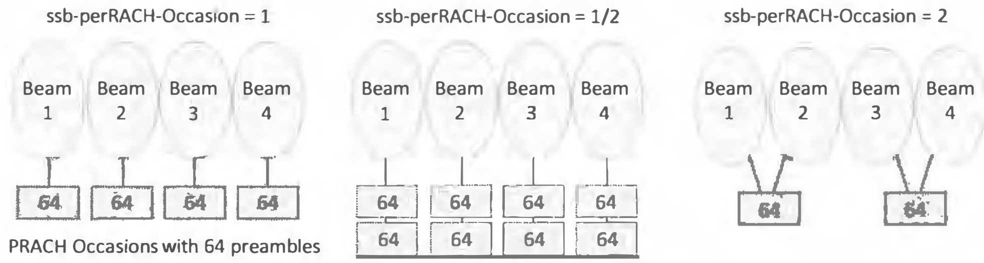


Figure 346 – Allocation of PRACH occasions to SS/PBCH beams

★ For example, if *ssb-perRACH-Occasion* is set to 1/2 and *CB-PreamblesPerSSB* is set to 40 then there are 80 Contention Based preambles available to each beam. The upper limit for *CB-PreamblesPerSSB* depends upon *ssb-perRACH-Occasion* because the preambles are evenly shared between beams. For example, if *ssb-perRACH-Occasion* is set to 2 then each beam can use up to 32 preambles

★ The Contention Based preambles are divided into 'Group A' and 'Group B' if *groupBconfigured* is included within *RACH-ConfigCommon*. The number of Contention Based preambles per PRACH occasion belonging to 'Group A' is defined by *numberOfRA-PreamblesGroupA*. The remaining Contention Based preambles belong to 'Group B'

★ Dividing the Contention Based preambles into two groups helps the Base Station to allocate an appropriate set of resources for MSG3. A UE selects a preamble from 'Group B' if the following conditions are satisfied:

Random Access initiated by CCCH, i.e. for transmission of *RRCSetupRequest*, *RRCResumeRequest*, *RRCResumeRequest1*, *RRCReestablishmentRequest* or *RRCSystemInfoRequest*, then 'Group B' is selected if:

CCCH SDU Size + MAC Subheader Size > *ra-Msg3SizeGroupA*

Otherwise, 'Group B' is selected if:

Potential MSG3 Size > *ra-Msg3SizeGroupA* AND

Path Loss < *PCMAX* – *preambleReceivedTargetPower* – *msg3-DeltaPreamble* – *messagePowerOffsetGroupB*

where, 'Potential MSG3 Size' includes uplink data available for transmission plus the MAC header and any MAC Control Elements

★ In the case of CCCH message transmission, 'Group B' is selected based upon only the message and MAC header sizes. This is important because CCCH messages cannot be segmented and the indication of a larger message should not depend upon path loss conditions. The majority of CCCH messages have a size of 48 bits which combine with the 8 bit MAC Subheader to generate a packet size of 56 bits. This corresponds to the smallest value that can be configured for *ra-Msg3SizeGroupA*, i.e. the majority of CCCH messages trigger 'Group A' preamble selection. The exception is the *RRCResumeRequest1* message which includes the full I-RNTI (40 bits) rather than the short I-RNTI (24 bits). The *RRCResumeRequest1* message is a 64 bit message rather than a 48 bit message so requires a larger MSG3 resource allocation, i.e. the *RRCResumeRequest1* message should trigger 'Group B' preamble selection so the Base Station can deduce that it needs to allocate a larger Transport Block size

★ In other cases, 'Group B' is selected if the MSG3 payload is relatively large and the path loss is relatively small. In this case, the path loss condition indicates that the UE has sufficient transmit power to transfer its payload using a larger resource allocation. The UE will select a preamble from 'Group A' if it has a large volume of data in its buffer but the path loss is large. This will allow the Base Station to deduce that it needs to allocate a smaller Transport Block size. In this case, the uplink data can be segmented and data remaining in the buffer can be transferred using a subsequent resource allocation

★ Figure 347 illustrates the grouping of the PRACH preambles belonging to a single PRACH occasion when the number of SS/PBCH Beams per PRACH occasion is ≤ 1

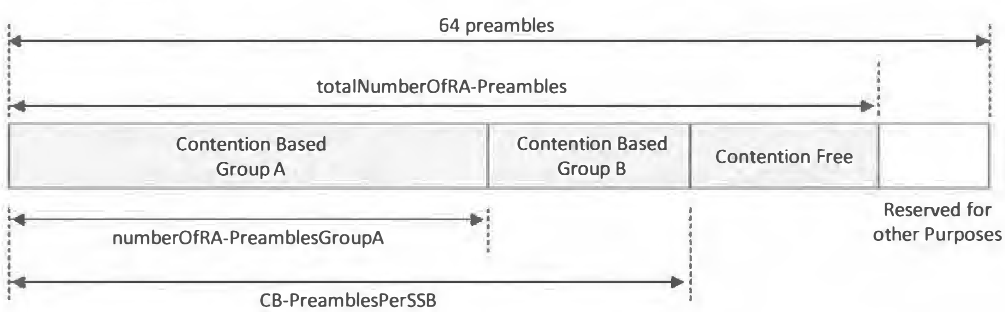


Figure 347 – Grouping of 64 PRACH preambles (SS/PBCH Beams per PRACH occasion ≤ 1)

★ Figure 348 illustrates the grouping of the PRACH preambles belonging to a single PRACH occasion when the number of SS/PBCH Beams per PRACH occasion is 2

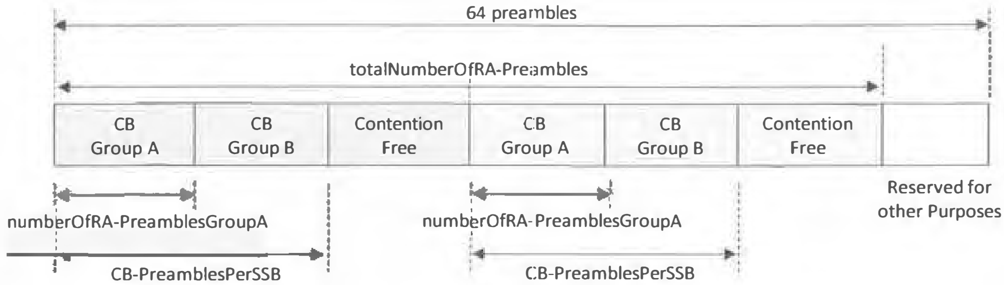


Figure 348 – Grouping of 64 PRACH preambles (SS/PBCH Beams per PRACH occasion = 2)

★ Before selecting a specific preamble from the appropriate group, the UE must select an SS/PBCH beam. The UE prioritises beams which have a Layer 1 RSRP exceeding the value of *rsrp-ThresholdSSB* (or *rsrp-ThresholdSSB-SUL* when using a Supplemental Uplink carrier). The UE is permitted to select any beam if none of the beams have a Layer 1 RSRP measurement which exceeds the threshold. Selecting a PRACH preamble which is linked to a specific SS/PBCH beam allows the Base Station to deduce the best beam for subsequent transmissions

★ Figure 349 summarises the overall procedure for PRACH preamble selection

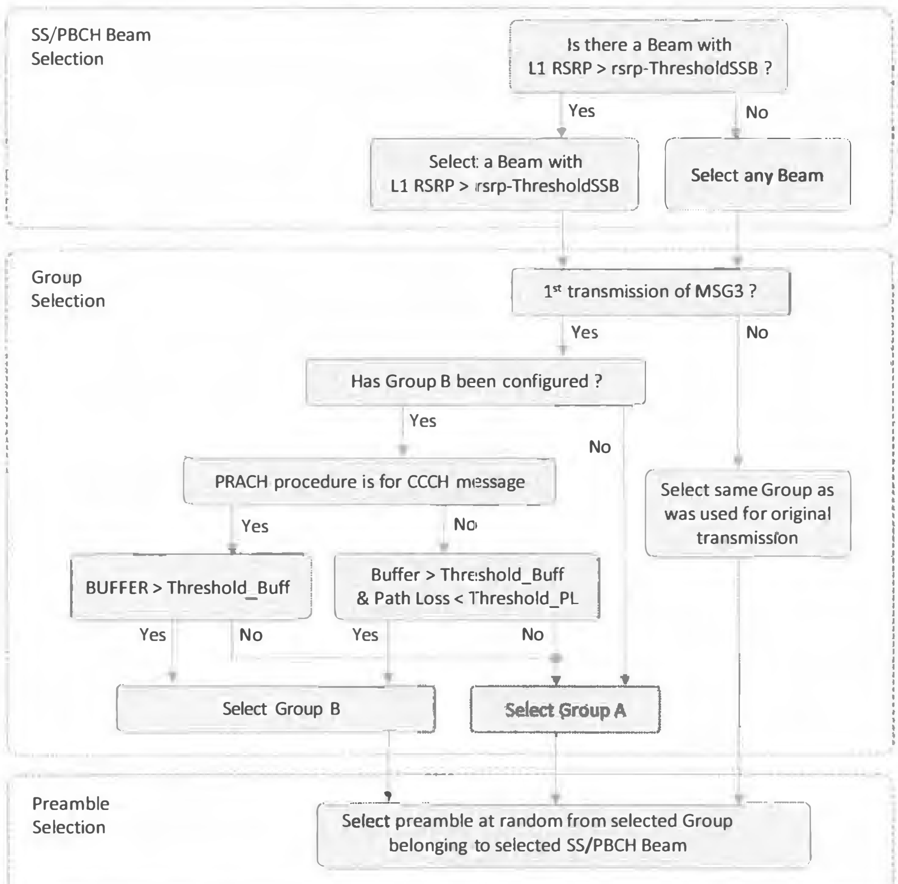


Figure 349 – PRACH Preamble selection for the Contention based Random Access procedure

★ Once the PRACH preamble has been selected, the UE is required to generate the corresponding PRACH sequence for transmission within that preamble (a PRACH preamble consists of one or more repetitions of a sequence plus a cyclic prefix). The sequence is generated using a combination of the selected PRACH preamble index, *prach-RootSequenceIndex*, *zeroCorrelationZoneConfig* and *restrictedSetConfig*. The Root Sequence index, Zero Correlation Zone configuration and the use of Restricted Sets are typically configured as part of Radio Network Planning. Section 7.2 describes the use of these parameters when generating a PRACH preamble sequence

★ The *zeroCorrelationZoneConfig* is determined by the cell range requirement. Larger cell ranges require larger cyclic shifts when generating the PRACH preambles from the Root Sequence. The Zero Correlation Zone configuration determines the size of the cyclic shift. Sections 7.2.3 and 7.2.4 present tables which illustrate the relationship between the maximum cell range and the Zero Correlation Zone configuration

★ The *zeroCorrelationZoneConfig* also determines the number of Root Sequences required per cell when generating the set of 64 preambles belonging to each PRACH occasion. Larger cell ranges require an increased number of Root Sequences due to the larger cyclic shift. For example, if a Root Sequence has a length of 839 digits and a cyclic shift of 119 is used then it is possible to generate ROUNDDOWN (839 / 119) = 7 sequences from each Root Sequence. This means that ROUNDUP (64 / 7) = 10 Root Sequences are required to generate the set of 64 PRACH preambles belonging to each PRACH occasion (the same set of 64 sequences are re-used for all time multiplexed and frequency multiplied PRACH occasions belonging to a specific cell). For this example, Radio Network Planning would allocate Root Sequences to cells using a step size of 10 because every cell requires 10 Root Sequences

★ *prach-RootSequenceIndex* identifies the first Root Sequence used by a cell. For example, if *prach-RootSequenceIndex* = 50 and a cell requires 10 Root Sequences to generate the set of 64 PRACH preambles, then the cell would use Root Sequences {50, 51, 52, 53, 54, 55, 56, 57, 58, 59}, and a neighbouring cell could be allocated *prach-RootSequenceIndex* = 60. It should be noted that these are 'logical' Root Sequence indices which are mapped onto 'physical' Root Sequence indices using a look-up table specified by 3GPP TS 38.211. The 'logical' Root Sequence indices are consecutive but the 'physical' root sequence indices are not consecutive

★ *restrictedSetConfig* is normally configured as 'unrestrictedSet'. The 'restrictedSetTypeA' and 'restrictedSetTypeB' values are applicable to high speed and very high speed deployment scenarios when using Long PRACH Formats. They provide increased resilience to Doppler frequency offsets by restricting the set of preambles which can be generated from each Root Sequence. These restricted sets are described in section 7.2.1

★ A UE is also required to identify the time and frequency domain positions of the PRACH occasions belonging to each SS/PBCH beam. This is achieved using the *prach-ConfigurationIndex* and *msg1-FDM* parameters. The *prach-ConfigurationIndex* defines a pointer to a row within a look-up table specified by 3GPP TS 38.211. There are separate PRACH Configuration Index tables for each duplexing method and Frequency Range. Examples entries are shown in Table 171 and Table 172 for the Long PRACH Formats and in Table 177, Table 178 and Table 179 for the Short PRACH Formats

★ Figure 350 illustrates an example of the timing for Short PRACH Preamble Format A2 when using the 30 kHz subcarrier spacing for TDD within Frequency Range 1. This example is based upon a PRACH Configuration Index of '94'. The values of 'x' and 'y' indicate that PRACH occasions only exist within odd numbered radio frames, i.e. $n_{SFN}\ mod\ 2 = 1$. This also indicates that the PRACH Configuration Period is 20 ms

★ The Subframe Number indicates that PRACH occasions exist within subframes 4 and 9. This example is based upon TDD so there is a requirement to ensure that the relevant symbols within these subframes are configured for the uplink. The 'Starting Symbol' indicates that the PRACH occasions start at symbol '0', while the 'Number of PRACH Slots within Subframe' indicates that both slots belonging to the subframe include PRACH occasions. This column is applicable because this example is based upon the 30 kHz subcarrier spacing so there are 2 slots per subframe. This column does not provide any information when using the 15 kHz subcarrier spacing because there is only 1 slot per subframe (this example is based upon Frequency Range 1 so only the 15 kHz and 30 kHz subcarrier spacings are applicable to the PRACH)

★ The 'Time Domain PRACH Occasions within PRACH Slot' indicates that 3 PRACH occasions are time multiplexed. The PRACH Duration indicates that each PRACH occasion occupies 4 symbols (corresponding to the duration of preamble format A2)

★ This example provides a total of 12 time multiplexed PRACH occasions per 20 ms. The number of PRACH occasions can be further increased by frequency multiplexing if the value of *msg1-FDM* is greater than 1

PRACH Configuration Index	Preamble Format	n_{SFN} mod x = y		Subframe Number	Starting Symbol	Number of PRACH Slots within Subframe	Time Domain PRACH Occasions within PRACH Slot	PRACH Duration
		x	y					
94	A2	2	1	4, 9	0	2	3	4

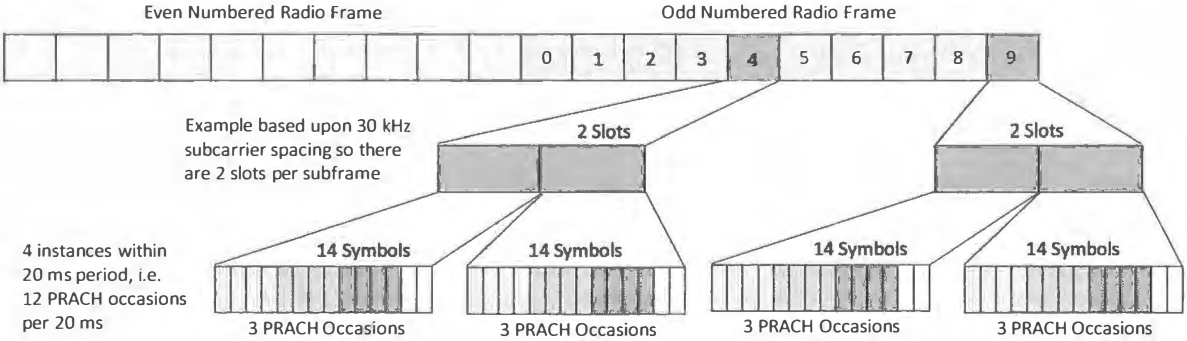


Figure 350 – Example PRACH occasion timing for 30 kHz Short Preamble Format A2 using TDD within Frequency Range 1

★ Figure 351 illustrates an example of the timing for Short PRACH Preamble Format A2 when using the 120 kHz subcarrier spacing for TDD within Frequency Range 2. This example is based upon a PRACH Configuration Index of '38'. The values of 'x' and 'y' indicate that PRACH occasions only exist within odd numbered radio frames, i.e. $n_{SFN}\ mod\ 2 = 1$. This also indicates that the PRACH Configuration Period is 20 ms

★ The previous example was based upon Frequency Range 1 and the look-up table included a 'Subframe Number' column. This second example is based upon Frequency Range 2 and the 'Subframe Number' column is replaced by a 'Slot Number' column. Slot numbering is based upon the 60 kHz subcarrier spacing so there are 40 slots per radio frame

★ The Slot Number indicates that PRACH occasions exist within 60 kHz slots {4, 9, 14, 19, 24, 29, 34, 39}. Similar to the first example, this example is based upon TDD so there is a requirement to ensure that the relevant symbols within these slots are configured for the uplink. The 'Starting Symbol' indicates that the PRACH occasions start at symbol '0', while the 'Number of PRACH Slots within 60 kHz Slot' indicates that only the first slot belonging to the 60 kHz slot includes PRACH occasions. This column is applicable because this example is based upon the 120 kHz subcarrier spacing so there are 2 slots per 60 kHz slot. This column does not provide any information when using the 60 kHz subcarrier spacing because there is only 1 slot per 60 kHz slot (this example is based upon Frequency Range 2 so only the 60 kHz and 120 kHz subcarrier spacings are applicable to the PRACH)

★ The 'Time Domain PRACH Occasions within PRACH Slot' indicates that 3 PRACH occasions are time multiplexed. The PRACH Duration indicates that each PRACH occasion occupies 4 symbols (corresponding to the duration of preamble format A2)

★ This example provides a total of 24 time multiplexed PRACH occasions per 20 ms. The number of PRACH occasions can be further increased by frequency multiplexing if the value of *msg1-FDM* is greater than 1

PRACH Configuration Index	Preamble Format	n_{SFN} mod x = y		Slot Number	Starting Symbol	Number of PRACH Slots within 60 kHz Slot	Time Domain PRACH Occasions within PRACH Slot	PRACH Duration
		x	y					
38	A2	2	1	4, 9, 14, 19, 24, 29, 34, 39	0	1	3	4

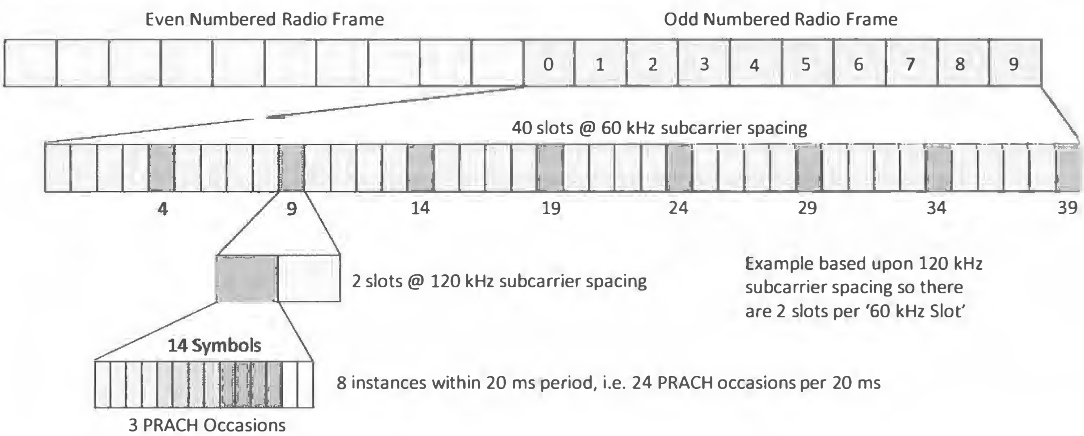


Figure 351 – Example PRACH occasion timing for 120 kHz Short Preamble Format A2 using TDD within Frequency Range 2

★ Figure 352 illustrates the general concept of frequency multiplexing PRACH occasions. *msg1-FDM* specifies the number of PRACH occasions which are multiplexed in the frequency domain. Figure 352 is based upon *msg1-FDM* = 4. The frequency multiplexed PRACH occasions occupy a contiguous set of Resource Blocks within the uplink Bandwidth Part

★ *msg1-FrequencyStart* specifies the position of the lowest Physical Resource Block (PRB) belonging to the first PRACH occasion. Resource Block numbering is based upon the subcarrier spacing used by the PUSCH within the uplink Bandwidth Part

★ The number of PUSCH Resource Blocks occupied by each PRACH occasion depends upon the subcarrier spacings of both the PRACH and the PUSCH. Figure 352 specifies that the PRACH occupies 6 Resource Blocks when the PRACH subcarrier spacing is 1.25 kHz and the PUSCH subcarrier spacing is 15 kHz (this configuration is equivalent to the most commonly used 4G configuration). The set of 6 Resource Blocks corresponds to a bandwidth of 1080 kHz which allows a guard band either side of the PRACH transmission. When using a PRACH subcarrier spacing of 1.25 kHz and a PUSCH subcarrier spacing of 60 kHz, the PRACH occupies 2 Resource Blocks which corresponds to a bandwidth of 1440 kHz, i.e. in this case, there is a larger guard band either side of the PRACH transmission

★ The PRACH occupies 12 Resource Blocks when both the PRACH and PUSCH subcarrier spacings are 120 kHz. The set of 12 Resource Blocks corresponds to a bandwidth of 17.28 MHz, i.e. PRACH transmissions can occupy relatively large bandwidths when the subcarrier spacing is high

★ After identifying both time and frequency domain multiplexing, a UE knows the total number of PRACH occasions within a PRACH Configuration Period. It is then necessary to link each PRACH occasion to a specific SS/PBCH beam

Long PRACH Preamble Formats
839 Subcarriers

PRACH Subcarrier Spacing	Occupied Bandwidth	Resource Blocks Occupied by PRACH		
		15 kHz PUSCH	30 kHz PUSCH	60 kHz PUSCH
1.25 kHz	1048.75 kHz	6	3	2
5 kHz	4195 kHz	24	12	6

Short PRACH Preamble Formats
139 Subcarriers

PRACH Subcarrier Spacing	Occupied Bandwidth	Resource Blocks Occupied by PRACH			
		15 kHz PUSCH	30 kHz PUSCH	60 kHz PUSCH	120 kHz PUSCH
15 kHz	2085 kHz	12	6	3	-
30 kHz	4170 kHz	24	12	6	-
60 kHz	8340 kHz	-	-	12	6
120 kHz	16680 kHz	-	-	24	12

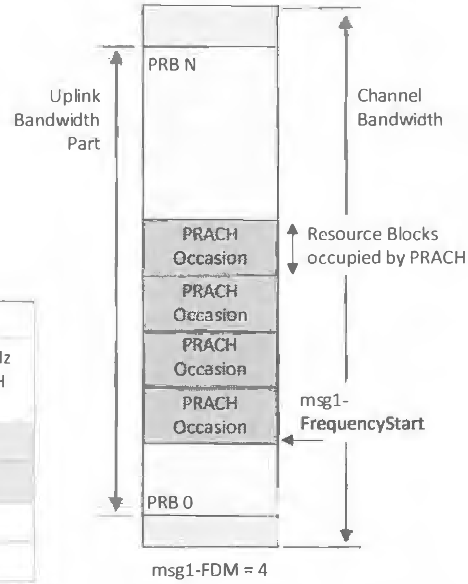


Figure 352 – Frequency multiplexing of PRACH preambles

★ A UE identifies an 'Association Period' as a minimum number of PRACH Configuration Periods which include sufficient PRACH occasions to allow every SS/PBCH beam to be mapped onto the set of PRACH occasions at least once. The number of PRACH Configuration Periods which can belong to an Association Period depends upon the PRACH Configuration Period. The set of permitted values is presented in Table 256. The Association Period and the PRACH Configuration Period have maximum durations of 160 ms

★ For example, if there are 24 PRACH occasions within a 20 ms PRACH Configuration Period, and if there 64 SS/PBCH beams with each beam configured to require 1 PRACH occasion then the Association Period is 80 ms (4 PRACH Configuration Periods). The 80 ms Association Period includes 4 × 24 = 96 PRACH occasions but only 64 of these PRACH occasions are mapped onto SS/PBCH beams. The remaining 32 PRACH occasions are not used by the PRACH

PRACH Configuration Period	Association Period
10 ms	{1, 2, 4, 8, 16} PRACH Configuration Periods
20 ms	{1, 2, 4, 8} PRACH Configuration Periods
40 ms	{1, 2, 4} PRACH Configuration Periods
80 ms	{1, 2} PRACH Configuration Periods
160 ms	1 PRACH Configuration Period

Table 256 – Permitted Association Periods for each PRACH Configuration Period

★ As a second example, assume there are 48 PRACH occasions within a 20 ms PRACH Configuration Period, and if there are 32 SS/PBCH beams with each beam configured to share a PRACH occasion with another beam, then the Association Period is 20 ms (1 PRACH Configuration Period). The 20 ms Association Period includes 1 × 48 = 48 PRACH occasions so each SS/PBCH beam is mapped 3 times within the Association Period and there are no unused PRACH occasions

★ Figure 353 illustrates an example with 24 PRACH occasions within a 10 ms Association Period and 10 SS/PBCH beams. It is assumed that *ssb-perRACH-Occasion* = 1 so the set of 24 PRACH occasions allow 2 cycles of the 10 SS/PBCH beams with 4 PRACH occasions unused

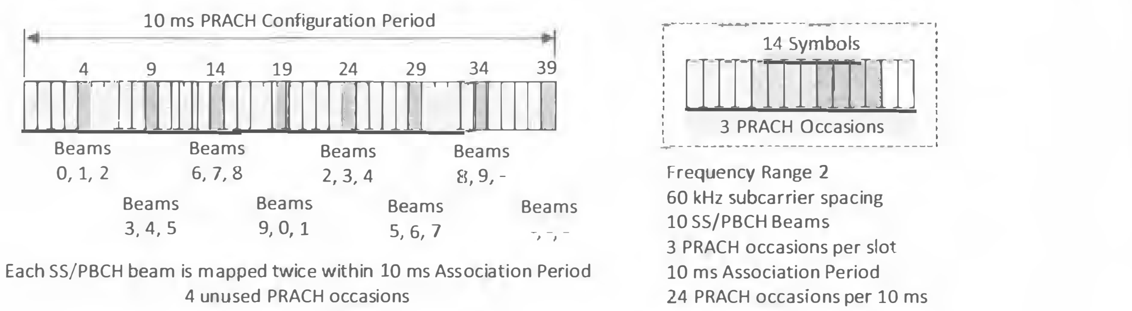


Figure 353 – Example mapping of SS/PBCH beams onto PRACH occasions within a 10 ms Association Period

★ Some PRACH occasions may not be valid if they collide with SS/PBCH Blocks or other downlink transmissions. This can cause the Association Period to change over time, and to consequently generate a pattern of Association Periods. 3GPP TS 38.413 specifies that a pattern of Association Periods must repeat with a maximum period of 160 ms. This repetition period is known as an Association Pattern Period

★ Figure 354 illustrates an example of a 160 ms Association Pattern Period. In this example, the PRACH Configuration Period is 10 ms and the SS/PBCH Block transmission period is 80 ms. It is assumed that there are no valid Random Access occasions during radio frames that include SS/PBCH Block transmissions. It is also assumed that the uplink/downlink transmission pattern leads to even numbered radio frames having 8 Random Access occasions, and odd numbered radio frames having 6 Random Access occasions

★ It is further assumed that there are 8 SS/PBCH beams and that the number of SS/PBCH beams per Random Access occasion is 1. This means that each Association period requires a minimum of 8 Random Access occasions. The first Association Period is 40 ms and includes 20 Random Access Occasions. There are sufficient Random Access occasions to serve all SS/PBCH beams after 30 ms but Table 256 indicates that the Association Period must be 1, 2, 4, 8 or 16 PRACH Configuration Periods. The Association Period of 40 ms allows each SS/PBCH beam to be served twice, with 4 unused Random Access occasions at the end of the period

★ The next Association Period is only 10 ms because the next PRACH Configuration Period includes 8 Random Access occasions which are sufficient to serve all SS/PBCH beams. The Association Periods continue to vary throughout the 160 ms time window. At the end of the 160 ms time window, there is a single PRACH Configuration Period with 6 Random Access occasions. These are insufficient to serve all 8 SS/PBCH beams so they are left unused. The Association Pattern then repeats during the next 160 ms

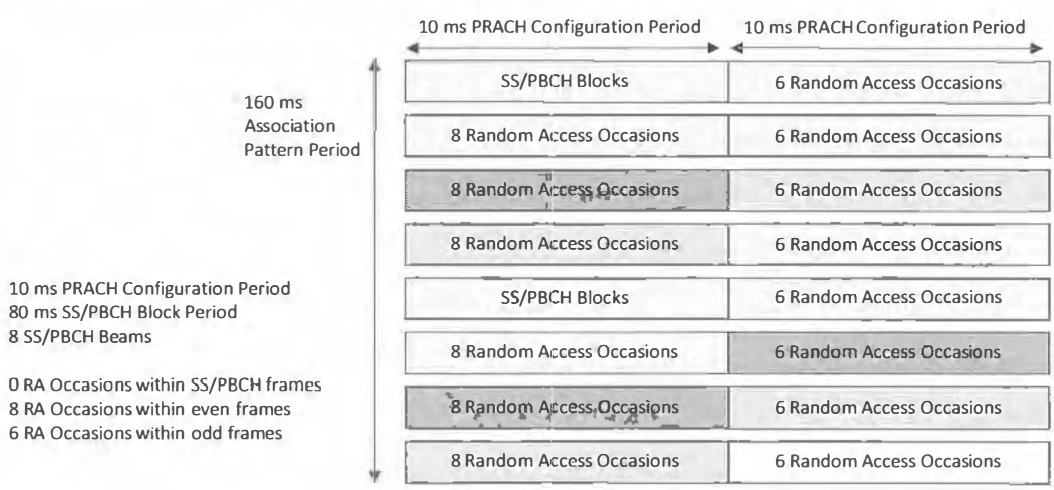


Figure 354 – Example of an Association Pattern Period

★ A UE determines the PRACH preamble transmit power using an open loop power control calculation based upon a downlink path loss measurement. The MAC layer completes the first part of the calculation using the following expression:

$$\text{PREAMBLE\_RECEIVED\_TARGET\_POWER} = \textit{preambleReceivedTargetPower} + \text{DELTA\_PREAMBLE} + (\text{PREAMBLE\_POWER\_RAMPING\_COUNTER} - 1) \times \textit{preamblePowerRampingStep}$$

★ *preambleReceivedTargetPower* is provided to the UE within the *RACH-ConfigCommon* parameter structure shown in Table 255. Its minimum value of -202 dBm is significantly lower than a normal received power level. This extremely low value has been specified to cater for Supplemental Uplink scenarios which involve the UE measuring the downlink path loss in one band and transmitting the uplink PRACH in another band. For example, a UE could measure the downlink path loss at 70 GHz while configured to transmit the PRACH using a Supplemental Uplink at 700 MHz. In this case, the downlink path loss measured at 70 GHz is significantly greater than the uplink path loss at 700 MHz. The combination of air-interface propagation loss and building penetration loss could be more than 70 dB higher at 70 GHz when compared to compared to 700 MHz. Configuring a very low value for the preamble received target power helps to ensure that the UE transmits at a power level which is appropriate for the lower operating band. The Base Station will then receive a 'normal' uplink power because the very low target power has compensated for the path loss difference

★ DELTA_PREAMBLE represents a power offset which adjusts the PRACH Preamble received power requirement according to the PRACH sequence duration. Its value is extracted from a look-up table standardised by 3GPP within TS 38.321. This look-up table is shown in Table 257. Preamble Format 0 has a sequence which spans 800 μs and is used as the baseline. The sequences belonging to Preamble Format 1 span 1600 μs so the received target power is reduced by 3 dB. Similarly, the sequences belonging to Preamble Formats 2 and 3 span 3200 μs and 800 μs so power offsets of 6 dB and 0 dB are applied

★ The same principle is applied for the short PRACH Preamble Formats. For example, the sequence belonging to PRACH Preamble Format A1 occupies $2 \times 2048 \times T_S = 133.33$ μs when using the 15 kHz subcarrier spacing. Comparing this result to the duration of Preamble Format 0 generates a ratio of $10 \times \text{LOG}(800 / 133.33) = 8$ dB. An additional 3 dB is added each time the subcarrier spacing doubles due to the time duration halving

Preamble Format	DELTA_PREAMBLE
0	0 dB
1	-3 dB
2	-6 dB
3	0 dB

Preamble Format	DELTA_PREAMBLE
A1	$8 + 3\mu$ dB
A2	$5 + 3\mu$ dB
A3	$3 + 3\mu$ dB
B1	$8 + 3\mu$ dB
B2	$5 + 3\mu$ dB
B3	$3 + 3\mu$ dB
B4	3μ dB
C0	$11 + 3\mu$ dB
C2	$5 + 3\mu$ dB

Table 257 – 3GPP specified values for DELTA_PREAMBLE

★ A UE maintains two counters when transmitting a series of PRACH preambles: PREAMBLE_TRANSMISSION_COUNTER and PREAMBLE_POWER_RAMPING_COUNTER. The former is used to limit the total number of PRACH preamble transmissions within a single Random Access procedure, whereas the latter is used to control the ramping of the PRACH Preamble transmit power (visible within the equation shown above). Figure 355 illustrates the logic applied to maintain these counters. Both counters are initialised with a value of 1 at the start of the random access procedure.

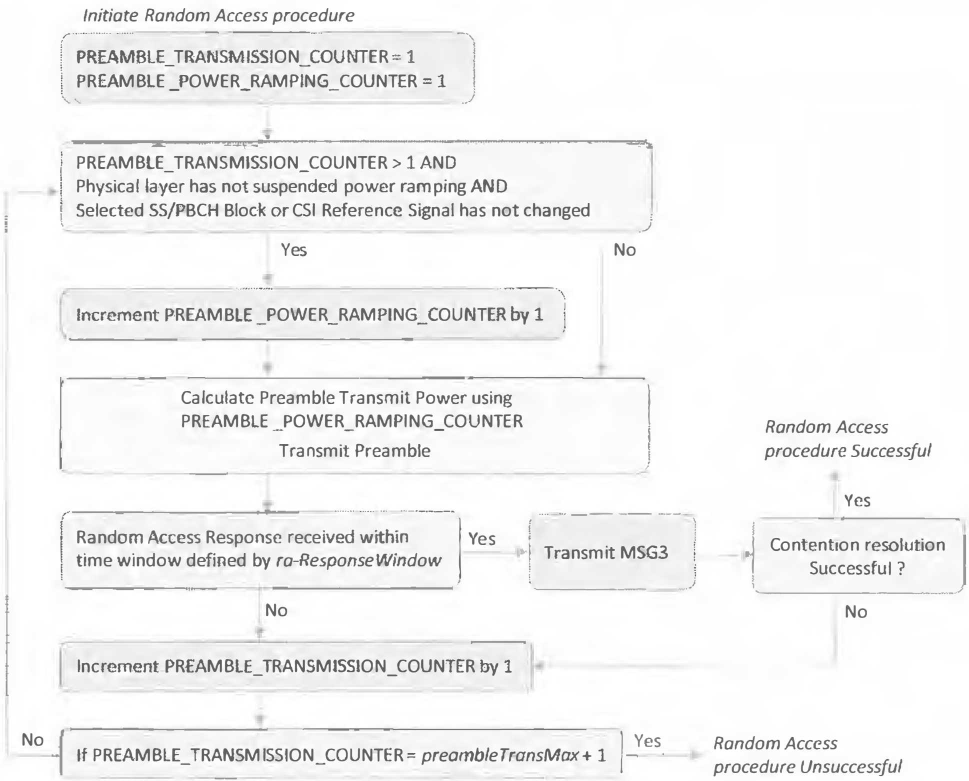


Figure 355 – Use of PREAMBLE_TRANSMISSION_COUNTER and PREAMBLE_POWER_RAMPING_COUNTER

★ PREAMBLE_POWER_RAMPING_COUNTER is incremented prior to calculating the PRACH Preamble transmit power if three conditions are satisfied. The first condition verifies that a PRACH preamble has already been transmitted at least once, i.e. a counter value of 1 is used for the first transmission. The second condition checks whether or not the Physical layer has provided an instruction to suspend power ramping. The Physical layer suspends power ramping if the UE changes its uplink transmit beam. The Physical layer can also suspend power ramping if the uplink transmit power is restricted by other transmissions, e.g. due to uplink power being allocated to LTE when using the Non-Standalone Base Station architecture. The third condition checks whether or not the UE has selected another Base Station beam, i.e. the UE has selected another SS/PBCH Block

★ PREAMBLE_TRANSMISSION_COUNTER is incremented if a Random Access Response has not been received within the time window defined by *ra-ResponseWindow*, i.e. it is assumed that the Base Station has not received the PRACH Preamble so another attempt is required if the maximum number of permitted attempts has not been reached. PREAMBLE_TRANSMISSION_COUNTER is also incremented if the Contention Resolution phase of the Random Access procedure fails

★ Returning to the calculation for PREAMBLE_RECEIVED_TARGET_POWER, *preamblePowerRampingStep* can be configured with either a 'normal' value or a 'high priority' value. The 'normal' value is provided to the UE within the *RACH-ConfigCommon* parameter structure shown in Table 255 (*powerRampingStep* parameter). The 'high priority' value can be used to override the 'normal' value when it is necessary to minimise latency, i.e. the 'high priority' step size can be configured with a higher value to allow more rapid power ramping

★ The 'high priority' value is provided to the UE using the *RA-Prioritization* parameter structure shown in Table 258, i.e. *powerRampingStepHighPriority*. This parameter structure can be used when configuring the UE for Beam Failure Recovery or when providing the UE with Contention Free Random Access resources

RA-Prioritization	
powerRampingStepHighPriority	0, 2, 4, 6 dB
scalingFactorBI	0, 0.25, 0.5, 0.75

Table 258 – RA-Prioritization parameter structure

★ Once, the MAC layer has calculated PREAMBLE_RECEIVED_TARGET_POWER, the result is passed to the Physical layer which then calculates the PRACH preamble transmit power for transmission occasion 'i' using uplink bandwidth part 'b', carrier 'f' and serving cell 'c', according to:

$$P_{RACH,b,f,c}(i) = \text{MIN}\{\, P_{CMAX,f,c}(i),\ \text{PREAMBLE\_RECEIVED\_TARGET\_POWER} + \text{Path\_Loss}_{b,f,c} \,\}\ \text{dBm}$$

★ $P_{CMAX,f,c}$ is the configured maximum UE transmission power. The UE calculates $Path\_Loss_{b,f,c}$ as *referenceSignalPower* – RSRP, where *referenceSignalPower* is provided by the Base Station, e.g. using *ss-PBCH-BlockPower* within SIB1 when using an SS/PBCH Block as a reference signal. Layer 3 filtering is applied to the RSRP measurement before calculating the path loss

★ The UE also calculates an RA-RNTI which is subsequently used to address the UE on the PDCCH when allocating the PDSCH resources for the Random Access Response. The RA-RNTI is calculated according to the following expression:

$$\text{RA-RNTI} = 1 + \text{s\_id} + (14 \times \text{t\_id}) + (14 \times 80 \times \text{f\_id}) + (14 \times 80 \times 8 \times \text{ul\_carrier\_id})$$

First Symbol belonging to PRACH (0 to 13)

First Slot belonging to PRACH (0 to 79)

PRACH Frequency Domain index (0 to 7)

Carrier Identity
Normal Uplink Carrier: 0
Supplemental Uplink : 1

★ The RA-RNTI is calculated based upon time domain and frequency domain indices associated with the PRACH occasion. It is not dependent upon the selected PRACH Preamble. This means that all UE using the same PRACH occasion will calculate the same RA-RNTI, i.e. they all decode the same PDCCH and the same corresponding PDSCH. The equation shown above generates an RA-RNTI within the range from 1 to 17920

★ The UE then proceeds to transmit the PRACH Preamble using the selected PRACH occasion and the calculated transmit power. The Random Access Response window (defined by *ra-ResponseWindow*) starts from the first Random Access Response CORESET that follows the end of the PRACH Preamble transmission by at least one symbol. The Random Access Response CORESET is identified using the Type 1 Common Search Space (CSS) configuration (defined by *ra-SearchSpace*). The UE monitors this CORESET for a DCI Format 1_0 which has its CRC bits scrambled by the RA-RNTI

★ If the Random Access Response window expires before the UE receives a DCI Format 1_0, the UE transmits another preamble using the logic presented in Figure 355

★ If the UE receives a DCI Format 1_0 which has its CRC bits scrambled by the RA-RNTI, the UE proceeds to decode the Transport Block (MAC PDU) within the corresponding PDSCH resource allocation. The MAC PDU can include up to three different types of MAC sub-PDU. The first is used to specify a Back-Off Indicator, the second is used to acknowledge a request for On-demand System Information, and the third is used to provide a Random Access Response. The structure of these MAC sub-PDU within a MAC PDU is illustrated in Figure 356

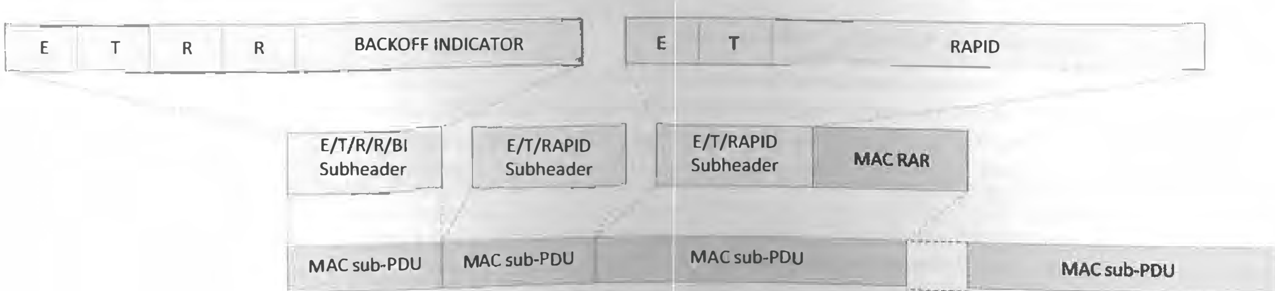


Figure 356 – Structure of MAC PDU for Random Access Response

★ At this point, the UE is addressed by its Random Access Preamble Identity (RAPID). The RAPID field occupies 6 bits which provide a range from 0 to 63, i.e. corresponding to the set of 64 PRACH Preambles within the PRACH occasion identified by the RA-RNTI. If contention has occurred and multiple UE have selected the same PRACH Preamble, then multiple UE will have the same RAPID value

★ Figure 357 illustrates the structure of each MAC subheader and the Random Access Response. The Back-Off Indicator subheader is not addressed to a specific RAPID. All UE store the value of the Back-Off Indicator if it is included within the MAC PDU. This does not mean that all UE will use the Back-Off Indicator – only those UE which do not receive a MAC subheader with a matching RAPID will be required to apply the Back-Off Indicator before transmitting another PRACH Preamble. The Back-Off Indicator is used to help manage congestion during periods of high load. Table 259 presents the set of Back-Off values standardised by 3GPP

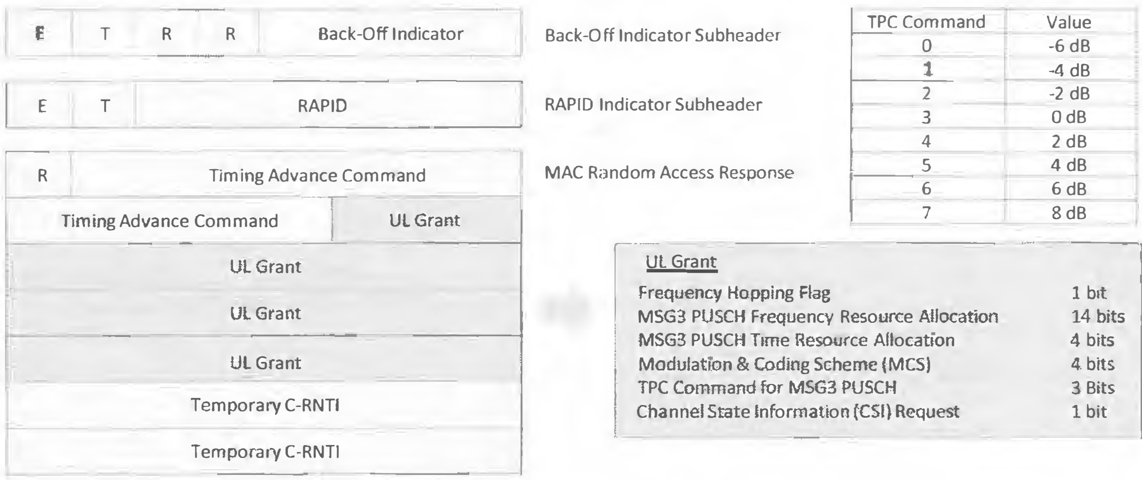


Figure 357 – Structure of MAC Subheaders and MAC Random Access Response

Index	Back-Off	Index	Back-Off	Index	Back-Off	Index	Back-Off
0	5 ms	4	40 ms	8	160 ms	12	960 ms
1	10 ms	5	60 ms	9	240 ms	13	1920 ms
2	20 ms	6	80 ms	10	320 ms	14	Reserved
3	30 ms	7	120 ms	11	480 ms	15	Reserved

Table 259 – 3GPP standardised Back-Off values

★ The 'Extension' (E) field is used to indicate that the MAC PDU includes another MAC sub-PDU. The 'Type' (T) field is used to differentiate between MAC subheaders which include the Back-Off Indicator and MAC subheaders which include the RAPID field

★ The MAC sub-PDU which includes a RAPID field but does not include a Random Access Response (RAR) is used to acknowledge a Physical layer request for On-demand System Information (in contrast to an *RRCSystemInfoRequest* at Layer 3). In this case, the UE knows that it should not expect a Random Access Response to follow the MAC subheader

★ The MAC sub-PDU which includes a Random Access Response provides the UE with a Timing Advance Command, an Uplink Grant and a Temporary C-RNTI (TC-RNTI). The Timing Advance Command is used to synchronise the uplink transmission timing of the UE at the Base Station receiver, i.e. to compensate for propagation delays which depend upon the UE location within the cell. Utilisation of the 12 bit Timing Advance Command is described in section 13.2

★ The Temporary C-RNTI (16 bits) is used to address the UE on the PDCCH when subsequently allocating the PDSCH resources for MSG4, i.e. during Contention Resolution

★ The Uplink Grant uses a total of 23 bits to provide an uplink resource allocation on the PUSCH for the transmission of MSG3. This avoids the requirement to allocate uplink resources using the PDCCH. The 'Frequency Hopping' flag indicates whether or not the UE should apply Frequency Hopping. When the flag indicates that Frequency Hopping is to be used, 1 or 2 bits from the 'Frequency Resource Allocation' field are used to specify the frequency offset for the 2nd hop. 1 bit is used if there are less than 50 Resource Blocks within the Bandwidth Part. Otherwise, 2 bits are used

★ The 'Frequency Resource Allocation' uses Uplink Resource Allocation Type 1, as described in section 7.4.4.2.2. The Random Access Response allocates 14 bits to the 'Frequency Resource Allocation' whereas the number of bits required by Uplink Resource Allocation Type 1 is: $\lceil LOG_2(N_{RB}^{BWP} \times (N_{RB}^{BWP} + 1) / 2 \rceil$ bits. This means that one or more bits can be ignored when the Bandwidth Part size is less than 180 Resource Blocks, i.e. $\lceil LOG_2(180 \times (181) / 2 \rceil = 14$ bits. In contrast, padding bits are added when the Bandwidth Part size is greater than 180 Resource Blocks

★ The 'Time Resource Allocation' uses a set of 4 bits to specify a pointer towards a row within a look-up table. The look-up table can be a table configured by the Base Station, or a table standardised by 3GPP. The Base Station can configure a table using the *pusch-TimeDomainAllocationList* parameter structure within *pusch-ConfigCommon*. This table is applied if it has been configured. Otherwise, the 'Default A' table standardised by 3GPP is applied. The 'Default A' look-up table is presented in Table 204 (section 7.4.4.1)

★ The 'MCS' field is limited to 4 bits so MSG3 is restricted to being allocated an MCS from the first 16 rows of the relevant MCS table. MSG3 is able to use either the '64QAM' MCS table or the '64QAM with Transform Precoding' MCS table. The value of *msg3-transformPrecoder* within *RACH-ConfigCommon* (Table 255) determines which MCS table is applied

★ The 'Transmit Power Control (TPC) Command' specifies a pointer to a row within the look-up table presented in Figure 357. This TPC Command is used when calculating the PUSCH transmit power for MSG3

★ The 'Channel State Information (CSI) Request' field is reserved when using the Contention Based Random Access procedure. This field can be used to request an aperiodic CSI report when using the Contention Free Random Access procedure

★ The UE then proceeds to transmit MSG3 on the PUSCH using the allocated resources and at the calculated transmit power. The transmit power is calculated according to the rules described in section 13.3.1. If contention has occurred and multiple UE have decoded the same uplink resource allocation then all of those UE will transmit their MSG3 using the same PUSCH resources

★ Figure 358 illustrates the structure of MSG3 when transferring a CCCH message. This is applicable to UE making the transition from RRC Idle or RRC Inactive to RRC Connected, i.e. the CCCH message can be an *RRCSetupRequest* or *RRCResumeRequest*. It is also applicable to UE re-establishing an RRC Connection and UE requesting On-demand System Information. In general, these messages have a size of 6 bytes but the *RRCResumeRequest1* message includes the full I-RNTI and has a size of 8 bytes. The header field does not include an explicit length indicator but the Logical Channel Identity (LCID) is used to indicate both the payload type and payload length. A value of '0' indicates a CCCH message with a length of 64 bits, whereas a value of '52' indicates a CCCH message with a length of 48 bits

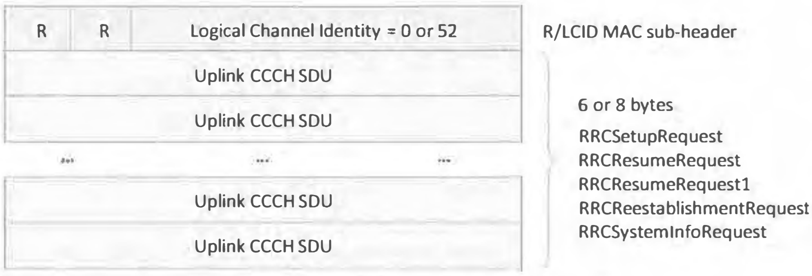


Figure 358 – MSG3 used to transfer an uplink CCCH message

★ Figure 359 illustrates the structure of MSG3 when transferring a DCCH or DTCH message. This could be applicable to a UE completing a handover procedure, i.e. the DCCH message could be an RRCReconfigurationComplete used to indicate completion of the handover (although handovers typically use the Contention Free Random Access procedure). MSG3 could include DTCH content if the Random Access procedure has been triggered by uplink data arrival while the UE is out-of-sync

★ MSG3 includes a C-RNTI MAC Control Element when used to transfer a DCCH or DTCH message. This MAC Control Element is placed at the end of the MAC PDU. In this case, Contention Resolution is based upon the C-RNTI provided by the UE within MSG3, rather than the Temporary C-RNTI provided by the Base Station within MSG2. The Logical Channel Identity (LCID) value of 58 indicates that the subsequent 2 bytes are the C-RNTI

★ The first MAC subheader illustrated in Figure 359 identifies the DCCH or DTCH logical channel. 3GPP TS 38.331 specifies default logical channel identities of 1, 2 and 3 for SRB 1, 2 and 3. Higher values can be allocated to DTCH logical channels. DCCH and DTCH payloads have variable length so the MAC subheader includes a length field which can have a length of 1 or 2 bytes (Figure 359 illustrates an example based upon 1 byte). The 'Format' (F) flag is used to indicate whether the Length field is 1 or 2 bytes

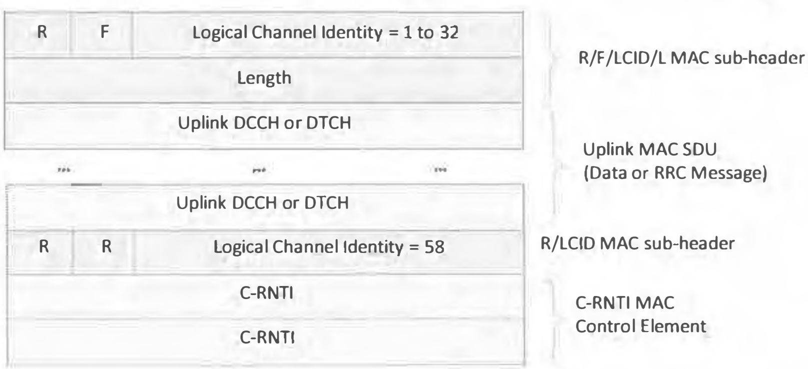


Figure 359 – MSG3 used to transfer a DTCH or DCCH message

★ The UE starts its Contention Resolution timer after the transmission of MSG3. This timer is configured within *RACH-ConfigCommon* using the *ra-ContentionResolutionTimer* parameter. It can be configured with values between 8 and 64 subframes, i.e. 8 and 64 ms. The Contention Resolution timer is maintained at the MAC layer. The RRC layer may also start a supervision timer depending upon the content of MSG3. For example, if MSG3 contained an *RRCSetupRequest* message then the RRC layer starts T300. Alternatively, if MSG3 contained an *RRCReestablishmentRequest* then the RRC layer starts T301. If MSG3 contained an *RRCResumeRequest* or *RRCResumeRequest1* then the RRC layer starts T319

★ The UE monitors the CORESET belonging to the Type 1 Common Search Space (defined by *ra-SearchSpace*) while the Contention Resolution timer is running. If the UE used MSG3 to transfer a CCCH message, then the UE attempts to decode a PDCCH transmission which has its CRC bits scrambled by the allocated Temporary C-RNTI (TC-RNTI). The UE may receive a PDCCH with a DCI Format 0_0 which allocates PUSCH resources for a re-transmission of MSG3, or the UE may decode a DCI Format 1_0 which allocates PDSCH resources for MSG4. Figure 360 illustrates the reception of DCI Format 1_0 allocating the PDSCH resources for MSG4. Section 3.5.6 presents the content of DCI Format 1_0 when the CRC bits are scrambled by a TC-RNTI

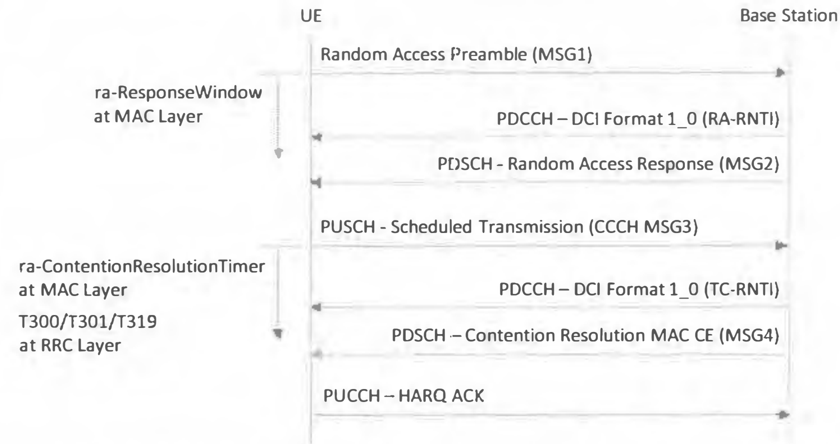


Figure 360 – Contention Based Random Access procedure – using Contention Resolution MAC CE

★ MSG4 includes the 'UE Contention Resolution Identity' MAC Control Element illustrated in Figure 361. This MAC Control Element includes the first 48 bits belonging to the uplink CCCH SDU within MSG3. The UE uses this MAC Control Element to determine whether or not the Random Access procedure has been successful. The procedure has been successful if the content of the MAC Control Element matches the content of the CCCH SDU transmitted by the UE. If the content does not match then it means that contention has occurred and the MAC Control Element is intended for a different UE. In this case, the UE returns to the transmission of PRACH Preambles (assuming the maximum number of PRACH preamble transmissions has not been reached)

R	R	Logical Channel Identity = 62	
		UE Contention Resolution Identity	6 bytes
		UE Contention Resolution Identity	
		UE Contention Resolution Identity	
		UE Contention Resolution Identity	
		UE Contention Resolution Identity	
		UE Contention Resolution Identity	

Figure 361 – UE Contention Resolution Identity MAC Control Element

★ If contention resolution is successful, the Temporary C-RNTI becomes the allocated C-RNTI. In addition, the UE uses the PUCCH to transmit a HARQ acknowledgement for MSG4. At this stage, the UE does not have dedicated PUCCH resources, so the UE relies upon a set of common resources defined by *PUCCH-ConfigCommon* provided within either SIB1 or dedicated signalling

★ If the UE used MSG3 to transfer a DCCH or DTCH message, then the UE attempts to decode a PDCCH transmission which has its CRC bits scrambled by the C-RNTI which was included in MSG3. This scenario is illustrated in Figure 362. In this case, contention resolution is successful if the UE receives a PDCCH transmission which has its CRC bits scrambled by the C-RNTI

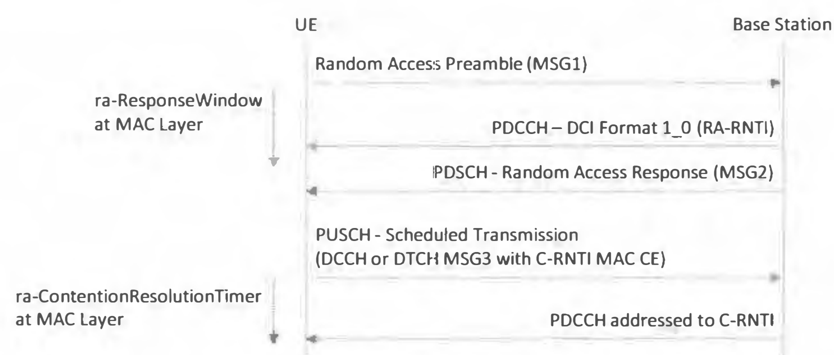


Figure 362 – Contention Based Random Access procedure – using C-RNTI for Contention Resolution

★ Figure 363 illustrates an example random access procedure which includes a re-transmission of MSG3. The Base Station triggers the re-transmission using DCI Format 0_0 to provide an uplink resource allocation on the PUSCH. The CRC bits belonging to the DCI are scrambled using the Temporary C-RNTI. The Contention Resolution timer is re-started after re-transmitting MSG3, whereas the RRC supervision timer is not re-started

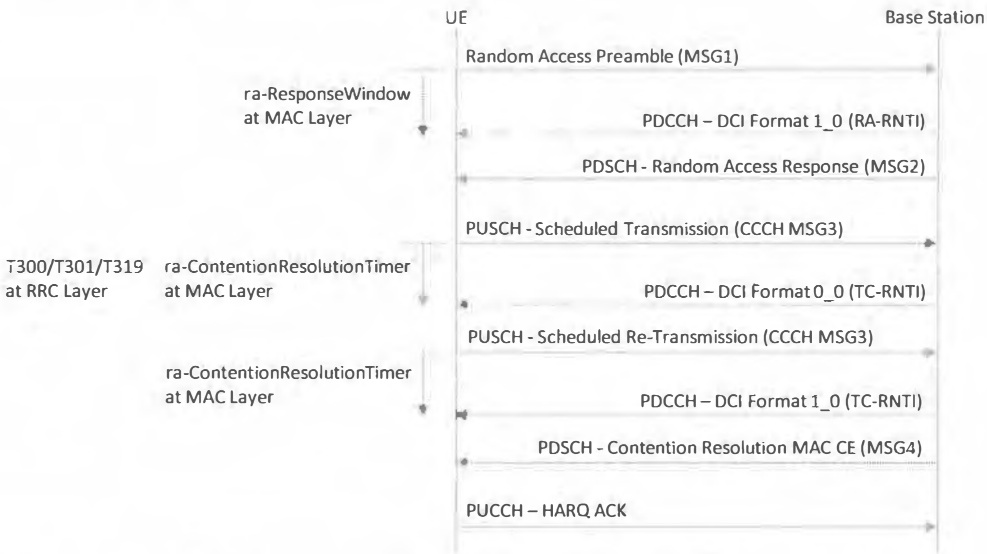


Figure 363 – Contention Based Random Access procedure with MSG3 re-transmission

★ 3GPP references: TS 38.321, TS 38.331, TS 38.213, TS 38.214, TS 38.212

13.1.2 CONTENTION FREE

★ The Contention Free Random Access procedure relies upon the Base Station providing the UE with PRACH Preamble resources. These resources can be signalled within DCI Format 1_0 on the PDCCH when initiating a PDCCH Order. The content of DCI Format 1_0 is presented in section 3.5.6. The 'Frequency Domain Resource Assignment' field is used to indicate that the DCI is being used to initiate a PDCCH Order, i.e. a value of all '1's indicates a PDCCH Order. The DCI provides the UE with a PRACH Preamble Index and a corresponding SS/PBCH Block Index

★ Figure 364 illustrates the Contention Free Random Access procedure initiated by a PDCCH Order. The PDCCH transmission used to initiate the procedure addresses the UE using its C-RNTI

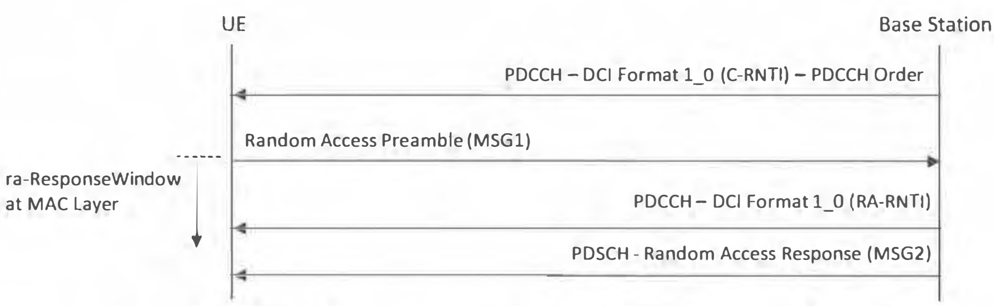


Figure 364 – Contention Free Random Access procedure initiated by a PDCCH Order

★ The UE transmits the allocated PRACH preamble as MSG1 and starts the timer for the Random Access Response window. The UE then monitors for a PDCCH transmission addressed to its RA-RNTI. If the timer expires before a PDCCH transmission is received, the UE returns to MSG1 transmission. If the receives a PDCCH transmission, the UE proceeds to decode the corresponding PDSCH and checks for a MAC sub-PDU which is addressed to the UE's Random Access Preamble Identity (RAPID). If the UE decodes a MAC sub-PDU with the appropriate RAPID then the Random Access Response is extracted. The Random Access Response includes the Timing Advance command which allows the UE to re-synchronise before transmitting on the uplink. This Random Access procedure does not require contention resolution so the procedure is categorised as successful after the reception of the Random Access Response

★ Other Contention Free Random Access procedures allow the Base Station to use the *RACH-ConfigDedicated* parameter structure shown in Table 260 to allocate the dedicated PRACH resources. This parameter structure can be provided to the UE using dedicated signalling

RACH-ConfigDedicated					
cfra	occasions	rach-ConfigGeneric	prach-ConfigurationIndex	0 to 255	
			msg1-FDM	1, 2, 4, 8	
			msg1-FrequencyStart	0 to 274	
			zeroCorrelationZoneConfig	0 to 15	
			preambleReceivedTargetPower	-202 to -60, step 2 dBm	
			preambleTransMax	3, 4, 5, 6, 7, 8, 10, 20, 50, 100, 200	
			powerRampingStep	0, 2, 4, 6 dB	
			ra-ResponseWindow	1, 2, 4, 8, 10, 20, 40, 80 slots	
		ssb-perRACH-Occasion	1/8, 1/4, 1/2, 1, 2, 4, 8, 16		
	resources	CHOICE			
		ssb			
		ssb-ResourceList	SEQUENCE {1 to 64 instances}		
			ssb	0 to 63	
			ra-PreambleIndex	0 to 63	
		ra-ssb-OccasionMaskIndex	0 to 15		
		csirs			
		csirs-ResourceList	SEQUENCE {1 to 96 instances}		
			csi-RS	0 to 95	
			ra-OccasionList	SEQUENCE {1 to 64 instances}	
				0 to 511	
			ra-PreambleIndex	0 to 63	
		rsrp-ThresholdCSI-RS	0 to 127		
	totalNumberOfRA-Preambles-v1530	1 to 63			
ra-Prioritization	powerRampingStepHighPriority	0, 2, 4, 6 dB			
	scalingFactorBI	0, 0.25, 0.5, 0.75			

Table 260 – *RACH-ConfigDedicated* parameter set

★ *RACH-ConfigDedicated* can be used to provide the UE with a relatively large set of parameters associated with the Random Access procedure. This is necessary because the UE may be required to complete the Random Access procedure without having an opportunity to decode SIB1. For example, the Base Station may provide this information to the UE within an *RRCReconfiguration* message during a handover procedure. In this case, the UE can complete the Random Access procedure with the target cell without having to first decode System Information

★ *rach-ConfigGeneric* appears within both *RACH-ConfigDedicated* and *RACH-ConfigCommon*. This parameter structure defines the set of time and frequency resources allocated to the set of PRACH occasions. It also specifies power control parameters and the Random Access Response window. *RACH-ConfigDedicated* includes the *ssb-perRACH-Occasion* parameter, whereas *RACH-ConfigCommon* includes the *ssb-perRACH-OccasionAndCB-PreamblesPerSSB* parameter. Both parameters allow the UE to link the set of PRACH occasions to the set of SS/PBCH Blocks

★ *RACH-ConfigDedicated* includes a *resources* section which allocates the dedicated PRACH preamble(s) to the UE. This section allows the Base Station to allocate a dedicated PRACH preamble for each SS/PBCH Block beam or each CSI Reference Signal beam. The Base Station does not have advance knowledge of which beam will be selected by the UE for the Random Access procedure so it is necessary to allocate dedicated preambles for each candidate beam

★ Figure 365 illustrates the Contention Free Random Access procedure initiated by an *RRCReconfiguration* message. After the initial trigger, this procedure is similar to the procedure triggered by a PDCCH Order

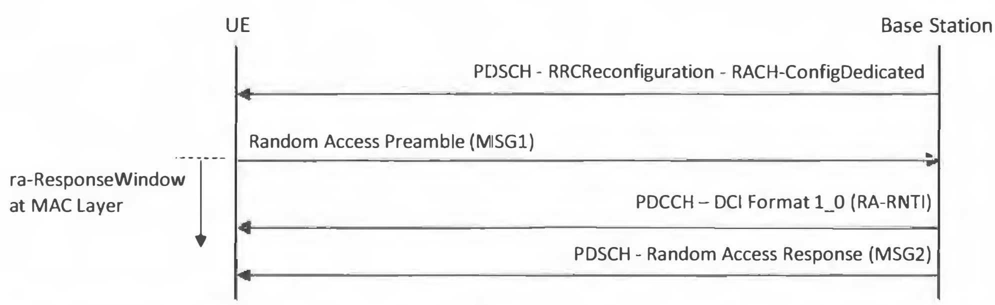


Figure 365 – Contention Free Random Access procedure initiated by an *RRCReconfiguration* message

★ Figure 366 illustrates the Contention Free Random Access procedure initiated by Beam Failure Recovery. In this case, the Base Station is unable to allocate dedicated PRACH resources immediately before the procedure because the Base Station is unable to contact the UE once Beam Failure has occurred. This means that the Base Station provides the dedicated PRACH resources in advance in case Beam Failure is experienced at a later time. The dedicated PRACH resources are provided by including the *BeamFailureRecovery Config* parameter structure within an *RRCReconfiguration* message (or alternatively, within an *RRCSetup* or *RRCResume* message)

- In the case of Beam Failure Recovery, the Base Station responds to the PRACH preamble by sending a PDCCH transmission which addresses the UE by its C-RNTI (instead of using an RA-RNTI). The Random Access procedure is then categorised as successful without the requirement to decode a Random Access Response within a MAC sub-PDU

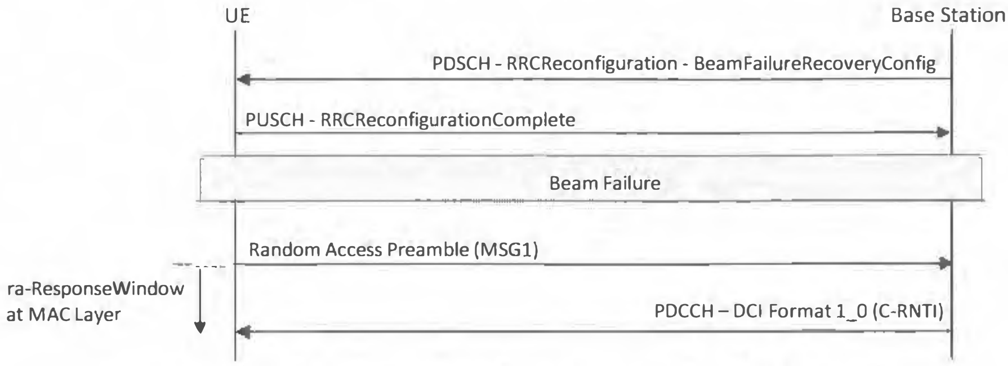


Figure 366 – Contention Free Random Access procedure initiated by Beam Failure Recovery

- The Contention Free Random Access procedure includes an RSRP check to ensure that the beams for which the UE has been provided dedicated PRACH preambles have sufficient strength. The UE reverts to using the Contention Based Random Access procedure if none of the beams with dedicated PRACH preambles exceed the RSRP threshold. The RSRP threshold is defined by *rsrp-ThresholdSSB* when selecting an SS/PBCH Block associated with a dedicated preamble. This information element can be provided using either the *BeamFailureRecoveryConfig* or the *RACH-ConfigCommon* parameter structures. The RSRP threshold is defined by *rsrp-ThresholdCSI-RS* when selecting a CSI Reference Signal associated with a dedicated preamble. This information element can be provided using the *RACH-ConfigDedicated* parameter structure

- 3GPP references: TS 38.321, TS 38.331, TS 38.213, TS 38.214, TS 38.212

13.1.3 PRIORITISED RANDOM ACCESS

- Prioritised Random Access has been standardised for:
  - Handover procedures using Contention Free Random Access
  - Beam Failure Recovery procedures

- Prioritised Random Access is achieved by increasing the rate at which the PRACH preamble transmit power is increased during power ramping, i.e. by increasing the step size. It also allows a reduction of the Back-off Indicator included within MSG2, i.e. allowing the UE to re-attempt PRACH preamble transmission sooner

- The *RA-Prioritization* parameter structure presented in Table 261 can be included within either *RACH-ConfigDedicated* or *BeamFailureRecoveryConfig*. The value of *powerRampingStepHighPriority* replaces the value of *powerRampingStep*, while the value of *scalingFactorBI* is multiplied by the value of the Back-off Indicator within MSG2

RA-Prioritization	
powerRampingStepHighPriority	0, 2, 4, 6 dB
scalingFactorBI	0, 0.25, 0.5, 0.75

Table 261 – RA-Prioritization parameter structure

- 3GPP references: TS 38.321, TS 38.331

13.2 TIMING ADVANCE

- Timing Advance is used to control the uplink transmission timing of individual UE. It is primarily applicable to the PUSCH, PUCCH and Sounding Reference Signal (SRS). The PRACH is restricted to using a static Timing Advance because the UE transmits the PRACH preambles before the Base Station is able to provide any timing instructions
- Timing Advance helps to ensure that uplink transmissions from all UE are synchronised when received by the Base Station. Inter-symbol interference can be avoided if all uplink transmissions are received with a time spread which is less than the duration of the cyclic prefix. Within this context, the set of uplink transmissions received by the Base Station is analogous to a set of multipath components belonging to a single uplink transmission, i.e. the set of multi-path components must have a delay spread smaller than the cyclic prefix to avoid inter-symbol interference
- The general concept of Timing Advance is shown in Figure 367. The UE furthest from the Base Station requires a larger Timing Advance to compensate for the larger propagation delay, i.e. UE 1 starts transmitting earlier than UE 2

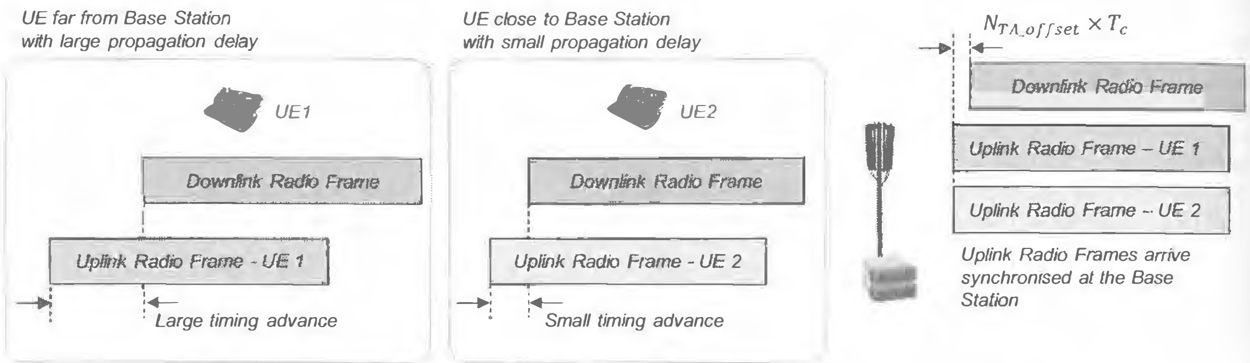


Figure 367 – General concept of Timing Advance and uplink / downlink radio frame timing

- Figure 368 illustrates the radio frame timing for the two UE shown in Figure 367. The downlink radio frame arrives at the UE furthest from the Base Station relatively late as a result of the larger propagation delay. This figure illustrates that the Timing Advance equals (2 × propagation delay) + $N_{TA\_offset} \times T_c$

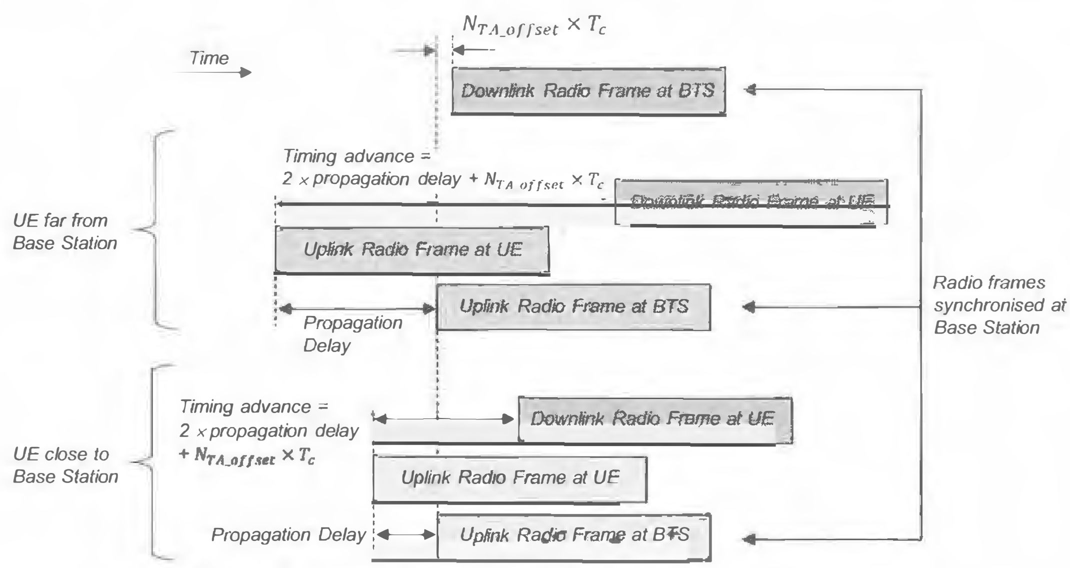


Figure 368 – Uplink / downlink radio frame timing from the UE and gNode B perspectives

- The inclusion of $N_{TA\_offset} \times T_c$ has been specified to ensure that an uplink radio frame finishes before the start of the subsequent downlink radio frame. A TDD Base Station requires this margin to allow for the delay associated with activating its transmitter. 3GPP TS 38.104 specifies that a Base Station is permitted 10 µs for activation in Frequency Range 1, and 3 µs for activation in Frequency Range 2. The margin is also used to avoid BTS to BTS interference which could result from non-ideal BTS synchronisation, i.e. to avoid one Base Station starting to transmit while a neighbouring Base Station is still receiving. 3GPP TS 38.133 specifies that the maximum allowed timing error for Base Stations with overlapping coverage is 3 µs
- 3GPP TS 38.133 specifies the set of N_{TA_offset} values presented in Table 262. Values are specified for both Frequency Ranges, both duplexing modes and both LTE coexistence scenarios. N_{TA_offset} has units of T_c which is given by 1 / (480 000 × 4096) seconds

Frequency Range	Coexistence with LTE	Duplex Mode	$N_{TA\ offset}$	$N_{TA\ offset} \times T_c$
FR1	No	FDD	25600	13 μs
		TDD		
	Yes	FDD	0	0 μs
		TDD	39936	20 μs
FR2	No	TDD	13792	7 μs

Table 262 – Values for N_{TA_offset}

★ N_{TA_offset} is applied to both FDD and TDD when deployments do not involve coexistence with LTE. The preceding arguments regarding Base Station transmitter activation delay and BTS to BTS interference only apply to TDD. N_{TA_offset} is also applied to FDD to ensure that uplink transmissions are time synchronised when using FDD/TDD Carrier Aggregation

★ Deployments which involve coexistence with LTE, e.g. Dynamic Spectrum Sharing (DSS), adopt the offsets used by LTE, i.e. 0 for FDD and 39936 T_c for TDD. In the case of LTE, 3GPP TS 36.211 specifies the TDD Timing Advance offset as 624 T_s, where T_s is given by 1 / (15 000 × 2048) seconds. Converting the units of T_s to T_c leads to 624 × (480 000 × 4096) / (15 000 × 2048) = 39936, i.e. the figure presented in Table 262. In the case of FDD/TDD Carrier Aggregation, the value of 39936 can be configured for both the FDD and TDD carriers to keep the uplink transmissions time synchronised

★ The operating bands belonging to Frequency Range 2 only support TDD, and coexistence with LTE is not required (LTE is only deployed in Frequency Range 1). The value specified for N_{TA_offset} provides 1 μs of margin above the sum of the 3 μs Base Station transmitter activation delay and the 3 μs BTS to BTS synchronisation accuracy

★ The *n-TimingAdvanceOffset* information element presented in Table 263 is used to instruct the UE to apply a specific value for N_{TA_offset}. This information element can be broadcast within SIB1 or provided using dedicated signalling. The UE assumes a default value of 25600 for Frequency Range 1 if the Base Station does not provide a value. It is not necessary to signal a value for Frequency Range 2 because 13792 is the only supported value

extract from *ServingCellConfigCommonSIB* or *ServingCellConfigCommon*	
n-TimingAdvanceOffset	n0, n25600, n39936

Table 263 – Information element used to signal N_{TA_offset}

★ The Timing Advance applied by a UE is given by:

$$T_{TA} = (N_{TA} + N_{TA\_offset}) \times T_c \quad \text{where, } T_c = 1 / (480\,000 \times 4096)$$

★ The value of N_{TA_offset} is applied when transmitting PRACH preambles but N_{TA} is set to 0

★ A UE receives its first Timing Advance command within the Random Access Response (MSG2). A set of 12 bits is used to provide a value within the range from 0 to 3846. This value corresponds to T_A which is then used to calculate N_{TA} according to:

$$N_{TA} = T_A \times 16 \times 64/2^{\mu} \quad \text{where, } \mu \text{ is the subcarrier spacing index (0, 1, 2 or 3 for 15, 30, 60 or 120 kHz)}$$

★ Inclusion of the subcarrier spacing index means that Timing Advance uses a time resolution which is proportional to the subcarrier spacing. This is aligned with the requirement to synchronise all uplink transmissions to have a delay spread which is less than the duration of the cyclic prefix, i.e. the cyclic prefix has a shorter duration for the higher subcarrier spacings so Timing Advance must operate with an increased resolution

★ As indicated by Figure 368, $N_{TA} \times T_c$ corresponds to the round trip propagation delay between the UE and Base Station. This means that the maximum value of N_{TA} defines the maximum supported cell range. Table 264 presents the maximum cell range associated with each numerology from the perspective of Timing Advance (note that the cell range is also limited by other factors, e.g. PRACH Format, PRACH Zero Correlation Zone and TDD guard period between downlink and uplink transmissions)

Subcarrier Spacing	μ	Timing Advance Step Size ($N_{TA} \times T_c$)		Maximum Timing Advance (T_A = 3846)	
		Time Domain	Equivalent Distance	Time Domain	Maximum Cell Range
15 kHz	0	520.83 ns	78.13 m	2.00 ms	300 km
30 kHz	1	260.42 ns	39.06 m	1.00 ms	150 km
60 kHz	2	130.21 ns	19.53 m	0.50 ms	75 km
120 kHz	3	65.10 ns	9.77 m	0.25 ms	37.5 km

Table 264 – Maximum cell range calculated from the maximum Timing Advance

★ It is necessary to maintain Timing Advance after a connection has been established, i.e. as a UE moves around a cell and the propagation delay changes over time. Timing Advance is maintained using the Timing Advance MAC Control Element which can be included as part of the MAC header. The structure of the Timing Advance MAC Control Element is illustrated in Figure 369

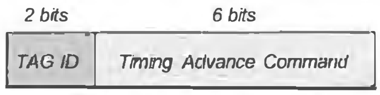


Figure 369 – Timing Advance command MAC Control Element

★ The Timing Advance MAC Control Element includes a 6 bit Timing Advance command (T_A) which provides a range from 0 to 63. This Timing Advance command is used to adjust the existing Timing Advance, i.e. the Timing Advance command provided during the Random Access procedure is an absolute timing advance, whereas the subsequent Timing Advance commands provided within the MAC Control Elements are relative. The value of N_{TA} is updated using the following equation:

$$N_{TA\_new} = N_{TA\_old} + (T_A - 31) \times 16 \times 64/2^{\mu}$$

★ Subtracting '31' from the value of T_A allows the Base Station to shift the Timing Advance in both positive and negative directions. The maximum correction is 16.67 μs which corresponds to 2.5 km when using the 15 kHz subcarrier spacing, and 2.08 μs which corresponds to 313 m when using the 120 kHz subcarrier spacing

★ The Base Station requires uplink transmissions from the UE to maintain Timing Advance. Uplink transmissions allow the Base Station to measure the existing timing and consequently determine whether or not any correction is required. Uplink transmissions on the PUSCH, PUCCH or SRS can be used for this purpose. For example, if the UE is configured to provide periodic CSI reports on the PUCCH then those periodic transmissions can be used to maintain Timing Advance. A specific Base Station implementation may send event driven Timing Advance commands when the uplink timing error exceeds a specific threshold, or the Base Station may send periodic Timing Advance commands

★ Figure 369 illustrates that the first 2 bits belonging to the Timing Advance command address the relevant Timing Advance Group (TAG). A TAG is a group of cells which share the same uplink transmission timing, i.e. they share the same downlink timing reference and the same Timing Advance commands. Cells belonging to different TAG are likely to be geographically separated and consequently have different air-interface propagation delays. A UE can be configured with up to 4 TAG belonging to the Master Cell Group (MCG) and up to 4 TAG belonging to the Secondary Cell Group (SCG). Table 265 presents the parameter set used to configure a TAG for a specific MCG or SCG

TAG-Config		
tag-ToReleaseList	SEQUENCE {1 to 4 instances}	
	tag-Id	0 to 3
tag-ToAddModList	SEQUENCE {1 to 4 instances}	
	tag-Id	0 to 3
	timeAlignmentTimer	500, 750, 1280, 1920, 2560, 5120, 10240 ms, infinity

Table 265 – Parameter set used to configure a Timing Advance Group (TAG)

★ Individual serving cells are linked to a specific TAG by including the '*tag-Id*' within the *ServingCellConfig* parameter structure. The TAG which includes the primary serving cell is known as the Primary TAG (PTAG), whereas other TAG are known as Secondary TAG (STAG). The PTAG is always allocated '*tag-Id*' = 0

★ The *timeAlignmentTimer* configured for each TAG defines the maximum time that a UE can remain uplink synchronised without having received a Timing Advance command from the Base Station, i.e. the UE assumes that it has lost uplink synchronisation if this timer expires. The timer for a specific TAG is restarted each time the UE receives a Timing Advance command for that TAG

★ If the *timeAlignmentTimer* expires for the Primary TAG, then all HARQ buffers are flushed, all PUCCH and SRS configurations are released and all uplink and downlink resource allocations are cleared. In this case, the UE is not permitted to transmit towards any serving cell until the random access procedure has been used to re-synchronise

★ If the *timeAlignmentTimer* expires for a Secondary TAG, a similar set of actions are taken but only for that specific TAG rather than for all TAG. The random access procedure has to be used to re-synchronise with the Base Station before transferring any further data with the relevant serving cells

★ Small cells which have limited cell range are able to operate without Timing Advance. In this case, the maximum round trip propagation delay is always less than the duration of the cyclic prefix. For example, when using the 15 kHz subcarrier spacing, the cyclic prefix has a duration of 4.69 μs which could absorb propagation delay variations resulting from a 700 meter cell range. Similarly, when using the 120 kHz subcarrier spacing, the cyclic prefix has a duration of 0.59 μs which could absorb propagation delay variations resulting from an 88 meter cell range

★ 3GPP References: TS 38.133, TS 38.211, TS 38.213, TS 38.321, TS 38.331

13.3 UPLINK POWER CONTROL

★ The main objectives of uplink power control are to limit both intracell and intercell interference, and to reduce UE power consumption

★ 3GPP TS 38.213 specifies uplink power control separately for the PUSCH, PUCCH, PRACH and Sounding Reference Signal. Power control for the PRACH is described in section 13.1

13.3.1 PUSCH

★ Conventional power control schemes attempt to maintain a constant Signal to Interference plus Noise Ratio (SINR) at the receiver. The UE increases its transmit power to fully compensate an increase in path loss

★ Fractional power control schemes allow the received SINR to decrease as the path loss increases, i.e. the received SINR decreases as the UE moves towards cell edge. The UE transmit power increases at a reduced rate as the path loss increases, when compared to a conventional power control scheme, i.e. increases in path loss are only partially compensated. Fractional power control schemes can improve air-interface efficiency and increase average cell throughputs by reducing intercell interference

★ The concepts of conventional and fractional power control schemes are illustrated in Figure 370

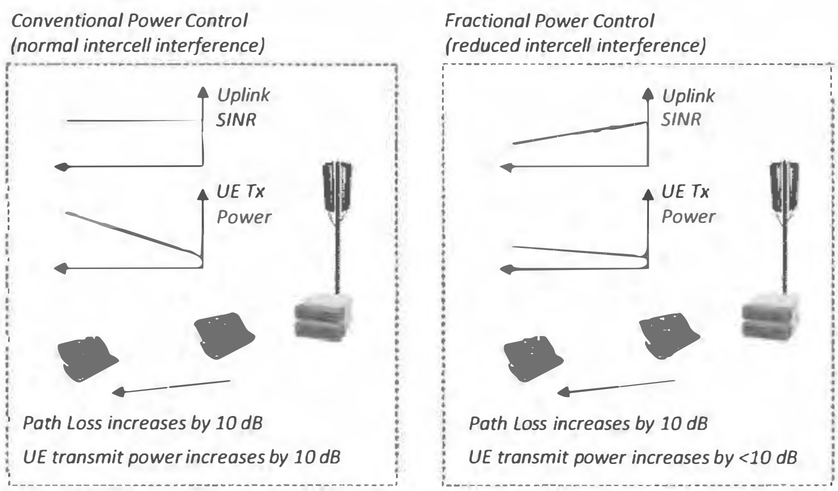


Figure 370 – Conventional and fractional power control schemes

★ 3GPP TS 38.213 specifies a fractional power control scheme for the PUSCH, but with the option to disable it and revert to a conventional power control scheme

★ Both open and closed loop power control components are specified for the PUSCH. The fractional power control scheme forms part of the open loop component. The closed loop component is based upon receiving feedback from the Base Station in the form of Transmit Power Control (TPC) commands. These TPC commands are received within Downlink Control Information (DCI) on the PDCCH

★ The Transmission Scheme can have some impact upon uplink power control. Section 8 describes both 'Codebook Based' and 'Non-Codebook Based' Transmission Schemes. Codebook based transmission allows the Base Station to provide the UE with instructions in terms of switching between transmit beams at the UE. These instructions are provided using the SRS Resource Indicator (SRI) field within DCI Format 0_1. The UE can maintain separate sets of power control parameters for each beam so the SRI instructs the UE to change beam and also change power control parameter sets. This general concept is illustrated in Figure 371

Figure 371 – SRI within DCI Format 0_1 used to select Power Control Parameter Set when using Codebook based Transmission

★ The majority of power control parameters are included within the *PUSCH-PowerControl* parameter structure presented in Table 266

<table>
<tr><th colspan="4">PUSCH-PowerControl</th></tr>
<tr><td>tpc-Accumulation</td><td colspan="3">disabled</td></tr>
<tr><td>msg3-Alpha</td><td colspan="3">0, 0.4, 0.5, 0.6, 0.7, 0.8, 0.9, 1.0</td></tr>
<tr><td>p0-NominalWithoutGrant</td><td colspan="3">-202 to 24 dBm</td></tr>
<tr><td rowspan="4">p0-AlphaSets</td><td colspan="3">SEQUENCE {1 to 30 instances of P0-PUSCH-AlphaSet }</td></tr>
<tr><td>p0-PUSCH-AlphaSetId</td><td colspan="2">0 to 29</td></tr>
<tr><td>p0</td><td colspan="2">-16 to 15</td></tr>
<tr><td>alpha</td><td colspan="2">0, 0.4, 0.5, 0.6, 0.7, 0.8, 0.9, 1.0</td></tr>
<tr><td rowspan="5">pathlossReferenceRSToAddModList</td><td colspan="3">SEQUENCE {1 to 4 instances of PUSCH-PathlossReferenceRS }</td></tr>
<tr><td>pusch-PathlossReferenceRS-Id</td><td colspan="2">0 to 3</td></tr>
<tr><td rowspan="3">referenceSignal</td><td colspan="2">CHOICE</td></tr>
<tr><td>ssb-Index</td><td>csi-RS-Index</td></tr>
<tr><td>0 to 63</td><td>0 to 191</td></tr>
<tr><td rowspan="2">pathlossReferenceRSToReleaseList</td><td colspan="3">SEQUENCE {1 to 4 instances of PUSCH-PathlossReferenceRS-Id }</td></tr>
<tr><td>pusch-PathlossReferenceRS-Id</td><td colspan="2">0 to 3</td></tr>
<tr><td>twoPUSCH-PC-AdjustmentStates</td><td colspan="3">twoStates</td></tr>
<tr><td>deltaMCS</td><td colspan="3">enabled</td></tr>
<tr><td rowspan="5">sri-PUSCH-MappingToAddModList</td><td colspan="3">SEQUENCE {1 to 16 instances of SRI-PUSCH-PowerControl }</td></tr>
<tr><td>sri-PUSCH-PowerControlId</td><td colspan="2">0 to 15</td></tr>
<tr><td>sri-PUSCH-PathlossReferenceRS-Id</td><td colspan="2">0 to 3</td></tr>
<tr><td>sri-P0-PUSCH-AlphaSetId</td><td colspan="2">0 to 29</td></tr>
<tr><td>sri-PUSCH-ClosedLoopIndex</td><td colspan="2">i0, i1</td></tr>
<tr><td rowspan="2">sri-PUSCH-MappingToReleaseList</td><td colspan="3">SEQUENCE {1 to 16 instances of SRI-PUSCH-PowerControlId }</td></tr>
<tr><td>sri-PUSCH-PowerControlId</td><td colspan="2">0 to 15</td></tr>
</table>

Table 266 – *PUSCH-PowerControl* parameter structure

★ The PUSCH transmit power on active Bandwidth Part '*b*' belonging to carrier '*f*' and serving cell '*c*' during transmission occason '*i*', using parameter set '*j*', path loss reference q_d and closed loop power control adjustment state '*l*', is given by:

Configured UE Transmit Power *Subcarrier Spacing* *Allocated Resource Blocks* *Path Loss Measurement* *Closed Loop Power Control Component*

$$P_{PUSCH,b,f,c}(i,j,q_d,l) = MIN\begin{cases} P_{CMAX,f,c}(i) \\ P_{O\_PUSCH,b,f,c}(j) + 10 \times LOG\left(2^{\mu} \times M^{PUSCH}_{RB,b,f,c}(i)\right) + \alpha_{b,f,c}(j) \times PL_{b,f,c}(q_d) + \Delta_{TF,b,f,c}(i) + f_{b,f,c}(i,l) \end{cases}$$

Nominal UE Transmit Power (can include compensation for Supplemental Uplink) *Fractional Power Control Multiplier* *Modulation and Coding Scheme Offset*

★ The nominal UE transmit power, $P_{O\_PUSCH,b,f,c}(j)$ represents the transmit power when allocated a single Resource Block with a subcarrier spacing of 15 kHz and a Path Loss of 0 dB. Its value is generated using the following expression:

$$P_{O\_PUSCH,b,f,c}(j) = P_{O\_NOMINAL\_PUSCH,f,c}(j) + P_{O\_UE\_PUSCH,b,f,c}(j)$$

★ The values of $P_{O\_NOMINAL\_PUSCH,f,c}(j)$ and $P_{O\_UE\_PUSCH,b,f,c}(j)$ depend upon the type of PUSCH transmission:

- $j = 0$: MSG3 PUSCH transmission, or PUSCH transmission when *P0-PUSCH-AlphaSet* has not been configured:
  - $P_{O\_NOMINAL\_PUSCH,f,c}(0) = P_{O\_PRE} + \Delta_{PREAMBLE\_MSG3}$
  - P_{O_PRE} is given by *preambleReceivedTargetPower* within either *RACH-ConfigCommon* (Table 255) or *RACH-ConfigDedicated* (Table 260). $\Delta_{PREAMBLE\_MSG3}$ is given by *msg3-DeltaPreamble* within *PUSCH-ConfigCommon* (Table 267), or is set to 0 if *msg3-DeltaPreamble* is not provided. Note that this part of the power control equation does not include the impact of PRACH Preamble power ramping
  - $P_{O\_UE\_PUSCH,b,f,c}(0) = 0$

- $j = 1$: Configured Grant PUSCH transmission:
  - $P_{O\_NOMINAL\_PUSCH,f,c}(1)$ is given by *p0-NominalWithoutGrant* within *PUSCH-PowerControl* (Table 266). Otherwise, if *p0-NominalWithoutGrant* is not provided then $P_{O\_NOMINAL\_PUSCH,f,c}(1) = P_{O\_NOMINAL\_PUSCH,f,c}(0)$
  - $P_{O\_UE\_PUSCH,b,f,c}(1)$ is given by *p0* from within a specific instance of *P0-PUSCH-AlphaSet*. The Base Station can use the *PUSCH-PowerControl* parameter structure shown in Table 266 to configure multiple instances of *P0-PUSCH-AlphaSet*. The Base Station can then instruct the UE to apply a specific instance of *P0-PUSCH-AlphaSet* by providing *P0-PUSCH-AlphaSetId* within the *ConfiguredGrantConfig* parameter structure (Table 210 in section 7.4.4.3)
- $j = 2$ to 31: Dynamic Grant PUSCH transmission:
  - in this case, $P_{O\_NOMINAL\_PUSCH,f,c}(j)$ represents a cell specific power level which is applicable to all UE within the cell, while $P_{O\_UE\_PUSCH,b,f,c}(j)$ represents a UE specific offset which can be used to adjust individual UE performance, e.g. reduce the uplink BLER for specific UE
  - $P_{O\_NOMINAL\_PUSCH,f,c}(j)$ is given by *p0-NominalWithGrant* within *PUSCH-ConfigCommon* (Table 267). This information element can be included within SIB1 or can be provided using dedicated RRC signalling. Otherwise, if *p0-NominalWithGrant* is not provided then $P_{O\_NOMINAL\_PUSCH,f,c}(j) = P_{O\_NOMINAL\_PUSCH,f,c}(0)$
  - $P_{O\_UE\_PUSCH,b,f,c}(j)$ is given by *p0* from within a specific instance of *P0-PUSCH-AlphaSet*. The appropriate instance of *P0-PUSCH-AlphaSet* is identified by:
    - Non-Codebook based Transmission (described in section 8.2): the UE selects the first instance of *P0-PUSCH-AlphaSet* provided by the *PUSCH-PowerControl* parameter structure shown in Table 266
    - Codebook based Transmission (described in section 8.1): the Base Station provides the UE with an SRS Resource Indicator (SRI) within DCI Format 0_1. The SRI is used as a pointer to an instance of *SRI-PUSCH-PowerControl* which includes a pointer towards an instance of *P0-PUSCH-AlphaSet*. If the Base Station has not provided the UE with an instance of *SRI-PUSCHPowerControl*, the UE selects the first instance of *P0-PUSCH-AlphaSet*

PUSCH-ConfigCommon	
groupHoppingEnabledTransformPrecoding	enabled
pusch-TimeDomainAllocationList	PUSCH-TimeDomainResourceAllocationList
msg3-DeltaPreamble	-1 to 6 dB
p0-NominalWithGrant	-202 to 24 dBm

Table 267 – PUSCH-ConfigCommon parameter structure

★ $M^{PUSCH}_{RB,b,f,c}(i)$ is the number of Resource Blocks allocated to the PUSCH during transmission occasion 'i'. The value is multiplied by 2^{μ}, where μ is the subcarrier spacing index, to scale the transmit power in proportion to the bandwidth of the resource allocation, i.e. Resource Blocks with larger subcarrier spacings occupy wider bandwidths so they are allocated higher transmit powers

★ $\alpha_{b,f,c}(j)$ represents the Fractional Power Control multiplier. A value of '1' means that Conventional power control is applied and the UE adjusts its transmit power to fully compensate the path loss. A value less than '1' means that Fractional power control is applied and the UE does not fully compensate the path loss. Figure 372 illustrates a comparison of Fractional and Conventional power control in terms of UE transmit power and received power spectral density. Fractional Power Control reduces the gradient of the UE transmit power characteristic, which consequently causes the received power spectral density to decrease

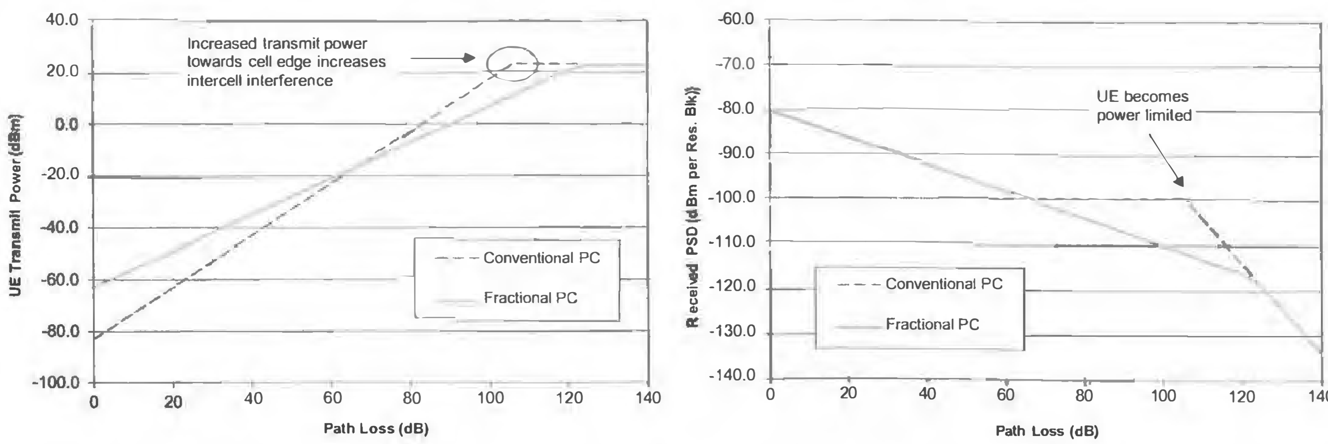


Figure 372 – Comparison of Fractional Power Control (α = 0.7) and Conventional Power Control (α = 1)

★ In general, the nominal transmit power ($P_{O\_PUSCH,b,f,c}(j)$) is increased when enabling Fractional power control. Adjusting the value of α changes the gradient of each characteristic, while adjusting the nominal transmit power lifts or lowers each characteristic. The nominal transmit power is visible as the received power spectral density when the path loss is 0 dB, i.e. this example is based upon nominal transmit powers of -100 dBm and -80 dBm. Increasing the nominal transmit power improves uplink performance when the UE is close to the serving Base Station. In combination with the reduced inter-cell interference, this helps to compensate for the impact of the reduced transmit power towards cell edge

★ Figure 372 also illustrates the impact of Fractional power control in terms of the UE reaching its maximum transmit power capability. The UE reaches its maximum transmit power at a higher path loss when using fractional power control. Beyond that point, the UE transmit power and the received power spectral density are the same for both Fractional and Conventional power control schemes

★ The value of $\alpha_{b,f,c}(i)$ depends upon the type of PUSCH transmission:

- o j = 0: MSG3 PUSCH transmission, or PUSCH transmission when *P0-PUSCH-AlphaSet* has not been configured:
  - $\alpha_{b,f,c}(0)$ is given by *msg3-Alpha* when provided within *PUSCH-PowerControl*, otherwise $\alpha_{b,f,c}(0) = 1$
- o j = 1: Configured Grant PUSCH transmission:
  - $\alpha_{b,f,c}(1)$ is given by *alpha* from within a specific instance of *P0-PUSCH-AlphaSet*. The Base Station can use the *PUSCH-PowerControl* parameter structure shown in Table 266 to configure multiple instances of *P0-PUSCH-AlphaSet*. The Base Station can then instruct the UE to apply a specific instance of *P0-PUSCH-AlphaSet* by providing *P0-PUSCH-AlphaSetId* within the *ConfiguredGrantConfig* parameter structure (Table 210 in section 7.4.4.3)
- o j = 2 to 31: Dynamic Grant PUSCH transmission:
  - $\alpha_{b,f,c}(j)$ is given by *alpha* from within a specific instance of *P0-PUSCH-AlphaSet*. The appropriate instance of *P0-PUSCH-AlphaSet* which is identified by:
    - Non-Codebook based Transmission (described in section 8.2): the UE selects the first instance of *P0-PUSCH-AlphaSet* provided by the *PUSCH-PowerControl* parameter structure shown in Table 266
    - Codebook based Transmission (described in section 8.1): the Base Station provides the UE with an SRS Resource Indicator (SRI) within DCI Format 0_1. The SRI is used as a pointer to an instance of *SRI-PUSCH-PowerControl* which includes a pointer towards an instance of *P0-PUSCH-AlphaSet*. If the Base Station has not provided the UE with an instance of *SRI-PUSCHPowerControl*, the UE selects the first instance of *P0-PUSCH-AlphaSet*

★ $PL_{b,f,c}(q_d)$ represents the Path Loss measured by the UE using the downlink Reference Signal with index 'q_d'. The Path Loss is calculated as *referenceSignalPower* – higher layer filtered RSRP, where *referenceSignalPower* defines the transmit power of either an SS/PBCH Block or a CSI Reference Signal, i.e. it is a beam level measurement rather than a cell level measurement. The selection of a specific SS/PBCH Block or CSI Reference Signal depends upon the type of PUSCH transmission:

- o MSG3 PUSCH transmission:
  - the UE uses the SS/PBCH Block which was selected for the transmission of the PRACH Preamble
- o Configured Grant PUSCH transmission:
  - if *rrc-ConfiguredUplinkGrant* is included within the *ConfiguredGrantConfig* parameter structure (Table 210 in section 7.4.4.3), then *rrc-ConfiguredUplinkGrant* specifies a Reference Signal resource using *pathlossReferenceIndex*. This acts as a pointer towards an instance of *PUSCH-PathlossReferenceRS* within *PUSCH-PowerControl*. The relevant instance of *PUSCH-PathlossReferenceRS* specifies either an SS/PBCH Block or a CSI Reference Signal to be used for the path loss measurement
  - if *rrc-ConfiguredUplinkGrant* is not included within the *ConfiguredGrantConfig* parameter structure then:
    - if the DCI Format used to activate the Configured Grant transmission includes an SRI then the corresponding instance of *SRI-PUSCH-PowerControl* is identified. *SRI-PUSCH-PowerControl* includes *sri-PUSCH-PathlossReferenceRS-Id* which acts as a pointer towards an instance of *PUSCH-PathlossReferenceRS*
    - if the DCI Format used to activate the Configured Grant transmission does not include an SRI then the *PUSCH-PathlossReferenceRS* with identity '0' is selected
- o Dynamic Grant PUSCH transmission:
  - The downlink transmission used for path loss measurements is given by an instance of *PUSCH-PathlossReferenceRS* within the *PUSCH-PowerControl* parameter structure:
    - Non-Codebook based Transmission (described in section 8.2): the UE selects the first instance of *PUSCH-PathlossReferenceRS* provided by the *PUSCH-PowerControl* parameter structure shown in Table 266
    - Codebook based Transmission (described in section 8.1): in this case, the Base Station provides the UE with an SRS Resource Indicator (SRI) within DCI Format 0_1. The SRI is used as a pointer to an instance of *SRI-PUSCH-PowerControl* which includes a pointer towards an instance of *PUSCH-PathlossReferenceRS*. If the Base Station has not provided the UE with an instance of *SRI-PUSCHPowerControl*, the UE selects the first instance of *PUSCH-PathlossReferenceRS*

★ $\Delta_{TF,b,f,c}(i)$ can be used to control the UE transmit power according to the allocated Modulation and Coding Scheme (MCS). The requirement for this mechanism depends upon the implementation of Link Adaptation at the Base Station:

- o if the Base Station uses Fast Adaptive Modulation and Coding (AMC) then the Base Station changes the allocated MCS according to the channel conditions. When channel conditions are good, the UE is allocated a high MCS and the Base Station receives a high SINR without having to instruct the UE to increase its transmit power. In this case, $\Delta_{TF,b,f,c}(i)$ can be set to 0 dB
- o if the Base Station allocates MCS without accounting for the channel conditions then it is necessary to instruct the UE to increase its transmit power when allocating a high MCS to ensure that the Base Station receives a high SINR. In this case, $\Delta_{TF,b,f,c}(i)$ should be used to increase the UE transmit power as a function of the allocated MCS

★ The Base Station instructs the UE to include $\Delta_{TF,b,f,c}(i)$ within the power control calculation by including the *deltaMCS* flag within the *PUSCH-PowerControl* parameter structure. $\Delta_{TF,b,f,c}(i)$ is set to 0 dB if the *deltaMCS* flag is excluded, or if the PUSCH transmission uses more than a single layer. 3GPP concluded that $\Delta_{TF,b,f,c}(i)$ should only be applied to single layer transmission because the relationship between the UE transmit power requirement and MCS is more complex when using multiple layers and those layers can have different MCS

★ When using the PUSCH to transfer UL-SCH data, $\Delta_{TF,b,f,c}(i)$ is calculated using the following expression:

$$\Delta_{TF,b,f,c}(i) = 10 \times LOG[2^{BPRE \times 1.25} - 1] \qquad \textit{where, BPRE = Bits Per Resource Element}$$

★ This expression for $\Delta_{TF,b,f,c}(i)$ can be derived from Shannon's Capacity Theorem:

$$Channel\ Capacity = Bandwidth \times LOG_2(1 + SINR)$$

★ Re-arranging for SINR leads to:

$$SINR = 2^{(Channel\ Capacity\ /\ Bandwidth)} - 1$$

★ Expressing in terms of dB and substituting BPRE for (Channel Capacity / Bandwidth) leads to:

$$SINR\ (dB) = 10 \times LOG[\ 2^{BPRE} - 1\ ]$$

★ The equation for $\Delta_{TF,b,f,c}(i)$ includes an additional factor of '1.25' to account for non-ideal practical system performance, i.e. a practical system is assumed to achieve 1/1.25 = 80 % of the ideal capacity defined by Shannon

★ When using the PUSCH to transfer UL-SCH data, the value of BPRE is given by:

$$BPRE = \sum_{r=0}^{C-1} K_r\ /\ N_{RE}$$

★ where 'C' is the number of codewords, 'K_r' is the size of codeword 'r', and N_{RE} is the number of Resource Elements excluding those which are allocated to the Demodulation Reference Signal (DMRS) and Phase Tracking Reference Signal (PTRS)

★ The calculation of $\Delta_{TF,b,f,c}(i)$ is modified when the PUSCH is used to transfer Channel State Information (CSI) without transferring any UL-SCH data. In this case, $\Delta_{TF,b,f,c}(i)$ is given by:

$$\Delta_{TF,b,f,c}(i) = 10 \times LOG\left[(2^{BPRE \times 1.25} - 1) \times \beta_{offset}^{PUSCH}\right]$$

★ In this case, the Bits Per Resource Element (BPRE) is given by:

$$BPRE = Q_m \times R\ /\ \beta_{offset}^{PUSCH}$$

★ where 'Q_m' is the modulation order and 'R' is the target coding rate based upon the allocated MCS. The UE can be provided with a value for β_{offset}^{PUSCH} using either DCI Format 0_1 or by RRC signalling. If *UCI-OnPUSCH* within *PUSCH-Config* or *CG-UCI-OnPUSCH* within *ConfiguredGrantConfig* is set to '*dynamic*' then β_{offset}^{PUSCH} is provided by DCI Format 0_1. Otherwise, if *UCI-OnPUSCH* or *CG-UCI-OnPUSCH* is set to '*semiStatic*' then β_{offset}^{PUSCH} is provided by RRC signalling. Larger values of β_{offset}^{PUSCH} decrease the resultant value of $\Delta_{TF,b,f,c}(i)$

- When β_{offset}^{PUSCH} is provided by DCI Format 0_1, RRC signalling is first used to configure the UE with a set of 4 candidate values for β_{offset}^{PUSCH}. DCI Format 0_1 includes 2 bits which are used to dynamically select between these 4 candidate values. The set of 4 candidate values can be selected from the values presented in Table 268
- When β_{offset}^{PUSCH} is provided by RRC signalling, the UE is configured with a single value from the set of values presented in Table 268

Index	β_{offset}^{PUSCH}	Index	β_{offset}^{PUSCH}	Index	β_{offset}^{PUSCH}	Index	β_{offset}^{PUSCH}
0	1	4	4	8	10	12	31
1	2	5	5	9	12.625	13	50
2	2.5	6	6.250	10	15.875	14	80
3	3.125	7	8	11	20	15	126

Table 268 – Values which can allocated to β_{offset}^{PUSCH}

- $f_{b,f,c}(i,l)$ represents the closed loop power control calculation. The variable '*l*' corresponds to the closed loop power control 'Adjustment State'. A UE can be configured with either 1 or 2 power control Adjustment States. The UE maintains a separate power control calculation for each Adjustment State. Transmit Power Control (TPC) commands are used to update a specific Adjustment State, i.e. the Base Station is required to indicate the Adjustment State in combination with the TPC command
- The *twoPUSCH-PC-AdjustmentStates* flag within the *PUSCH-PowerControl* parameter structure is used to indicate the number of Adjustment States to be maintained by the UE. A value of '*twoStates*' indicates that the UE should maintain 2 Adjustment States
- In the case of Configured Grants, the use of a specific power control adjustment state is indicated using the *powerControlLooptoUse* information element within the *ConfiguredGrantConfig* presented in Table 210 (section 7.4.4.3).
- In the case of Dynamic Grants using Codebook based Transmission, the SRI within DCI Format 0_1 can be used as a pointer towards an instance of *SRI-PUSCH-PowerControl*, which specifies a specific Adjustment State using *sri-PUSCH-ClosedLoopIndex*. If the UE does not receive an SRI then the first Adjustment State is used
- In the case of Dynamic Grants using Non-Codebook based Transmission the UE uses the first Adjustment State
- If a UE receives a TPC command using DCI Format 2_2, the TPC command is applied to the Adjustment State which is explicitly signalled within the payload of DCI Format 2_2
- If the UE receives a TPC command using DCI Format 0_0 or 0_1, the TPC command is applied to the Adjustment State applicable to the PUSCH resource allocation, e.g. based upon the SRI when using Codebook based Transmission
- Closed loop power control can operate with or without TPC command accumulation. Accumulation is the default mode of operation and is enabled when *tpc-Accumulation* is excluded from *PUSCH-PowerControl* (this sounds like reverse logic but when *tpc-Accumulation* is included then it can only have the value 'disabled'). If accumulation is enabled then $f_{b,f,c}(i,l)$ is given by:

$$f_{b,f,c}(i,l) = f_{b,f,c}(i-i_0,l) + \sum_{m=0}^{C(D_i)-1} \delta_{PUSCH,b,f,c}(m,l)$$

- $\delta_{PUSCH,b,f,c}(m,l)$ represents the m^{th} TPC command for Adjustment State '*l*'. The summation adds all TPC commands for Adjustment State '*l*' that have been received since the PDCCH resource allocation for the previous PUSCH transmission using Adjustment State '*l*'
- A TPC command occupies 2 bits and maps onto one of the four values presented in Table 269. TPC command accumulation allows fine tuning of the UE transmit power, while potentially allowing $f_{b,f,c}(i,l)$ to have a large value (because individual TPC commands are summed over time). The value of 0 dB means that a TPC command can be sent without impacting the UE transmit power

TPC Command	Accumulated $\delta_{PUSCH,b,f,c}$	Absolute $\delta_{PUSCH,b,f,c}$
0	-1 dB	-4 dB
1	0 dB	-1 dB
2	1 dB	1 dB
3	3 dB	4 dB

Table 269 – Interpretation of TPC commands for Accumulated and Absolute modes of operation

- Closed loop power control operates in 'absolute' mode when TPC command accumulation is disabled. In this case, TPC commands are mapped onto the {-4,-1, 1, 4} dB values within Table 269, and $f_{b,f,c}(i,l) = \delta_{PUSCH,b,f,c}(i,l)$, i.e. in this case, closed loop power control can generate a maximum change of 4 dB

- A special case is applied to the closed loop power control calculation when the UE receives a Random Access Response (MSG2). In this case, the closed loop power control calculation is used to include the impact of PRACH Preamble power ramping, and $f_{b,f,c}(i, l)$ is given by:

$$f_{b,f,c}(0, l) = \Delta P_{rampup,b,f,c} + \delta_{msg2,b,f,c}$$

- $\Delta P_{rampup,b,f,c}$ corresponds to the total power ramp-up which was applied while transmitting PRACH Preambles, and $\delta_{msg2,b,f,c}$ is the TPC command included within MSG2 (shown in Figure 357 within section 13.1.1). In this case, the TPC command can range from -6 dB to 8 dB

- 3GPP References: TS 38.213, TS 38.331, TS 38.321, TS 38.212

13.3.2 PUCCH

- The PUCCH uses a power control mechanism which is similar to the PUSCH. However, the PUCCH does not support fractional power control so the UE fully compensates the path loss, unless its transmit power capability has become exhausted

- Transmit Power Control (TPC) commands for the PUSCH are provided on the PDCCH in combination with uplink resource allocations, i.e. using DCI Formats 0_0 and 0_1. In contrast, TPC commands for the PUCCH are provided on the PDCCH in combination with downlink resource allocations, i.e. using DCI Formats 1_0 and 1_1. This approach allows the Base Station to update the UE transmit power in advance of the UE returning a HARQ acknowledgement on the PUCCH

- TPC commands for both the PUSCH and PUCCH can be provided using DCI Format 2_2 (the UE is addressed by its TPC-PUSCH-RNTI when receiving TPC commands on DCI Format 2_2 for the PUSCH, and by its TPC-PUCCH-RNTI when receiving TPC commands on DCI Format 2_2 for the PUCCH)

- In the case of the PUSCH, the Base Station instructs the UE to switch between power control parameter sets using SRI transmissions on the PDCCH. These SRI also instruct the UE to change the beam that it uses for PUSCH transmission so the UE changes both beam and power control parameter sets at the same time

- In the case of the PUCCH, the Base Station instructs the UE to switch between power control parameter sets using the 'PUCCH Spatial Relation Activation / Deactivation' MAC Control Element on the PDSCH. This MAC Control Element also instructs the UE to change the beam that it uses for PUCCH transmission so the UE changes both beam and power control parameter sets at the same time. This general concept is illustrated in Figure 373

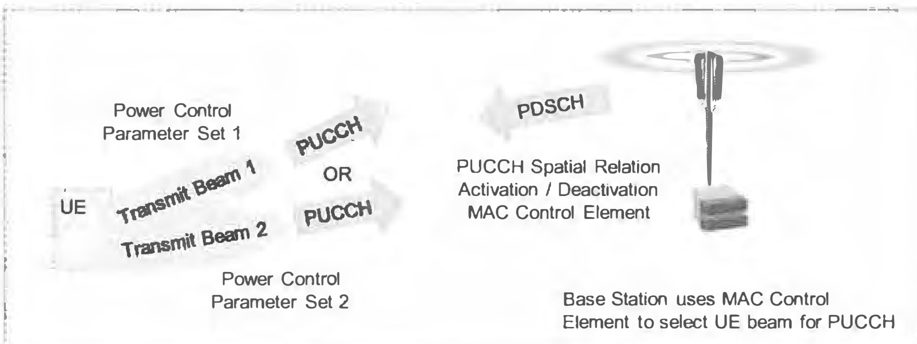


Figure 373 – MAC Control Element used to select the Power Control parameter set for the PUCCH

- Figure 374 illustrates the structure of the 'PUCCH Spatial Relation Activation / Deactivation' MAC Control Element. It starts by specifying the serving cell identity, the Bandwidth Part identity and the PUCCH Resource identity. These fields are followed by a set of flags which indicate whether or not a specific PUCCH Spatial Relation is active. Each flag corresponds to a specific instance of the *PUCCH-SpatialRelationInfo* parameter set (Table 272 shown later in this section). This parameter set includes a first pointer towards a specific Reference Signal to be used for path loss measurements, and a second pointer towards a specific nominal transmit power. Only one Spatial Relation can be active at any point in time so only a single flag should be set to '1'

<table>
<tr><td>R</td><td colspan="5">Serving Cell ID</td><td colspan="2">BWP ID</td></tr>
<tr><td>R</td><td colspan="7">PUCCH Resource ID</td></tr>
<tr><td>S7</td><td>S6</td><td>S5</td><td>S4</td><td>S3</td><td>S2</td><td>S1</td><td>S0</td></tr>
</table>

Figure 374 – PUCCH Spatial Relation Activation / Deactivation MAC Control Element

★ The majority of power control parameters are included within the *PUCCH-PowerControl* parameter structure presented in Table 270

PUCCH-PowerControl			
deltaF-PUCCH-f0	-16 to 15		
deltaF-PUCCH-f1	-16 to 15		
deltaF-PUCCH-f2	-16 to 15		
deltaF-PUCCH-f3	-16 to 15		
deltaF-PUCCH-f4	-16 to 15		
p0-Set	SEQUENCE {1 to 8 instances of *P0-PUCCH* }		
	p0-PUCCH-Id	1 to 8	
	p0-PUCCH-Value	-16 to 15	
pathlossReferenceRSToAddModList	SEQUENCE {1 to 4 instances of *PUCCH-PathlossReferenceRS* }		
	pucch-PathlossReferenceRS-Id	0 to 3	
	referenceSignal	CHOICE	
		ssb-Index	csi-RS-Index
		0 to 63	0 to 191
twoPUCCH-PC-AdjustmentStates	twoStates		

Table 270 – *PUCCH-PowerControl* parameter structure

★ The PUCCH transmit power on active Bandwidth Part '*b*' belonging to carrier '*f*' and serving cell '*c*' during transmission occason '*i*', using parameter set q_u, path loss reference q_d and closed loop power control adjustment state '*l*', is given by:

Configured UE Transmit Power — *Subcarrier Spacing* — *Allocated Resource Blocks* — *PUCCH Format specific Offset* — *Closed Loop Power Control Component*

$$P_{PUCCH,b,f,c}(i, q_u, q_d, l) = MIN \begin{cases} P_{CMAX,f,c}(i) \\ P_{O\_PUCCH,b,f,c}(q_u) + 10 \times LOG\left(2^{\mu} \times M^{PUCCH}_{RB,b,f,c}(i)\right) + PL_{b,f,c}(q_d) + \Delta_{F\_PUCCH}(F) + \Delta_{TF,b,f,c}(i) + g_{b,f,c}(i, l) \end{cases}$$

Nominal UE Transmit Power (can include compensation for Supplemental Uplink) — *Path Loss Measurement* — *Modulation and Coding Scheme Offset*

★ The nominal UE transmit power, $P_{O\_PUCCH,b,f,c}(q_u)$ represents the transmit power for a single Resource Block with a subcarrier spacing of 15 kHz and a Path Loss of 0 dB. Its value is generated using the following expression:

$$P_{O\_PUCCH,b,f,c}(q_u) = P_{O\_NOMINAL\_PUCCH} + P_{O\_UE\_PUCCH}(q_u)$$

★ $P_{O\_NOMINAL\_PUCCH}$ represents a cell specific power level which is applicable to all UE within the cell, while $P_{O\_UE\_PUCCH}(q_u)$ represents a UE specific offset which can be used to adjust individual UE performance

★ $P_{O\_NOMINAL\_PUCCH}$ is given by *p0-nominal* within the *PUCCH-ConfigCommon* parameter structure shown in Table 271. This parameter structure can be included within SIB1 or can be provided using dedicated RRC signalling. Otherwise, if *p0-nominal* is not provided then a value of 0 dBm is assumed

★ The -202 dBm minimum value for *p0-nominal* is significantly lower than a normal received power level. This extremely low value has been specified to cater for Supplemental Uplink scenarios which involve the UE measuring the downlink path loss in one band and transmitting the PUCCH in another band. For example, a UE could measure the downlink path loss at 70 GHz while configured to transmit the PUCCH using a Supplemental Uplink at 700 MHz. In this case, the downlink path loss measured at 70 GHz is significantly greater than the uplink path loss at 700 MHz. The combination of air-interface propagation loss and building penetration loss could be more than 70 dB higher at 70 GHz when compared to compared to 700 MHz. Configuring a very low value for the nominal power helps to ensure that the UE transmits at a power level which is appropriate for the lower operating band

PUCCH-ConfigCommon	
pucch-ResourceCommon	0 to 15
pucch-GroupHopping	neither, enable, disable
hoppingId	0 to 1023
p0-nominal	-202 to 24 dBm

Table 271 – *PUCCH-ConfigCommon* parameter structure

★ $P_{O\_UE\_PUCCH}(q_u)$ is given by *p0-PUCCH-Value* from within a specific instance of *p0-PUCCH* (Table 270). The appropriate instance of *p0-PUCCH* can be controlled using the 'PUCCH Spatial Relation Activation / Deactivation' MAC Control Element. This MAC Control Element activates a specific instance of the *PUCCH-SpatialRelationInfo* parameter set shown in Table 272. This parameter set includes a *p0-PUCCH-Id* which points towards a specific instance of *p0-PUCCH*

★ If the UE is not configured with the *PUCCH-SpatialRelationInfo* parameter set then the UE selects the instance of *p0-PUCCH* which has identity '0'

PUCCH-SpatialRelationInfo				
pucch-SpatialRelationInfoId	1 to 8			
servingCellId	0 to 31			
referenceSignal	CHOICE			
	ssb-Index	csi-RS-Index	srs	
	0 to 63	0 to 191	resource	0 to 63
			uplinkBWP	0 to 4
pucch-PathlossReferenceRS-Id	0 to 3			
p0-PUCCH-Id	1 to 8			
closedLoopIndex	i0, i1			

Table 272 – *PUCCH-SpatialRelationInfo* parameter structure (up to 8 instances within *PUCCH-Config*)

★ $M_{RB,b,f,c}^{PUCCH}(i)$ is the number of Resource Blocks occupied by the PUCCH during transmission occasion 'i'. The value is multiplied by 2^{μ}, where μ is the subcarrier spacing index, to scale the transmit power in proportion to the bandwidth of the resource allocation, i.e. Resource Blocks with larger subcarrier spacings occupy wider bandwidths so they are allocated higher transmit powers

★ $PL_{b,f,c}(q_d)$ represents the Path Loss measured by the UE using the downlink Reference Signal with index 'q_d'. The Path Loss is calculated as *referenceSignalPower* – higher layer filtered RSRP, where *referenceSignalPower* defines the transmit power of either an SS/PBCH Block or a CSI Reference Signal, i.e. it is a beam level measurement rather than a cell level measurement

★ The Reference Signal to be used for path loss measurements is identified using an instance of *PUCCH-PathlossReferenceRS* within the *PUCCH-PowerControl* parameter structure. The appropriate instance of *PUCCH-PathlossReferenceRS* can be controlled using the 'PUCCH Spatial Relation Activation / Deactivation' MAC Control Element. This MAC Control Element activates a specific instance of the *PUCCH-SpatialRelationInfo* parameter set shown in Table 272. This parameter set includes a *pucch-PathlossReferenceRS-Id* information element which points towards a specific instance of *PUCCH-PathlossReferenceRS*

★ If the UE is not configured with the *PUCCH-SpatialRelationInfo* parameter set then the UE selects the instance of *PUCCH-PathlossReferenceRS* which has identity '0'. If the UE is not configured with an instance of *PUCCH-PathlossReferenceRS* then the UE calculates path loss using the SS/PBCH Block which was selected when acquiring the Master Information Block (MIB). This latter scenario is applicable if the UE transmits the PUCCH before being fully configured by the RRC layer

★ $\Delta_{F\_PUCCH}(F)$ represents a UE transmit power offset which is dependent upon the PUCCH Format. Transmit power offsets for each PUCCH Format can be configured within the *PUCCH-PowerControl* parameter structure shown in Table 270

★ $\Delta_{TF,b,f,c}(i)$ can be used to control the UE transmit power according to the coding rate of the data being transferred by the PUCCH. It is calculated using the expressions shown below:

$$\Delta_{TF,b,f,c}(i) = 10 \times LOG\left[\, 2 \,/\, N_{symb}^{PUCCH}(i) \,\right] \qquad \textit{PUCCH Format 0}$$

$$\Delta_{TF,b,f,c}(i) = 10 \times LOG\left[\, 14 \,/\, N_{symb}^{PUCCH}(i) \,\right] + 10 \times LOG\left[\, O_{UCI}(i) \,\right] \qquad \textit{PUCCH Format 1 (normal cyclic prefix)}$$

$$\Delta_{TF,b,f,c}(i) = 10 \times LOG\left[\, 12 \,/\, N_{symb}^{PUCCH}(i) \,\right] + 10 \times LOG\left[\, O_{UCI}(i) \,\right] \qquad \textit{PUCCH Format 1 (extended cyclic prefix)}$$

$$\Delta_{TF,b,f,c}(i) = 10 \times LOG\left[\, 6 \times (O_{ACK}(i) + O_{SR}(i) + O_{CSI}(i)) \,/\, N_{RE}(i) \,\right] \qquad \textit{PUCCH Formats 2, 3, 4 \quad payload} \le \textit{11 bits}$$

$$\Delta_{TF,b,f,c}(i) = 10 \times LOG\left[\, 2^{2.4 \times BPRE(i)} - 1 \,\right] \qquad \textit{PUCCH Formats 2, 3, 4 \quad payload} > \textit{11 bits}$$

$$BPRE(i) = \left(O_{ACK}(i) + O_{SR}(i) + O_{CSI}(i) + O_{CRC}(i)\right) / N_{RE}(i)$$

★ PUCCH Format 0 occupies either 1 or 2 symbols. $\Delta_{TF,b,f,c}(i) = 3$ dB when occupying 1 symbol, and 0 dB when occupying 2 symbols. This reflects a higher transmit power requirement for a higher coding rate, i.e. the transmit power is higher when the information content is sent using a single symbol rather than two symbols

- PUCCH Format 1 occupies between 4 and 14 symbols when using the normal cyclic prefix. The first part of the $\Delta_{TF,b,f,c}(i)$ calculation generates a result of 5.4 dB when occupying 4 symbols and a result of 0 dB when occupying 14 symbols. This corresponds to an increased transmit power for an increased coding rate. The second part of the $\Delta_{TF,b,f,c}(i)$ calculation is based upon the number of Uplink Control Information (UCI) bits, i.e. increasing the payload size increases the power offset
- In the case of PUCCH Formats 2, 3 and 4, the calculation of $\Delta_{TF,b,f,c}(i)$ depends upon the size of the payload
  - the first expression is applicable when the number of Uplink Control Information (UCI) bits is less than or equal to 11 bits. In this case, the calculation is based upon the total number of UCI bits divided by the number of Resource Elements used to transfer those UCI bits (excluding Resource Elements allocated to the Demodulation Reference Signal (DMRS))
  - the second expression is applicable when the number of UCI bits is greater than 11 bits. In this case, the calculation is based upon Shannon's Capacity Theorem and uses the same format as the $\Delta_{TF,b,f,c}(i)$ calculation for PUSCH power control
- $g_{b,f,c}(i,l)$ represents the closed loop power control calculation. The variable '*l*' corresponds to the closed loop power control 'Adjustment State'. A UE can be configured with either 1 or 2 power control Adjustment States. The UE maintains a separate power control calculation for each Adjustment State. Transmit Power Control (TPC) commands are used to update a specific Adjustment State, i.e. the Base Station is required to indicate the Adjustment State in combination with the TPC command
- The *twoPUCCH-PC-AdjustmentStates* flag within the *PUCCH-PowerControl* parameter structure is used to indicate the number of Adjustment States to be maintained by the UE. A value of '*twoStates*' indicates that the UE should maintain 2 Adjustment States
- TPC commands within DCI Format 1_0 and 1_1 do not indicate the Adjustment State to be applied. Instead, the Base Station can use the 'PUCCH Spatial Relation Activation / Deactivation' MAC Control Element illustrated in Figure 374 to activate a specific instance of the *PUCCH-SpatialRelationInfo* parameter set presented in Table 272. This parameter set includes a *closedLoopIndex* information element which identifies the appropriate Adjustment State
- If a UE receives a TPC command using DCI Format 2_2, the TPC command is applied to the Adjustment State which is explicitly signalled within the payload of DCI Format 2_2
- Closed loop power control for the PUCCH operates with TPC command accumulation. $g_{b,f,c}(i,l)$ is given by:

$$g_{b,f,c}(i,l) = g_{b,f,c}(i-i_0,l) + \sum_{m=0}^{C(C_i)-1} \delta_{PUCCH,b,f,c}(m,l)$$

- $\delta_{PUCCH,b,f,c}(m,l)$ represents the m^{th} TPC command for Adjustment State '*l*'. The summation adds all TPC commands for Adjustment State '*l*' that have been received since the last update. A TPC command occupies 2 bits and maps onto one of the four values presented in Table 273

TPC Command	Accumulated $\delta_{PUCCH,b,f,c}$
0	-1 dB
1	0 dB
2	1 dB
3	3 dB

Table 273 – Interpretation of TPC commands for PUCCH power control

- A special case is applied to the closed loop power control calculation when the UE receives a Random Access Response (MSG2). In this case, the closed loop power control calculation is used to include the impact of PRACH Preamble power ramping, and $g_{b,f,c}(i,l)$ is given by:

$$g_{b,f,c}(0,l) = \Delta P_{rampup,b,f,c} + \delta_{msg2,b,f,c}$$

- $\Delta P_{rampup,b,f,c}$ corresponds to the total power ramp-up which was applied while transmitting PRACH Preambles, and $\delta_{msg2,b,f,c}$ is the TPC command included within MSG2 (shown in Figure 357 within section 13.1.1). In this case, the TPC command can range from -6 dB to 8 dB
- 3GPP References: TS 38.213, TS 38.331, TS 38.321, TS 38.212

13.3.3 SRS

★ The Sounding Reference Signal (SRS) uses a power control mechanism which is similar to the PUSCH. However, power control for the SRS does not include an MCS dependent term because the SRS does not transfer any information bits

★ The SRS can be configured to use the same closed loop Transmit Power Control (TPC) commands as the PUSCH, i.e. to use TPC commands within DCI Formats 0_0, 0_1 and 2_2. This provides coherence between the PUSCH and SRS transmit powers. Alternatively, the SRS can be configured to receive its own TPC commands using DCI Format 2_3. In this case, the UE is addressed using a TPC-SRS-RNTI

★ Figure 371 in section 13.3.1 illustrates a UE changing its PUSCH power control parameter set when receiving an SRS Resource Indicator (SRI) from the Base Station. Figure 371 is also applicable to the SRS, i.e. each SRS Resource Set can be configured with different SRS power control parameters (nominal transmit power, fractional power control multiplier and path loss Reference Signal)

★ The SRS transmit power on active Bandwidth Part '*b*' belonging to carrier '*f*' and serving cell '*c*' during transmission occason '*i*', using parameter set 'q_s' and closed loop power control adjustment state '*l*', is given by:

Configured UE Transmit Power *Subcarrier Spacing* *Allocated Resource Blocks* *Path Loss Measurement*

$$P_{SRS,b,f,c}(i,q_s,l) = MIN\begin{cases} P_{CMAX,f,c}(i) \\ P_{O\_SRS,b,f,c}(q_s) + 10 \times LOG(2^{\mu} \times M_{SRS,b,f,c}(i)) + \alpha_{SRS,b,f,c}(q_s) \times PL_{b,f,c}(q_d) + h_{b,f,c}(i,l) \end{cases}$$

Nominal UE Transmit Power (can include compensation for Supplemental Uplink) *Fractional Power Control Multiplier* *Closed Loop Power Control Component*

★ The nominal UE transmit power, $P_{O\_SRS,b,f,c}(q_s)$ represents the transmit power per Resource Block when using a subcarrier spacing of 15 kHz and a Path Loss of 0 dB. The value of $P_{O\_SRS,b,f,c}(q_s)$ is configured using *p0* within the *SRS-ResourceSet* parameter structure presented in Table 219 in section 7.5.3. Each instance of *SRS-ResourceSet* can be configured with a different nominal UE transmit power. The Base Station can use an SRI within DCI Format 0_1 to instruct the UE to change SRS Resource Set and thus change the instance of *p0* which defines the nominal UE transmit power. The variable 'q_s' references a specific instance of *SRS-ResourceSet*

★ $M_{SRS,b,f,c}(i)$ is the number of SRS Resource Blocks during transmission occasion 'i'. The value is multiplied by 2^{μ}, where μ is the subcarrier spacing index, to scale the transmit power in proportion to the bandwidth of the SRS transmission, i.e. Resource Blocks with larger subcarrier spacings occupy wider bandwidths so they are allocated higher transmit powers

★ $\alpha_{SRS,b,f,c}(q_s)$ represents the Fractional Power Control multiplier. A value of '1' means that conventional power control is applied and the UE adjusts its transmit power to fully compensate the path loss. A value less than '1' means that fractional power control is applied and the UE does not fully compensate the path loss. The value of $\alpha_{SRS,b,f,c}(q_s)$ is configured using *alpha* within the *SRS-ResourceSet* parameter structure presented in Table 219 in section 7.5.3

★ $PL_{b,f,c}(q_d)$ represents the Path Loss measured by the UE using the downlink Reference Signal with index 'q_d'. The Path Loss is calculated as *referenceSignal Power* – higher layer filtered RSRP, where *referenceSignal Power* defines the transmit power of either an SS/PBCH Block or a CSI Reference Signal. The *SRS-ResourceSet* parameter structure includes the *pathlossReferenceRS* information element to specify the Reference Signal to be used for the Path Loss measurement

★ The closed loop power control component for the SRS ($h_{b,f,c}(i,l)$) is set equal to the closed loop power control component for the PUSCH ($f_{b,f,c}(i,l)$) if *srs-PowerControlAdjustmentStates* within the *SRS-ResourceSet* is set to 'sameAsFci2'

★ Otherwise, the UE maintains a separate closed loop power control calculation for the SRS. This case is also applicable if the UE is transmitting the SRS on a carrier which is not configured for PUSCH transmission. Similar to the PUSCH, closed loop power control for the SRS can operate with or without TPC command accumulation. Accumulation is the default mode of operation and is enabled when *tpc-Accumulation* is excluded from *SRS-Config*. If accumulation is enabled then $h_{b,f,c}(i)$ is given by:

$$h_{b,f,c}(i) = h_{b,f,c}(i-1) + \sum_{m=0}^{C(S_i)-1} \delta_{SRS,b,f,c}(m)$$

★ $\delta_{SRS,b,f,c}(m)$ represents the m^{th} TPC command provided using DCI Format 2_3. The TPC command values are the same as those used for the PUSCH, i.e. the values presented in Table 269

★ Closed loop power control operates in 'absolute' mode when TPC command accumulation is disabled. In this case, TPC commands are mapped onto the {-4,-1, 1, 4} dB values within Table 269, and $h_{b,f,c}(i) = \delta_{SRS,b,f,c}(i)$

★ A special case is applied to the closed loop power control calculation when the UE receives a Random Access Response (MSG2). In this case, the closed loop power control calculation includes the impact of PRACH Preamble power ramping, and $h_{b,f,c}(i)$ is given by:

$$h_{b,f,c}(0) = \Delta P_{rampup,b,f,c} + \delta_{msg2,b,f,c}$$

★ $\Delta P_{rampup,b,f,c}$ corresponds to the total power ramp-up which was applied while transmitting PRACH Preambles, and $\delta_{msg2,b,f,c}$ is the TPC command included within MSG2 (shown in Figure 357 within section 13.1.1)

★ 3GPP References: TS 38.213, TS 38.331, TS 38.321, TS 38.212

13.3.4 UE POWER CLASS

★ The UE Power Class defines the maximum output power for a UE transmitting within the channel bandwidth of an NR carrier. Differences in the UE hardware architecture mean that UE Power Classes are specified differently in Frequency Ranges 1 and 2. Hardware architectures for Frequency Range 1 allow the UE transmit power to be measured at the UE antenna connector. Hardware architectures for Frequency Range 2 are highly integrated and it is impractical to provide antenna connectors. In this case, UE Power Classes are specified using Over The Air (OTA) measurements

★ 3GPP TS 38.101-1 specifies the UE Power Classes for Frequency Range 1. The release 15 version specifies Power Classes 2 and 3. These Power Classes are presented in Table 274. Power Class 3 is the default Power Class and is applicable to all operating bands within Frequency Range 1

	Maximum Output Power	Operating Bands
Power Class 2	26 dBm	n41, n77, 78, n79
Power Class 3	23 dBm	All Bands within Frequency Range 1

Table 274 – UE Power Classes for Frequency Range 1

★ Power Class 2 is applicable to specific operating bands and may only be used when specific conditions are satisfied:

- o if *P-Max* is configured with a value of 23 dBm or lower then the UE operates using Power Class 3
- o if the UE has provided the *maxUplinkDutyCycle-PC2-FR1* information element within its UE capability information, then the UE operates using Power Class 3 if the percentage of uplink symbols exceeds the value of *maxUplinkDutyCycle-PC2-FR1*
- o if the UE has not provided the *maxUplinkDutyCycle-PC2-FR1* information element within its UE capability information, then the UE operates using Power Class 3 if the percentage of uplink symbols exceeds 50 %
- o if *P-Max* is not provided, or is configured with a value greater than 23 dBm
  - ▪ if the UE has provided *maxUplinkDutyCycle-PC2-FR1* within its UE capability information, then the UE operates using Power Class 2 if the percentage of uplink symbols does not exceed the value of *maxUplinkDutyCycle-PC2-FR1*
  - ▪ if the UE has not provided *maxUplinkDutyCycle-PC2-FR1* within its UE capability information, then the UE operates using Power Class 2 if the percentage of uplink symbols does not exceed 50 %

★ 3GPP TS 38.101-2 specifies the UE Power Classes for Frequency Range 2. The release 15 version specifies Power Classes 1, 2, 3 and 4. These Power Classes are presented in Table 275

	Application	Operating Bands	Min Peak EIRP	Max EIRP	Max TRP	Min EIRP CDF
Power Class 1	Fixed Wireless Access UE	n257, n258, n261	40 dBm	55 dBm	35 dBm	32 dBm @ 85 %-tile
		n260	38 dBm			30 dBm @ 85 %-tile
Power Class 2	Vehicular UE	n257, n258, n261	29 dBm	43 dBm	23 dBm	18 dBm @ 60 %-tile
		n260	Power Class 2 not specified for band n260			
Power Class 3	Handheld UE	n257, n258, n261	22.4 dBm	43 dBm	23 dBm	11.5 dBm @ 50 %-tile
		n260	20.6 dBm			8 dBm @ 50 %-tile
Power Class 4	High Power Non-Handheld UE	n257, n258, n261	34 dBm	43 dBm	23 dBm	25 dBm @ 20 %-tile
		n260	31 dBm			19 dBm @ 20 %-tile

Table 275 – UE Power Classes for Frequency Range 2

★ In the case of Frequency Range 2, 3GPP has specified an assumed application for each UE Power Class. Power Class 1 devices are intended for Fixed Wireless Access (FWA) and have the highest transmit power capability. These devices can be used to provide a broadband connection at residential or business properties. The remaining Power Classes have equal maximum Effective Isotropic Radiated Power (EIRP) and Total Radiated Power (TRP) requirements but different minimum Peak EIRP and minimum EIRP CDF requirements

★ Operating bands n257, n258 and n261 support transmissions within the 24 to 29 GHz range, whereas operating band n260 supports transmissions within the 37 to 40 GHz range. Power Class 2 devices have not been specified for operating band n260 because vehicular applications are expected to use the 24 to 29 GHz frequency range

★ The maximum EIRP figures are used to satisfy regulatory requirements, i.e. ensuring that devices do not transmit power levels which could pose a risk to health or generate excessive interference. The maximum EIRP accounts for the maximum antenna gain which can be generated by the device. 3GPP has adopted a set of figures which have been defined by the Federal Communications Commission (FCC) within section 30.202 of 'Title 47 Code of Federal Regulations (CFR)'. Mobile devices are specified to have a maximum EIRP of 43 dBm, while 'transportable' devices are specified to have a maximum EIRP of 55 dBm. Maximum EIRP measurements use a spherical grid to generate measurement results at a large number of positions around the device. A check is completed to ensure that the maximum EIRP threshold is not exceeded at any of the positions

★ The minimum Peak EIRP figures are used to ensure that a device can generate at least a minimum output power in one specific direction. Larger values can be more challenging from a UE implementation perspective but they help to ensure that uplink link budgets can be achieved. Peak EIRP measurements use a spherical grid to generate measurement results at a large number of positions around the device. A check is completed to ensure that at least one measurement exceeds the minimum Peak EIRP threshold. The requirements are lower for operating band n260 due to a lower assumed transceiver power for the 37 to 40 GHz range

★ The minimum EIRP Cumulative Distribution Function (CDF) requirement is used to ensure that a device is capable of generating sufficient output power across an appropriate percentage of directions. This requirement helps to ensure that uplink budgets can be satisfied irrespective of the orientation of the device, i.e. the device is always able to generate sufficient transmit power in the direction of the Base Station. The UE is likely to have multiple antenna arrays to satisfy this requirement. For example, the UE may have antenna patch arrays on the front and back of the device, or the UE may have multiple linear dipole arrays distributed around the edges of the device

★ Figure 375 illustrates the concept of the minimum EIRP CDF requirement (this figure is 2-dimensional whereas conformance testing measurements are completed using a 3-dimensional spherical grid around the device). A large percentile corresponds to a UE satisfying its EIRP requirement across a small range of angles. For example, when using operating band n257, the Fixed Wireless Access application is required to have an EIRP of at least 32 dBm at the 85 percentile point on the CDF. This means that 85 % of measurement samples can have an EIRP less than 32 dBm, while 15 % of measurement samples must have an EIRP greater than 32 dBm. 15 % is appropriate for the Fixed Wireless Access application because the device antenna will be fixed and directed towards the Base Station. This means that it is only necessary to be capable of transmitting in one direction

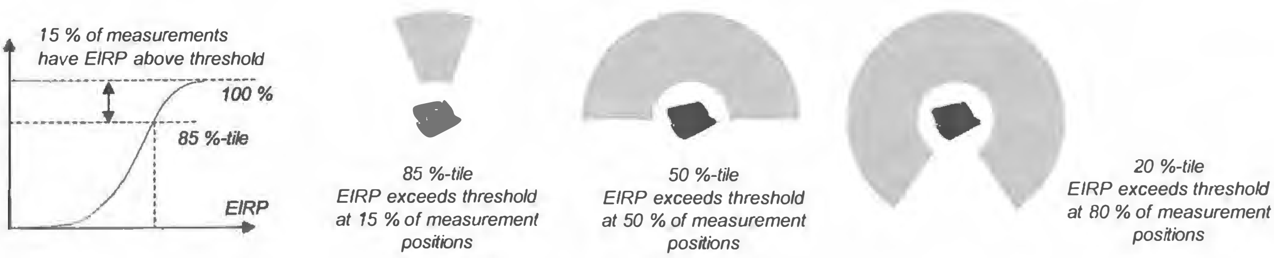


Figure 375 – Minimum EIRP CDF requirement

★ Handheld devices (Power Class 3) are specified using a 50 percentile figure due to the assumption that some devices will have only a single antenna array on one side of the device. A full size display could prevent the integration of a front-facing antenna panel. Similarly, an all-metal frame could prevent antenna element placement around the edges of the device

★ The Total Radiated Power (TRP) requirement defines an upper limit on the total power radiated in all directions. The TRP is quantified by taking an average of the EIRP measurements which have been recorded at a large number of positions around a spherical grid. Averaging the measurements means that the maximum TRP requirement is less than the maximum EIRP requirement. 3GPP has specified maximum TRP requirements which are 20 dB lower than the maximum EIRP requirements. The maximum TRP requirement is important from the perspective of both overall system performance and coexistence with other systems. Interference levels are minimised if a device can achieve its minimum Peak EIRP requirement in the direction of the Base Station while maintaining a low spatially averaged EIRP

★ 3GPP TS 38.101-2 specifies upper limits for Out-of-Band Emissions and Spurious Emissions using TRP rather than EIRP to reflect the total interference power generated by a device. In the case of the wanted signal, directional beamforming can be achieved by controlling the phase of the signals transmitted by each antenna element. In the case of Out-of-Band Emissions and Spurious Emissions, it is not possible to control the phase so these emissions tend to be radiated in all directions

★ 3GPP References: TS 38.101-1, TS 38.101-2, TS 38.521-1, TS 38.521-2

13.3.5 MULTIPLE UPLINK CARRIERS

★ A UE can be configured with multiple uplink carriers when using Carrier Aggregation (CA) or Dual Connectivity (DC)

- in some cases, the UE is permitted to transmit at maximum power on each carrier simultaneously, i.e. the total power summed across carriers exceeds the limit for an individual carrier. This increases UE power consumption but maintains the uplink link budget on each carrier
- in other cases, the UE is required to share its transmit power across carriers such that the total power does not exceed the limit for an individual carrier. This impacts the uplink link budget because the maximum power per carrier is reduced while sharing the power across carriers

★ If a UE is using uplink Carrier Aggregation with multiple carriers belonging to the same Frequency Range, e.g. all carriers belong to Frequency Range 1, then the UE must share its single carrier transmit power across the set of carriers. In contrast, if the UE is using Carrier Aggregation with carriers distributed across Frequency Ranges then the UE is permitted to transmit at maximum power for Frequency Range 1, while simultaneously transmitting at maximum power for Frequency Range 2

★ When using E-UTRA - NR Dual Connectivity (EN-DC), the E-UTRA carrier always belongs to Frequency Range 1. If the NR carrier also belongs to Frequency Range 1 then the UE must share its transmit power across carriers such that the total power does not exceed the limit for an individual carrier. If the NR carrier belongs to Frequency Range 2 then the UE is permitted to transmit at maximum power for E-UTRA, while simultaneously transmitting at maximum power for NR

★ In the case of EN-DC, a UE signals its support for dynamic power sharing between E-UTRA and NR using the *dynamicPowerSharing* flag shown in Table 276. This flag belongs to the *MRDC-Parameters* which are signalled for each band combination

MRDC-Parameters	
singleUL-Transmission	supported
dynamicPowerSharing	supported
tdm-Pattern	supported
ul-SharingEUTRA-NR	tdm, fdm, both
ul-SwitchingTimeEUTRA-NR	type1, type2

MRDC-Parameters	
simultaneousRxTxInterBandENDC	supported
asyncIntraBandENDC	supported
dualPA-Architecture	supported
intraBandENDC-Support-v1540	non-contiguous, both
Ul-TimingAlignmentEUTRA-NR	required

Table 276 – *MRDC-Parameters* parameter structure

★ If a UE does not support dynamic power sharing then the UE is expected to support the use of a 'Reference TDD Configuration' (indicated using the *tdm-Pattern* flag shown in Table 276). The E-UTRA Base Station is then responsible for configuring the 'Reference TDD Configuration' using an *RRC Connection Reconfiguration* message. The relevant part of the *RRC Connection Reconfiguration* message is shown in Table 277. The *subframeAssignment-r15* specifies an LTE uplink/downlink subframe configuration to be used as the 'Reference TDD Configuration'. The UE does not expect to transmit using NR during an NR slot when the corresponding E-UTRA subframe is an uplink subframe, i.e. E-UTRA is given priority during these uplink subframes

<table>
<tr><th colspan="4">RRCConnectionReconfiguration-v1510-IEs</th></tr>
<tr><td rowspan="4">tdm-PatternConfig-r15</td><td colspan="3">CHOICE</td></tr>
<tr><td rowspan="3">release</td><td colspan="2">setup</td></tr>
<tr><td>subframeAssignment-r15</td><td>sa0, sa1, sa2, sa3, sa4, sa5, sa6</td></tr>
<tr><td>harq-Offset-r15</td><td>0 to 9</td></tr>
</table>

Table 277 – Subset of parameters belonging to *RRCConnectionReconfiguration-v1510-IEs*

★ If a UE does support dynamic power sharing and the UE becomes power limited due to the sum of the E-UTRA and NR powers exceeding the upper limit, then the UE prioritises transmission on E-UTRA and reduces the transmit power on NR. The UE is not required to transmit on NR if the power reduction is greater than the value of *xScale*. The Base Station uses the *PhysicalCellGroupConfig* shown in Table 278 to configure a value of either 0 dB or 6 dB for *xScale*. The value of 0 dB means that the UE is not required to transmit on NR if there is any power reduction due to sharing the uplink power with E-UTRA

PhysicalCellGroupConfig	
xScale	0, 6 dB

Table 278 – Subset of parameters belonging to *PhysicalCellGroupConfig*

★ Similar rules apply for NR – E-UTRA Dual Connectivity (NE-DC). Similar to EN-DC, E-UTRA is given priority when there is a requirement to share the UE transmit power across carriers

★ 3GPP References: TS 38.101-1, TS 38.101-2, TS 38.521-1, TS 38.521-2

13.4 DOWNLINK POWER CONTROL

★ The Secondary Synchronisation Signal (SSS) is the main reference for transmit powers in the downlink direction. The Base Station uses the *ss-PBCH-BlockPower* information element to provide the UE with an absolute value for the transmit power of the SSS. This information element can be included as part of *ServingCellConfigCommonSIB* within SIB1, or it can be included as part of *ServingCellConfigCommon* within dedicated signalling. The value of *ss-PBCH-BlockPower* represents the transmit power of a single Resource Element. It can have any integer value within the range from -60 to 50 dBm. The SSS occupies 127 Resource Elements so the total power consumed by the SSS is given by *ss-PBCH-BlockPower* + 10 × LOG(127). From the UE perspective, the SSS transmit power originates from a single 'virtual' transceiver. In reality, if the Base Station is configured with an active antenna, then the SSS transmit power will originate from an array of transceivers. The UE can use the value of *ss-PBCH-BlockPower* when completing path loss measurements for open loop power control, i.e. Path Loss = *ss-PBCH-BlockPower* – higher layer filtered RSRP

★ Figure 376 illustrates the transmit power of other downlink signals and channels relative to the SSS. The PBCH and the Demodulation Reference Signal (DMRS) for the PBCH are transmitted with the same power per Resource Element as the SSS. The power per Resource Element is typically referred to as the Energy per Resource Element (EPRE). Thus, the SSS, PBCH and DMRS for PBCH have an equal EPRE

★ The Primary Synchronisation Signal (PSS) may be transmitted using an EPRE which is equal to the SSS EPRE, or it may be transmitted with an EPRE which is 3 dB greater than the SSS EPRE. There is scope to increase the transmit power of the PSS because there are unused Resource Elements both above and below the PSS (within the set of 20 Resource Blocks used by an SS/PBCH Block). Increasing the EPRE by 3 dB means that the total power within each symbol of an SS/PBCH Block remains approximately constant. The UE is not provided with information regarding the transmit power of the PSS so the UE must deduce the value of the transmit power offset. Having knowledge of the offset is useful for UE which are capable of Interference Cancellation (IC). Knowledge of the offset simplifies the generation of the signal to be subtracted from the wanted signal. In addition, having knowledge of the offset is useful for the UE receiver Automatic Gain Control (AGC) which can be tuned according to the power of each symbol belonging to the SS/PBCH Block

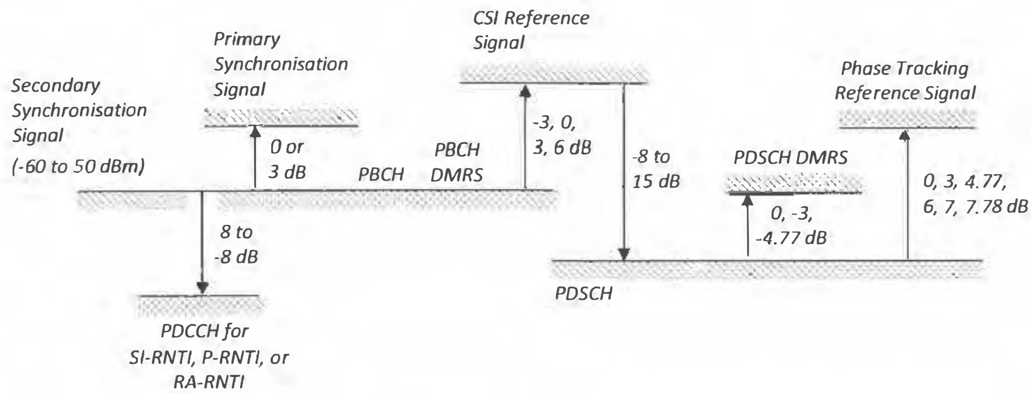


Figure 376 – Relative power levels for the downlink

★ A UE can receive the following power offset information within the *NZP-CSI-RS-Resource* parameter structure. If a UE is configured with multiple CSI Reference Signals then it will receive multiple instances of the *NZP-CSI-RS-Resource* parameter structure. Each instance can specify different power offset values. For example, a CSI Reference Signal used for Beam Management can have a different EPRE relative to a CSI Reference Signal used for the measurement of Channel State Information (CSI), or relative to a CSI Reference Signal used for Tracking

- o *powerControlOffsetSS*: defines the power offset between a CSI Reference Signal and the SSS. This offset is important within the context of measuring path loss for open loop power control (a CSI Reference Signal can be used for path loss measurements instead of an SS/PBCH Block). The *powerControlOffsetSS* information element can be configured with values of -3, 0, 3 or 6 dB, indicating that the EPRE for the CSI Reference Signal can be greater than or less than the EPRE of the SSS. The power offset defines the ratio of the CSI Reference Signal EPRE to the SSS EPRE so a positive value indicates that the CSI Reference Signal has a higher power

- o *powerControlOffset*: defines the power offset between the PDSCH and a CSI Reference Signal. This offset is important within the context of generating CQI values. CQI values are based upon CSI Reference Signal measurements but they quantify the ability of the PDSCH to support a specific modulation scheme and coding rate. The UE must be aware of the PDSCH to CSI Reference Signal power offset to allow an appropriate scaling of the CSI Reference Signal measurements. The *powerControlOffset* information element can be configured with a value between -8 and 15 dB. Positive values indicate that the PDSCH has a higher EPRE than the CSI Reference Signal

★ The transmit power of the PDSCH relative to its DMRS can change dynamically with each Resource Allocation. Downlink Control Information (DCI) Format 1_1 includes an 'Antenna Ports' field which defines a pointer to a row within a look-up table which specifies the 'Number of DMRS CDM Groups without Data'. This value has a direct impact upon the transmit power of the PDSCH relative to its DMRS (refer to section 3.7.3 for a description of the DMRS and the concept of Code Division Multiplexing (CDM) Groups)

- DMRS Configuration Type 1 supports 2 CDM Groups:
  - DMRS ports belonging to a single CDM Group share the same Resource Element allocation. Similarly, PDSCH ports share the same Resource Element allocation. This leads to the PDSCH and DMRS powers remaining aligned, i.e. if only 1 CDM group is transmitted without data (this means that only 1 CDM Group is being used) then it is assumed that the PDSCH and DMRS are transmitted with equal EPRE
  - DMRS ports belonging to separate CDM Groups are frequency multiplexed and use different Resource Element allocations, i.e. they do not need to share their EPRE. In contrast, PDSCH ports continue to share the same Resource Element allocation. This means that the PDSCH has to share its EPRE across ports while the DMRS does not have to share its EPRE. This leads to a 3 dB reduction in PDSCH power relative to the DMRS
- DMRS Configuration Type 2 supports 3 CDM Groups:
  - the principles are the same as for DMRS Configuration Type 1. In this case, up to 3 DMRS CDM Groups can be frequency multiplexed, while the PDSCH has to share its EPRE across ports. This leads to a 10×LOG(3) = 4.77 dB reduction in the PDSCH EPRE relative to the DMRS

★ 3GPP TS 38.214 uses the look-up table presented as Table 279 to specify the relationship between the PDSCH and DMRS EPRE. The values within this table are aligned with the description above

Number of DMRS CDM Groups without Data	DMRS Configuration Type 1	DMRS Configuration Type 2
1	0 dB	0 dB
2	-3 dB	-3 dB
3	-	-4.77 dB

Table 279 – Ratio of PDSCH EPRE to DMRS EPRE

★ Similar to the DMRS, the Phase Tracking Reference Signal (PTRS) has its EPRE configured relative to the PDSCH. The PTRS is transmitted using a single logical antenna port. The Base Station applies DTX to the PTRS Resource Elements on all other antenna ports. The DTX Resource Elements allow the power of the PTRS to be boosted without impacting the power allocated to other Physical Channels and Signals. The PTRS power can be doubled when 2 ports are used for the PDSCH (3 dB increase). Similarly, the PTRS power can be tripled when 3 ports are used for the PDSCH (4.77 dB increase)

★ 3GPP TS 38.214 uses the look-up table presented as Table 280 to specify the relationship between the PTRS and PDSCH EPRE. The UE is configured with an *epre-Ratio* within the *PTRS-DownlinkConfig* parameter structure. A value of '0' corresponds to the description above, whereas a value of '1' leads to the PDSCH and PTRS having equal EPRE irrespective of the number of PDSCH ports

★ Sharing downlink transmit power across antenna ports is only possible when the set of antenna ports share the same power amplifier. It is not possible to share downlink transmit power when antenna ports use different power amplifiers. This means that the rows within Table 280 correspond to different Base Station architectures. The *epre-Ratio* value of '1' corresponds to a Base Station architecture which uses different power amplifiers for each antenna port. This could correspond to analogue beamforming which uses a separate power amplifier for each beam. The *epre-Ratio* value of '0' corresponds to a Base Station architecture which allows antenna ports to share power amplifiers. This could correspond to digital beamforming which uses a set of shared power amplifiers to generate multiple beams

	Number of PDSCH Layers					
epre-Ratio	1	2	3	4	5	6
0	0 dB	3 dB	4.77 dB	6 dB	7 dB	7.78 dB
1	0 dB	0 dB	0 dB	0 dB	0 dB	0 dB

Table 280 – Ratio of PTRS EPRE to PDSCH EPRE per Layer per Resource Element

★ 3GPP TS 38.213 specifies that in the absence of high layer configuration information, UE should assume that PDCCH transmissions used for DCI Format 1_0 with the CRC bits scrambled by the SI-RNTI, P-RNTI or RA-RNTI, have an EPRE which is within +/- 8 dB of the SSS EPRE

★ 3GPP References: TS 38.214, TS 38.331, TS 38.213

13.5 HARQ

- Automatic Repeat reQuest (ARQ) refers to a re-transmission protocol in which the receiver checks for errors within the received data and if an error is detected than the receiver discards the data and requests a re-transmission from the sender. The RLC layer uses an ARQ protocol for Acknowledged Mode
- Hybrid ARQ (HARQ) refers to a re-transmission protocol in which the receiver checks for errors in the received data and if an error is detected then the receiver buffers the data and requests a re-transmission from the sender. A HARQ receiver is then able to combine the buffered data with the re-transmitted data prior to channel decoding and error detection. This improves the performance of the re-transmissions. The MAC layer uses a HARQ protocol
- HARQ re-transmissions can benefit from either Chase Combining or Incremental Redundancy
- Chase Combining means that the Physical layer applies the same puncturing pattern to both the original transmission and each re-transmission. This results in re-transmissions which include the same set of Physical layer bits as the original transmission. The principle of Chase Combining is shown in Figure 377. The benefits of Chase Combining are its simplicity and lower UE memory requirement

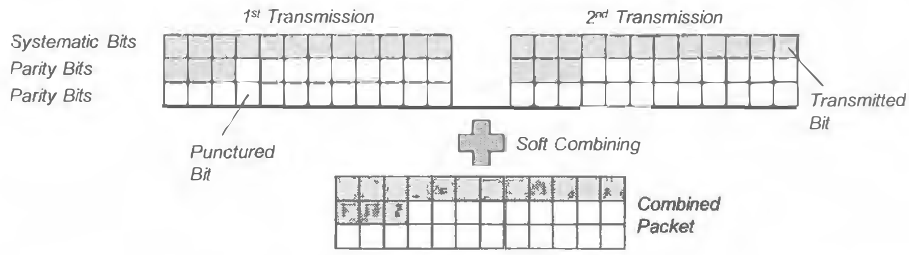


Figure 377 – Principle of HARQ Chase Combining

- Low Density Parity Check (LDPC) coding generates systematic and parity bits. The systematic bits are the same as the original bit sequence. These bits are the most important to the receiver and are provided with the greatest priority, i.e. the parity bits are punctured in preference to the systematic bits when using Chase Combining
- A receiver using Chase Combining benefits from a soft combining gain because the received symbols are combined prior to demodulation. This improves the received signal to noise ratio if it is assumed that the signal power is correlated while the noise power is uncorrelated
- Incremental Redundancy means that the Physical layer applies different puncturing patterns to the original transmission and re-transmissions. This results in re-transmissions which include a different set of Physical layer bits to the original transmission. The principle of Incremental Redundancy is illustrated in Figure 378. The drawbacks associated with Incremental Redundancy are its increased complexity and increased UE memory requirements

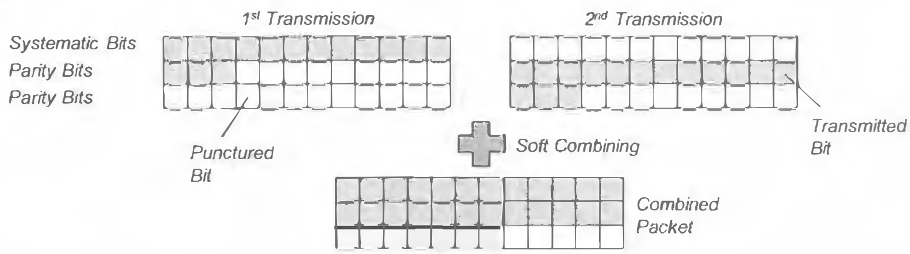


Figure 378 – Principle of HARQ incremental redundancy

- The first transmission provides the systematic bits with the greatest priority while subsequent re-transmissions can provide either the systematic or the parity bits with the greatest priority
- The performance of Incremental Redundancy is similar to the performance of Chase Combining when the coding rate is low, i.e. there is little puncturing. The performance of Incremental Redundancy becomes greater when there is an increased quantity of puncturing. Incremental Redundancy performs better than Chase Combining when the coding rate is high because channel coding gain is greater than soft combining gain
- The HARQ protocol relies upon the sender receiving acknowledgements from the receiver. The round trip time, which includes both the sender and receiver processing times as well as the propagation delays, means that these acknowledgements are not received instantaneously
- The impact of waiting for an acknowledgement is shown in Figure 379. The sender becomes inactive while waiting for the acknowledgement so the average throughput is relatively low. This corresponds to using a single Stop And Wait (SAW) process. A SAW process stops and waits for an acknowledgement before proceeding to transfer any further data

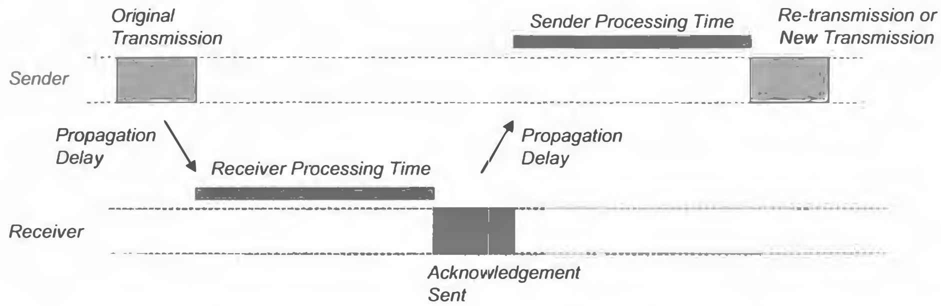


Figure 379 – Data transfer using a single Stop And Wait (SAW) process

★ Multiple parallel SAW processes are used to avoid the round trip time having an impact upon throughput, i.e. additional SAW processes transfer data while the first SAW process is waiting for its acknowledgement. Larger round trip times require an increased number of parallel SAW processes. The concept of multiple parallel SAW processes is illustrated in Figure 380

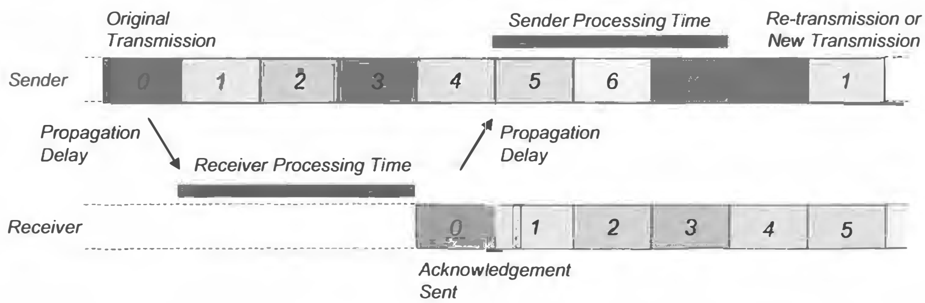


Figure 380 – Data transfer using multiple parallel Stop And Wait (SAW) process

★ The example in Figure 380 requires 8 parallel SAW processes to maintain a constant flow of data. These SAW processes are also referred to as HARQ processes. The HARQ entity within the MAC layer manages these multiple HARQ processes

★ The sender buffers the transmitted data until a positive acknowledgement has been received in case a re-transmission is required. Data is cleared from the transmit buffer once a positive acknowledgement has been received or the maximum number of allowed re-transmissions has been reached. New data can be sent by a specific HARQ process once its transmit buffer has been cleared

13.5.1 DOWNLINK HARQ

★ Downlink HARQ refers to the transfer of downlink data on the PDSCH with HARQ acknowledgements returned on either the PUCCH or the PUSCH

★ Each serving cell has its own HARQ entity and its own set of HARQ processes. A HARQ entity can be configured to use up to 16 HARQ processes. A UE is configured using the *PDSCH-ServingCellConfig* parameter structure presented in Table 281. A UE assumes a maximum of 8 HARQ processes if it has not received any configuration information from the Base Station

PDSCH-ServingCellConfig		
codeBlockGroupTransmission	maxCodeBlockGroupsPerTransportBlock	2, 4, 6, 8
	codeBlockGroupFlushIndicator	True, False
xOverhead	6, 12, 18	
nrofHARQ-ProcessesForPDSCH	2, 4, 6, 10, 12, 16	
pucch-Cell	ServCellIndex	

Table 281 – Number of HARQ processes configured within the *PDSCH-ServingCellConfig* parameter structure

★ A single HARQ process can be associated with either 1 or 2 transport blocks in the downlink. Each of these transport blocks can include multiple Code Block Groups (CBG). Downlink HARQ is responsible for achieving reliable downlink data transfer by managing the re-transmission of transport blocks or the re-transmission of individual Code Block Groups

★ Downlink HARQ is asynchronous which means that there is no fixed timing pattern for each HARQ process. Instead, the Base Station must signal the identity of the relevant HARQ process with each downlink resource allocation. Asynchronous HARQ increases the signalling overhead but also increases flexibility because re-transmissions do not have to be scheduled during specific slots

★ Dynamic downlink resource allocations are provided on the PDCCH using Downlink Control Information (DCI) Formats 1_0 and 1_1. These DCI Formats include key information for the operation of downlink HARQ:

- HARQ Process Number
- New Data Indicator (NDI)
- Redundancy Version (RV)
- PDSCH-to-HARQ Feedback Timing Indicator
- PUCCH Resource Indicator
- Downlink Assignment Index (DAI)
- CBG Transmission Information (CBGTI)
- CBG Flushing Information (CBGFI)

★ The HARQ process number occupies 4 bits within the DCI providing a range from 0 to 15. The value specifies the HARQ process belonging to the transmission within the downlink resource allocation

★ The New Data Indicator (NDI) is a single bit flag used to inform the UE of whether the Base Station is sending a new Transport Block or a re-transmission. Toggling the value relative to the previous value for the same HARQ process indicates that new data is being sent rather than a re-transmission. In the case of DCI Format 1_1, a New Data Indicator field is included for each Transport Block when 2 Transport Blocks are transferred

★ The Redundancy Version (RV) is a set of 2 bits used to inform the UE of which puncturing pattern has been applied to the PDSCH payload during rate matching. This allows the UE to use the correct positions within the soft combining buffer when entering the downlink data for combining and subsequent decoding. The set of 4 Redundancy Versions are described in section 3.6.3

★ Interpretation of the 'PDSCH-to-HARQ Feedback Timing Indicator' depends upon the DCI Format used to allocate the PDSCH resources. In the case of DCI Format 1_0, the timing indicator maps directly onto the set of values {1, 2, 3, 4, 5, 6, 7, 8}. In the case of DCI Format 1_1, the timing indicator represents a pointer towards a row within a look-up table configured by the RRC layer. This look-up table is configured as part of the *PUCCH-Config* parameter structure. The relevant information element from within this parameter structure is presented in Table 282. The look-up table can be configured with up to 8 rows which corresponds to the 'PDSCH-to-HARQ Feedback Timing Indicator' field occupying up to 3 bits within DCI Format 1_1

PUCCH-Config	
dl-DataToUL-ACK	Sequence of 1 to 8 instances of {0 to 15}

Table 282 – Information element used to generate look-up table for 'PDSCH-to-HARQ Feedback Timing Indicator'

★ The 'PDSCH-to-HARQ Feedback Timing Indicator' determines the delay between the end of the slot used to transfer the PDSCH and the start of the slot used to return the HARQ acknowledgement. Figure 381 illustrates the pattern for a PDSCH subcarrier spacing which is equal to the PUCCH subcarrier spacing. It also illustrates the patterns for PDSCH subcarrier spacings which are less than, or greater than the PUCCH subcarrier spacing. Slot numbering is always based upon the PUCCH numerology and the timing reference is the PUCCH slot number during which the PDSCH transmission finishes

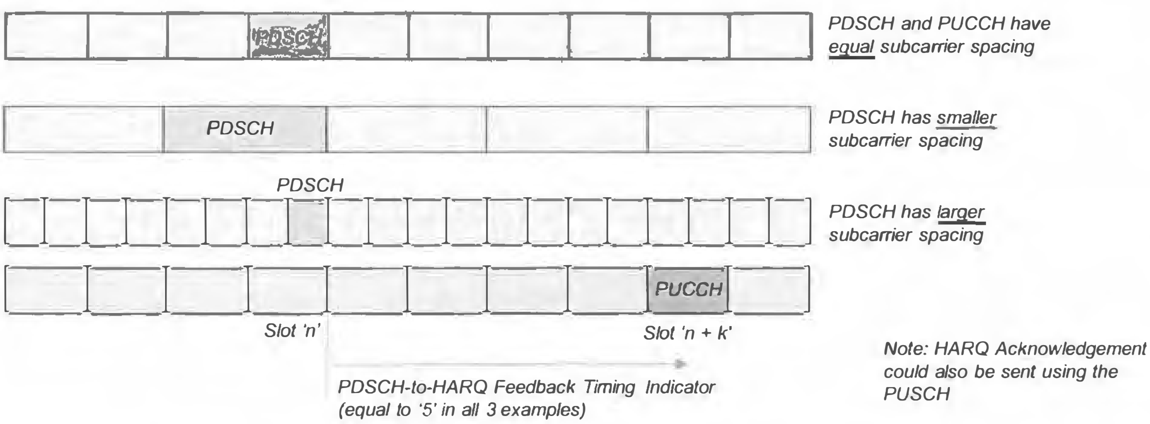


Figure 381 – HARQ Acknowledgement timing based upon PDSCH-to-HARQ Feedback Timing Indicator

★ The 'PDSCH-to-HARQ Feedback Timing Indicator' look-up table associated with DCI Format 1_1 can be configured with a larger range of values relative to those used by DCI Format 1_0. In particular, the look-up table can be configured with a value of 0 which corresponds to the special case required when generating a 'self contained' slot. This refers to a single slot which includes the resource allocation, the data transfer and the HARQ acknowledgement

★ An example downlink self contained slot is illustrated in Figure 382. This example, uses a single symbol for the resource allocation on the PDCCH. The data transfer on the PDSCH occupies 9 symbols, while a 'short' PUCCH format is used at the end of the slot to provide the HARQ acknowledgement. There is a guard period of 2 symbols to allow time for transceiver switching and this example also includes a symbol allocated to the Sounding Reference Signal (SRS) which the Base Station can use to measure the propagation channel in preparation for its next downlink transmission (assuming channel reciprocity)

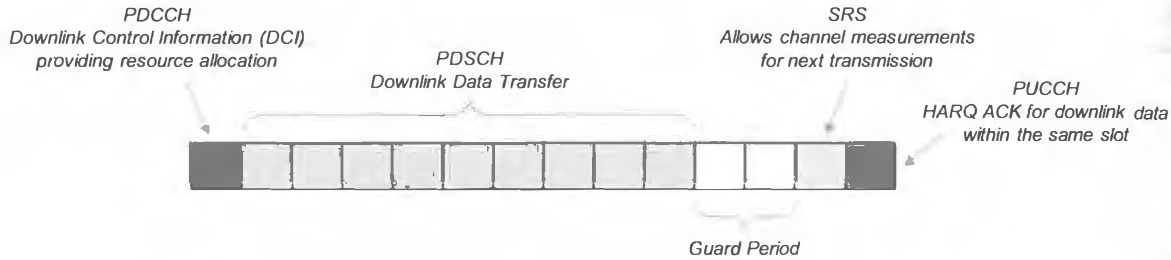


Figure 382 – Example of a Self Contained slot

★ A self contained slot is a significant challenge for the UE processing capability. It requires very fast processing times for both the PDSCH decoding and the preparation for PUCCH transmission. 3GPP TS 38.214 specifies 2 categories of UE processing capability. PDSCH Processing Capability 1 is a mandatory requirement for all UE. PDSCH Processing Capability 2 is an optional requirement intended for more powerful devices with low latency requirements. PDSCH Processing Capabilities define the minimum time that a UE requires between the end of PDSCH reception and the start of PUCCH transmission, i.e. not all devices can support the self contained slot illustrated in Figure 382

★ Table 283 presents the requirements associated with PDSCH Processing Capabilities 1 and 2. These requirements have a dependence upon a $d_{1,1}$ variable which is presented in Table 284. The processing time requirements decrease for the higher subcarrier spacings (the number of symbols increases by less than a factor of 2 between consecutive subcarrier spacings, while the symbol duration decreases by a factor of 2). This is aligned with the general requirement for lower latency and faster processing at the high subcarrier spacings

★ The processing time requirements increase when additional Demodulation Reference Signals (DMRS) are included. This is because those additional DRMS are distributed across the PDSCH transmission in the time domain. This delays the start of PDSCH decoding because the UE typically waits until the DMRS has been received at multiple instants before starting the decoding process. This approach is adopted to allow the interpolation of the channel estimate between DMRS transmissions

★ The $d_{1,1}$ variable has a dependence upon the PDSCH 'finishing' time when using PDSCH Mapping Type A. PDSCH Mapping Type A means that resource allocations start during symbols 0, 1, 2, or 3, with durations of between 3 and 14 symbols. The processing time requirement is more stringent when the resource allocation finishes during the second half of the slot. Additional processing time is permitted if the resource allocation finishes during the first half of the slot. This is aligned with the PUCCH transmission at the end of the slot

★ The $d_{1,1}$ variable has a dependence upon the PDSCH duration when using PDSCH Mapping Type B. PDSCH Mapping Type B means that resource allocations start during symbols 0 to 12, with durations of 2, 4 or 7 symbols. The processing time requirement is more stringent when the resource allocation is long, i.e. the resource allocation is more likely to finish later in the slot. In this case, an additional 'd' variable is introduced to represent the number of overlapping symbols between the scheduling PDCCH and the corresponding PDSCH. There is one case for Mapping Type B and Processing Capability 2 where $d_{1,1}$ equals '3' or 'd'. The '3' value is adopted if the scheduling PDCCH was within a 3-symbol Control Resource Set (CORESET) and both the CORESET and the PDSCH had the same starting symbol. Otherwise the 'd' value is adopted

	PDSCH Processing Capability 1		PDSCH Processing Capability 2
	Front Loaded DMRS Only	Front Loaded and Additional DMRS	Front Loaded DMRS Only
15 kHz	$8 + d_{1,1}$ symbols	$13 + d_{1,1}$ symbols	$3 + d_{1,1}$ symbols
30 kHz	$10 + d_{1,1}$ symbols		$4.5 + d_{1,1}$ symbols
60 kHz	$17 + d_{1,1}$ symbols	$20 + d_{1,1}$ symbols	$9 + d_{1,1}$ symbols *
120 kHz	$20 + d_{1,1}$ symbols	$24 + d_{1,1}$ symbols	-

* applicable to frequency range 1

Table 283 – PDSCH processing time requirements for the UE as a function of subcarrier spacing

	PDSCH Mapping Type A
	PDSCH Processing Capabilities 1 & 2
PDSCH finishes during symbol 'i' within first half of the slot	$d_{1,1} = 7 - i$
PDSCH finishes during symbol 'i' within second half of the slot	$d_{1,1} = 0$

Note: 'd' is the number of overlapping symbols between the scheduling PDCCH and the corresponding PDSCH

	PDSCH Mapping Type B	
	PDSCH Processing Capability 1	PDSCH Processing Capability 2
PDSCH duration is 7 symbols	$d_{1,1} = 0$	$d_{1,1} = 0$
PDSCH duration is 4 symbols	$d_{1,1} = 3$	$d_{1,1} = d$
PDSCH duration is 2 symbols	$d_{1,1} = 3 + d$	$d_{1,1} = 3$ or d

Table 284 – '$d_{1,1}$' variable used as an input when calculating PDSCH processing time requirements

★ Processing Capability 2 is only applicable to Frequency Range 1 (450 MHz to 6 GHz), i.e. the lower subcarrier spacings. The example illustrated in Figure 382 is based upon Processing Capability 2 with the 15 kHz subcarrier spacing and PDSCH Mapping Type A

★ Another way to use the 'PDSCH-to-HARQ Feedback Timing Indicator' field is to group HARQ acknowledgements such that multiple PDSCH transmissions are acknowledged within a single uplink transmission. An example of this concept is illustrated in Figure 383. In this example, the 'PDSCH-to-HARQ Feedback Timing Indicator' is configured with decreasing values for 3 sequential PDSCH transmissions. The values are selected such that they all identify the same slot for returning the HARQ acknowledgements

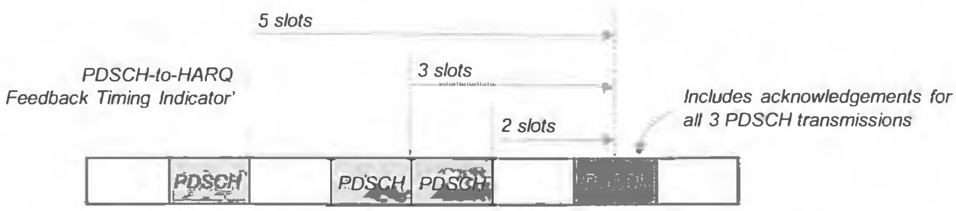


Figure 383 – Example of multiple PDSCH transmissions being acknowledged using a single PUCCH transmission

★ This approach increases the number of HARQ acknowledgements transferred by the PUCCH, so PUCCH Formats 2, 3 or 4 must be used (PUCCH Formats 0 and 1 are able to transfer a maximum of 2 HARQ acknowledgements). This example is based upon the PUCCH but the HARQ acknowledgements could also be returned using the PUSCH. The HARQ ACK codebooks described in section 13.5.1.3 are used when transferring groups of acknowledgements on the PUCCH or PUSCH

★ The PUCCH Resource Indicator (listed towards the start of this section) is a 3 bit field within the DCI which defines a pointer towards a specific PUCCH Resource. The UE uses this PUCCH Resource to send the HARQ acknowledgement(s) for the downlink transmission. The PUCCH Resource Indicator is ignored if the UE is allocated PUSCH resources which coincide with the timing of the transmission of the HARQ acknowledgement(s), i.e. the HARQ acknowledgement(s) are transferred using the PUSCH rather than the PUCCH

★ The Downlink Assignment Index (DAI) field (listed towards the start of this section) is used when a 'dynamic' HARQ ACK codebook has been configured. 3GPP has specified the use of both 'counter' and 'total' DAI fields. The use of these fields is described in section 13.5.1.3

★ The CBG Transmission Information (CBGTI) and CBG Flushing Information (CBGFI) fields are used when a transmission is configured to use Code Block Groups (CBG). The use of these fields is described in section 13.5.1.1

13.5.1.1 CODE BLOCK GROUPS (CBG)

★ The complexity of channel coding/decoding increases for large packet sizes. The complexity can be limited if the maximum packet size is restricted. In the case of the PDSCH, 3GPP has specified a maximum packet size of 8448 bits when using Low Density Parity Check (LDPC) Base Graph 1, and a maximum packet size of 3840 bits when using LDPC Base Graph 2

★ The Physical Layer applies segmentation to large Transport Blocks after CRC attachment to ensure that these maximum packet sizes are not exceeded. An additional CRC with a size of 24 bits is attached to each segment prior to channel coding so the segmentation procedure generates maximum packet sizes of 8448 – 24 = 8424 bits and 3840 – 24 = 3816 bits. The packets processed by the channel coding algorithm are known as Code Blocks. Each Code Block has its own set of CRC bits for error detection at the UE

★ If error detection and HARQ re-transmissions are managed 'per Transport Block' then a single bit error requires the whole Transport Block to be re-transmitted. The probability of a Transport Block including a bit error becomes greater as the Transport Block Size becomes larger. This can lead to inefficient resource utilisation because large volumes of data are re-transmitted due to a potentially small number of bit errors

★ If error detection and HARQ re-transmissions are managed 'per Code Block' then a single bit error requires only a single Code Block to be re-transmitted. This avoids the requirement to re-transmit large volumes of data when a single bit error occurs. The drawback to this solution is the increased requirement for HARQ acknowledgement signalling. The UE would be required to return a HARQ acknowledgement for each individual Code Block rather than a single HARQ acknowledgement per Transport Block

★ 3GPP has introduced support for a compromise solution based upon Code Block Groups (CBG). In this case, each individual Code Block still has its own CRC bits for error detection but HARQ acknowledgements and re-transmissions are managed 'per CBG'. Figure 384 illustrates the generation of CBG by segmenting a relatively large Transport Block

★ UE support for CBG is optional and is signalled to the Base Station using the *cbg-TransIndication-DL* information element shown in Table 285. This information element belongs to the *Phy-ParametersCommon* parameter structure which also includes the *cbg-FlushIndication-DL* information element. The *cbg-FlushIndication-DL* information element indicates whether or not the UE supports the reception of a CBG Flush Indicator (CBGFI) within DCI Format 1_1. This Flush Indicator is used to instruct the UE to empty its HARQ soft combining buffer when some of its downlink data may be corrupt, e.g. due to pre-emption (described in section 3.6.6)

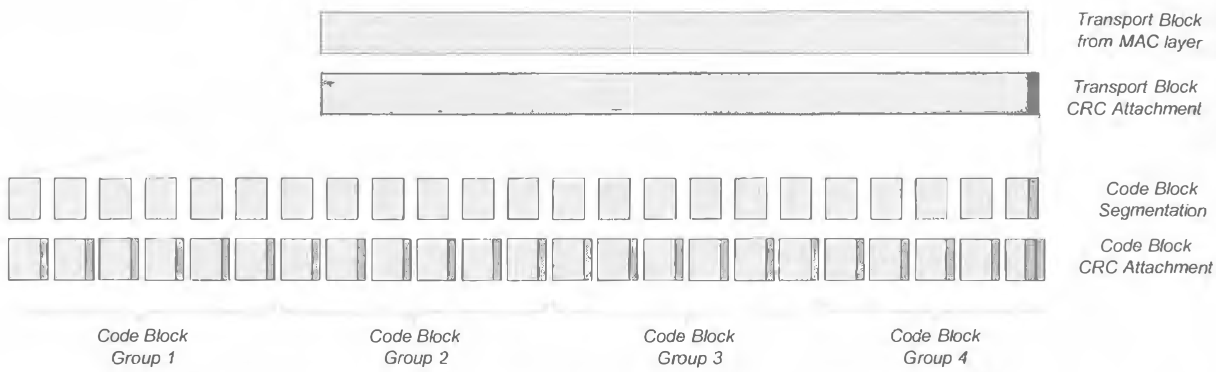


Figure 384 – Generating Code Block Groups (CBG) by segmentation

Phy-ParametersCommon	
cbg-TransIndication-DL	supported
cbg-FlushIndication-DL	supported

Table 285 – UE capability information for downlink Code Block Groups (CBG)

- The Base Station configures a UE to use Code Block Groups using the *PDSCH-ServingCellConfig* parameter structure presented in Table 281. This parameter structure can include the *maxCodeBlockGroupsPerTransmportBlock* information element which can be configured with values of 2, 4, 6 or 8 CBG. A maximum of 8 CBG can be specified when the UE is configured to receive a single Transport Block (up to 4 layers can be generated from a single Transport Block for the purposes of MIMO). A maximum of 4 CBG can be specified when the UE is configured to receive 2 Transport Blocks (more than 4 layers can be generated from a pair of Transport Blocks for the purposes of MIMO). Both the Base Station and the UE use the *maxCodeBlockGroupsPerTransmportBlock* information element to determine the number of CBG associated with a specific Transport Block. The number of CBG is given by MIN(Number of Code Blocks, *maxCodeBlockGroupsPerTransmportBlock*)
- A first Transport Block transmission includes all CBG, whereas re-transmissions include only those CBG which have been linked to a negative acknowledgement. The CBG Transmission Information (CBGTI) field within DCI Format 1_1 indicates which CBG are included within a specific transmission. This field can have a length of 0, 2, 4, 6 or 8 bits according to the configured maximum number of CBG, i.e. the CBGTI field is a bitmap where a '1' indicates that a specific CBG is included within the transmission
- The Base Station also uses the *PDSCH-ServingCellConfig* parameter structure to configure the use of the CBG Flush Indicator (CBGFI) field within DCI Format 1_1. When included, this field is a single bit which can be used as a flag to instruct the UE to empty its soft combining buffers for all CBG which are included within the PDSCH transmission (as indicated by the CBGTI field)

13.5.1.2 SPATIAL BUNDLING

- Spatial Bundling reduces the signalling overhead generated by HARQ acknowledgements, but can increase the volume of re-transmitted data. Spatial Bundling is applicable when the UE receives 2 Transport Blocks from a single cell, i.e. the UE receives more than 4 layers of downlink data. Rather than returning 1 HARQ acknowledgement per Transport Block, the UE returns one HARQ acknowledgement per pair of Transport Blocks
- The single HARQ acknowledgement is generated by completing a logical AND operation between the 2 HARQ acknowledgements generated from the 2 Transport Blocks. The logical AND operation means that the UE only sends a positive HARQ acknowledgement if both of the original HARQ acknowledgements are positive. Otherwise, the UE sends a negative HARQ acknowledgement. Sending a negative HARQ acknowledgement triggers the re-transmission of both Transport Blocks because the Base Station does not know which was received in error
- UE support for Spatial Bundling is optional and is signalled to the Base Station using the *spatialBundlingHARQ-ACK* information element shown in Table 286. This information element belongs to the *Phy-ParametersCommon* parameter structure

Phy-ParametersCommon	
spatialBundlingHARQ-ACK	supported

Table 286 – UE capability information for Spatial Bundling

- The Base Station configures a UE to use Spatial Bundling using the information elements presented in Table 287. These information elements belong to the *PhysicalCellGroupConfig* parameter structure. Their inclusion within the parameter structure indicates that Spatial Bundling should be applied. Spatial Bundling can be configured independently for the PUCCH and PUSCH. Reducing the signalling overhead may be more important for the PUCCH due to its lower capacity

PhysicalCellGroupConfig	
harq-ACK-SpatialBundlingPUCCH	true
harq-ACK-SpatialBundlingPUSCH	true

Table 287 – Information elements used to configure Spatial Bundling

13.5.1.3 HARQ ACK CODEBOOKS

- The HARQ ACK codebook defines the format used to signal a set of HARQ acknowledgements to the Base Station. The codebook allows the UE to multiplex the HARQ acknowledgements from multiple slots, multiple carriers, multiple Transport Blocks and multiple Code Block Groups (CBG) within a single transmission. It is important that both the UE and Base Station share the same understanding of the codebook format to ensure that each acknowledgement is linked to the appropriate transmission
- 3GPP has specified 2 categories of codebook:
  - Type 1 codebook (semi-static): the size of this codebook is fixed by information provided by RRC signalling
  - Type 2 codebook (dynamic): the size of this codebook changes according to the number of resource allocations
- The Base Station configures the use of a specific codebook category using the *pdsch-HARQ-ACK-Codebook* information element. This information element (shown in Table 288) belongs to the *PhysicalCellGroupConfig* parameter structure

PhysicalCellGroupConfig	
pdsch-HARQ-ACK-Codebook	semiStatic, dynamic

Table 288 – Information element used to configure HARQ ACK codebook

- The size of a semi-static codebook is defined as the sum of all possible transmission opportunities within a specific time window. This sum accounts for the possibility of multiple PDSCH transmitted within a single slot; multiple PDSCH transmitted across slots; multiple PDSCH transmitted across carriers; multiple Transport Blocks belonging to a specific PDSCH; and multiple Code Block Groups (CBG) belonging to a specific Transport Block
- The time window across which the transmission opportunities are summed depends upon the Downlink Control Information (DCI) format used to allocate the PDSCH resources
  - if DCI Format 1_0 is used, the 'PDSCH-to-HARQ_feedback timing indicator' field can have a value from the set: {1, 2, 3, 4, 5, 6, 7, 8}. This means that the transmission of a HARQ ACK codebook during slot 'n' can include acknowledgements from PDSCH transmissions which were received during slots n-1, n-2, n-3, … n-8, i.e. the time window can include 8 consecutive slots
  - if DCI Format 1_1 is used, the 'PDSCH-to-HARQ_feedback timing indicator' field can have a value selected from the set of values configured by the *dl-DataToUL-ACK* information element. The *dl-DataToUL-ACK* information element can be configured with up to 8 values within the range 0 to 15. For example, values {0,2,4,6,8,10,12,14} could be configured meaning that the transmission of a HARQ ACK codebook during slot 'n' can include acknowledgements from PDSCH transmissions which were received during slots n, n-2, n-4, n-6, n-8, n-10, n-12, n-14
- As an example, consider a UE which is configured with 2 carriers, where the first carrier transfers up to 4 layers (meaning a single Transport Block per transmission) and a maximum of 4 Code Block Groups per Transport Block, while the second carrier transfers up to 8 layers (meaning potentially 2 Transport Blocks per transmission) without using Code Block Groups. If 8 values are assumed for the 'PDSCH-to-HARQ_feedback timing indicator' field for both carriers and only a single transmission per slot is assumed then the codebook size is given by $(1 \times 4 \times 8) + (2 \times 1 \times 8) = 48$ bits, i.e. there is an entry within the codebook for each potential HARQ acknowledgement
- The semi-static codebook includes entries for multiple PDSCH transmissions per slot if the UE has been configured with {Start Symbol and Length} combinations which allow multiple non-overlapping PDSCH transmissions per slot. For example, if a UE is configured with a *PDSCH-TimeDomainResourceAllocationList* which includes {Start Symbol and Length} combinations of {0, 10}, {2, 4}, {3, 7}, {6, 4}, {10, 4} then the codebook allows for 3 transmissions per slot based upon the possibility of using the following sequence of resource allocations {2, 4}, {6, 4}, {10, 4}. If this configuration is applied to both carriers of the previous example then the codebook size increases from 48 bits to $3 \times 48 = 144$ bits
- A drawback of the semi-static codebook is that it has a fixed size. The previous example quotes a codebook size of 144 bits. The UE has to transmit these 144 bits irrespective of the number of actual resource allocations, e.g. the UE may receive only 2 resource allocations on the first carrier requiring only 8 acknowledgements (resulting from 4 Code Block Groups per resource allocation) but the UE would still need to transmit 144 bits. This example illustrates that the semi-static codebook can require a UE to transmit a relatively large number of bits for a small number of acknowledgements
- A benefit of the semi-static codebook is that it is robust against the UE failing to detect/decode a resource allocation on the PDCCH. All entries within the codebook for which the UE has not received a downlink resource allocation are populated with negative HARQ

PhysicalCellGroupConfig	
harq-ACK-SpatialBundlingPUCCH	true
harq-ACK-SpatialBundlingPUSCH	true

Table 287 – Information elements used to configure Spatial Bundling

13.5.1.3 HARQ ACK CODEBOOKS

★ The HARQ ACK codebook defines the format used to signal a set of HARQ acknowledgements to the Base Station. The codebook allows the UE to multiplex the HARQ acknowledgements from multiple slots, multiple carriers, multiple Transport Blocks and multiple Code Block Groups (CBG) within a single transmission. It is important that both the UE and Base Station share the same understanding of the codebook format to ensure that each acknowledgement is linked to the appropriate transmission

★ 3GPP has specified 2 categories of codebook:

- o Type 1 codebook (semi-static): the size of this codebook is fixed by information provided by RRC signalling
- o Type 2 codebook (dynamic): the size of this codebook changes according to the number of resource allocations

★ The Base Station configures the use of a specific codebook category using the *pdsch-HARQ-ACK-Codebook* information element. This information element (shown in Table 288) belongs to the *PhysicalCellGroupConfig* parameter structure

PhysicalCellGroupConfig	
pdsch-HARQ-ACK-Codebook	semiStatic, dynamic

Table 288 – Information element used to configure HARQ ACK codebook

★ The size of a semi-static codebook is defined as the sum of all possible transmission opportunities within a specific time window. This sum accounts for the possibility of multiple PDSCH transmitted within a single slot; multiple PDSCH transmitted across slots; multiple PDSCH transmitted across carriers; multiple Transport Blocks belonging to a specific PDSCH; and multiple Code Block Groups (CBG) belonging to a specific Transport Block

★ The time window across which the transmission opportunities are summed depends upon the Downlink Control Information (DCI) format used to allocate the PDSCH resources

- o if DCI Format 1_0 is used, the 'PDSCH-to-HARQ_feedback timing indicator' field can have a value from the set: {1, 2, 3, 4, 5, 6, 7, 8}. This means that the transmission of a HARQ ACK codebook during slot 'n' can include acknowledgements from PDSCH transmissions which were received during slots n-1, n-2, n-3, … n-8, i.e. the time window can include 8 consecutive slots
- o if DCI Format 1_1 is used, the 'PDSCH-to-HARQ_feedback timing indicator' field can have a value selected from the set of values configured by the *dl-DataToUL-ACK* information element. The *dl-DataToUL-ACK* information element can be configured with up to 8 values within the range 0 to 15. For example, values {0,2,4,6,8,10,12,14} could be configured meaning that the transmission of a HARQ ACK codebook during slot 'n' can include acknowledgements from PDSCH transmissions which were received during slots n, n-2, n-4, n-6, n-8, n-10, n-12, n-14

★ As an example, consider a UE which is configured with 2 carriers, where the first carrier transfers up to 4 layers (meaning a single Transport Block per transmission) and a maximum of 4 Code Block Groups per Transport Block, while the second carrier transfers up to 8 layers (meaning potentially 2 Transport Blocks per transmission) without using Code Block Groups. If 8 values are assumed for the 'PDSCH-to-HARQ_feedback timing indicator' field for both carriers and only a single transmission per slot is assumed then the codebook size is given by $(1 \times 4 \times 8) + (2 \times 1 \times 8) = 48$ bits, i.e. there is an entry within the codebook for each potential HARQ acknowledgement

★ The semi-static codebook includes entries for multiple PDSCH transmissions per slot if the UE has been configured with {Start Symbol and Length} combinations which allow multiple non-overlapping PDSCH transmissions per slot. For example, if a UE is configured with a *PDSCH-TimeDomainResourceAllocationList* which includes {Start Symbol and Length} combinations of {0, 10}, {2, 4}, {3, 7}, {6, 4}, {10, 4} then the codebook allows for 3 transmissions per slot based upon the possibility of using the following sequence of resource allocations {2, 4}, {6, 4}, {10, 4}. If this configuration is applied to both carriers of the previous example then the codebook size increases from 48 bits to $3 \times 48 = 144$ bits

★ A drawback of the semi-static codebook is that it has a fixed size. The previous example quotes a codebook size of 144 bits. The UE has to transmit these 144 bits irrespective of the number of actual resource allocations, e.g. the UE may receive only 2 resource allocations on the first carrier requiring only 8 acknowledgements (resulting from 4 Code Block Groups per resource allocation) but the UE would still need to transmit 144 bits. This example illustrates that the semi-static codebook can require a UE to transmit a relatively large number of bits for a small number of acknowledgements

★ A benefit of the semi-static codebook is that it is robust against the UE failing to detect/decode a resource allocation on the PDCCH. All entries within the codebook for which the UE has not received a downlink resource allocation are populated with negative HARQ

★ The second carrier is configured to transfer > 4 layers with Spatial Bundling enabled. This means that each transmission can include either 1 or 2 Transport Blocks but in both cases only a single HARQ acknowledgement is generated to populate the codebook. The single HARQ acknowledgement is generated by applying a logical AND operation to the pair of acknowledgements belonging to the pair of Transport Blocks. If only a single Transport Block has been transmitted then the HARQ acknowledgement is set equal to the acknowledgement for that Transport Block

★ Similar to the first carrier, the *dl-DataToUL-ACK* information element can be configured with up to 8 values between 0 and 15. These values determine the slots during which downlink data may be received (they do not have to be equal for each carrier). The example illustrated in Figure 385 indicates that downlink data may be transferred during the slots which precede the transmission of the HARQ ACK codebook by {15, 13, 12, 10, 4, 3, 1, 0} slots. In this example, it is assumed that downlink data is only transferred during the slots indexed as -13, -12, -3 and 0. HARQ acknowledgements are generated for these slots based upon the success or failure of the decoding process. Downlink data is not transferred during the slots indexed as -15, -10, -4 and -1. The UE populates these entries within the codebook using negative acknowledgements

★ The third carrier is configured to transfer > 4 layers without Spatial Bundling enabled. This means that each transmission can include either 1 or 2 Transport Blocks and in both cases, the UE has to generate 2 entries within the codebook. If the transmission includes 2 Transport Blocks then the 2 entries are based upon the success or failure of the decoding process for each Transport Block. If the transmission includes only 1 Transport Block then the first entry is based upon the success or failure of the decoding process, while the second entry is populated using a negative acknowledgement. Figure 385 illustrates examples of the UE receiving only a single Transport Block in slots indexed as -11 and -2. Similar to the other carriers, the UE populates the codebook with negative acknowledgements when it does not receive a downlink transmission

★ The fourth carrier is configured to transfer ≤ 4 layers with a maximum of 4 Code Block Groups (CBG). All 4 CBG will be present when the single Transport Block is relatively large, i.e. it requires segmentation into 4 or more code blocks. Less than 4 CBG will be present when the single Transport Block is relatively small. The semi-static codebook contains entries for all 4 CBG irrespective of the actual number of CBG. The UE populates unused codebook entries with a negative acknowledgement when less than 4 CBG are received. Otherwise, codebook entries are based upon the success or failure of the decoding process for each CBG. Negative acknowledgements are generated for all CBG if the final Transport Block fails its CRC check after each individual CBG has passed its CRC check, i.e. there is a small probability that the individual CRC checks do not detect a bit error which is subsequently detected by the Transport Block CRC check

★ The dynamic (Type 2) codebook helps to improve efficiency by excluding codebook entries which correspond to unused transmission opportunities. This type of codebook poses a challenge in terms of maintaining the correct relationship between acknowledgement and transmission. In the case of a static codebook, if a UE misses a resource allocation on the PDCCH then the UE populates the codebook entry with a negative acknowledgement, i.e. it does not impact the one-to-one mapping between codebook entry and transmission. In the case of a dynamic codebook, if a UE misses a resource allocation on the PDCCH then the codebook size becomes smaller from the UE perspective and the Base Station starts to map acknowledgements onto incorrect transmissions. This potential issue is illustrated in Figure 386

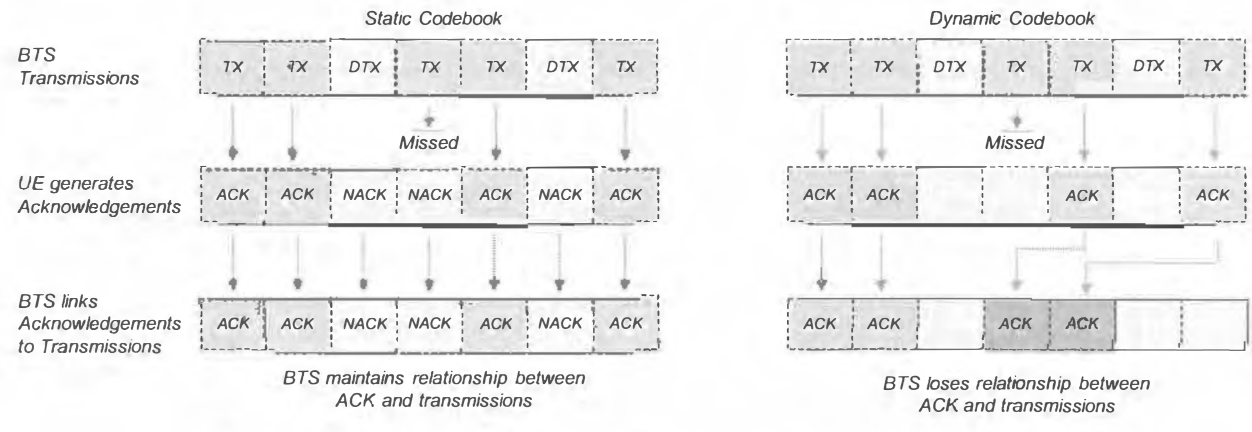


Figure 386 – Potential impact of missed transmission upon dynamic HARQ ACK codebook (3GPP has specified a solution to avoid this potential impact)

★ 3GPP has specified the use of a 'counter' Downlink Assignment Indicator (DAI) and a 'total' DAI to help avoid issues created by missed transmissions. If the UE is configured with a single serving cell then only the counter DAI is required. Both DCI Formats 1_0 and 1_1 include a 2 bit field for the counter DAI. Figure 387 illustrates the general principle of using the counter DAI. The UE detects a missed transmission if it receives non-consecutive counter values. The UE can then insert a negative acknowledgement and maintain the relationship between the acknowledgements and the transmissions. The counter DAI has a range from 1 to 4 so is able to detect up to 3 consecutive missed transmissions. The counter value wraps after every 4th transmission so 4 consecutive missed transmissions would not be detected. 5 consecutive missed transmissions would be detected as a single missed transmission, etc.

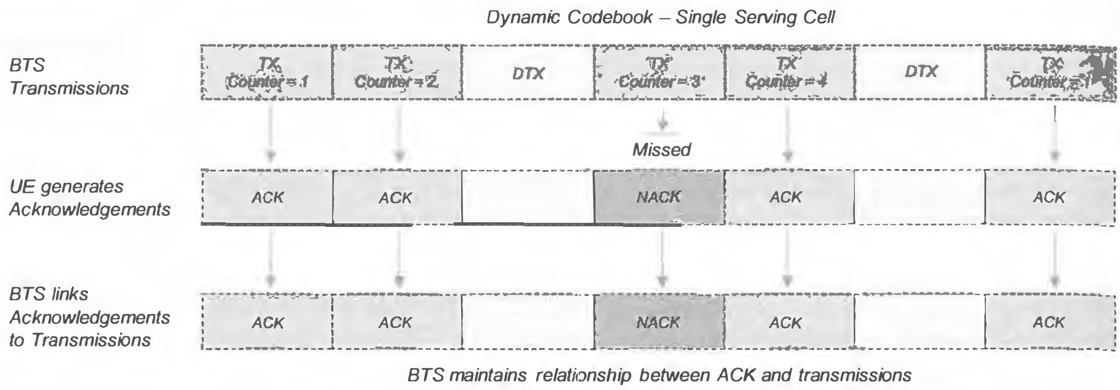


Figure 387 – Use of the counter DAI for a single serving cell

★ A combination of the counter DAI and total DAI is used when the UE is configured with multiple serving cells. DCI Format 1_1 includes a 2 bit field for the total DAI (in addition to the 2 bit field for the counter DAI). Figure 388 illustrates the general principle of using the combination of counter and total DAI. The counter DAI is incremented with each transmission across the set of carriers for each time domain transmission opportunity. The total DAI indicates the total number of transmissions at the end of each time interval. The UE can detect one or more missed transmissions by comparing the total DAI with the actual number of received transmissions at the end of each time interval. The counter DAI can be used to identify the location of any missed transmissions, i.e. identify the codebook position where a negative acknowledgement should be inserted. Similar to the counter DAI, the total DAI has a range from 1 to 4 so a group of 4 missed transmissions could go undetected

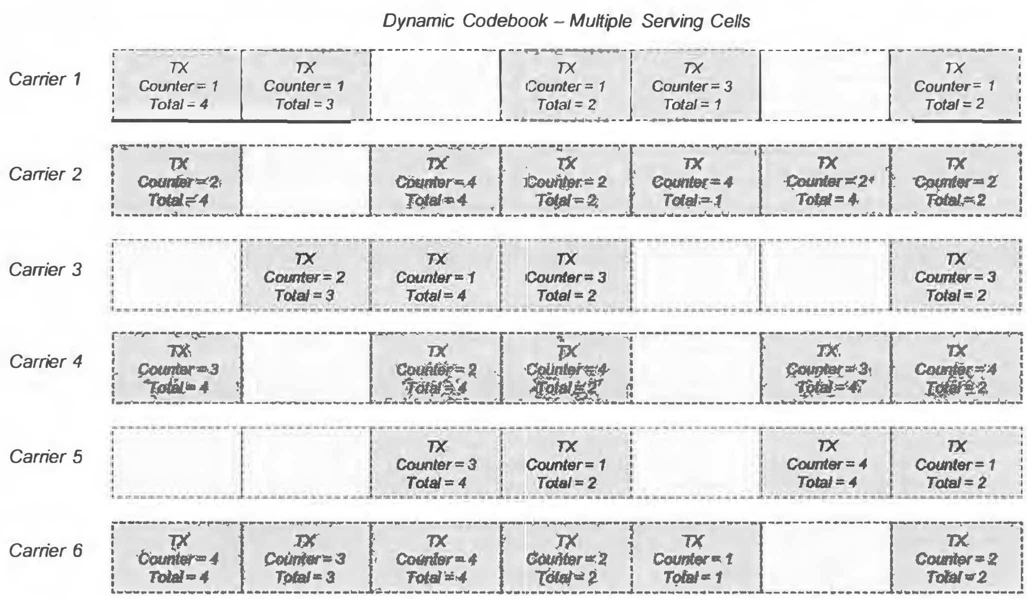


Figure 388 – Use of the counter and total DAI for multiple serving cells

★ An additional challenge associated with the dynamic HARQ ACK codebook occurs when a subset of carriers are configured to transfer 2 Transport Blocks, while the remaining carriers are configured to transfer 1 Transport Block. This scenario could potentially lead to an incorrect mapping between transmission and acknowledgement at the Base Station. An example based upon 4 carriers is illustrated in Figure 389. An important point is that the counter and total DAI are used to track the number of transmissions rather than the number of expected HARQ acknowledgements. For example, the counter DAI is incremented by 1 when a carrier transmits 2 Transport Blocks requiring 2 HARQ acknowledgements. A UE can use the counter and total DAI to detect a missed transmission, but the UE may not be able to deduce whether it should add 1 or 2 negative acknowledgements. In the case of Figure 389, the UE does not know whether it should add 2 negative acknowledgements for carrier 2 or 1 negative acknowledgement for carrier 3

★ 3GPP has solved this problem by specifying that if at least one carrier is configured to transfer 2 Transport Blocks, then the UE must generate acknowledgements as if all carriers are configured to transfer 2 Transport Blocks, i.e. 2 acknowledgements are generated for every transmission on every carrier. If the UE actually only receives 1 Transport Block on a carrier then it generates a negative acknowledgement to populate the second entry within the codebook. If the UE detects a missed transmission, then it knows that it must add 2 negative acknowledgements to the codebook. This solution increases the size of the codebook but avoids the risk of an incorrect mapping between acknowledgement and transmission at the Base Station

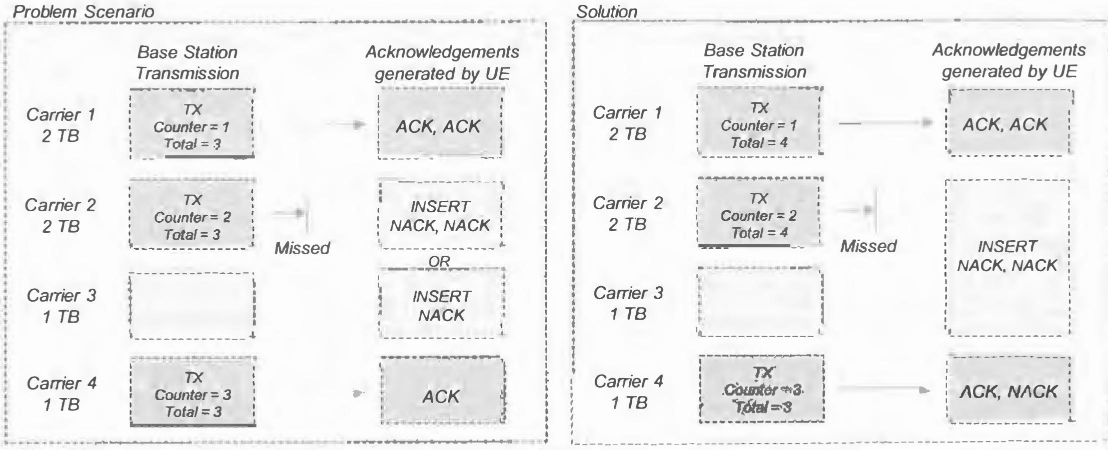


Figure 389 – Dynamic HARQ ACK codebook when a subset of carriers are configured for 2 Transport Blocks (TB)

★ A similar issue exists when a UE is configured to use Code Block Groups (CBG). For example, if carrier 2 within Figure 389 was configured to transfer 6 CBG while carrier 3 was configured to transfer 1 Transport Block without any CBG, then the UE would not know whether it should generate 6 negative acknowledgements for carrier 2 or 1 negative acknowledgement for carrier 3. It would be possible to adopt a similar solution as used for the 1 and 2 Transport Block scenario, i.e. generate 6 acknowledgements for all carriers. However, this would generate an unnecessarily large additional overhead when some carriers are not using CBG

★ 3GPP has adopted the solution illustrated in Figure 390. This solution divides the set of carriers into 2 groups and allows the UE to generate a HARQ ACK sub-codebook for each group. The first sub-codebook is generated from the carriers which require Transport Block based acknowledgements, whereas the second sub-codebook is generated from the carriers which require CBG based acknowledgements. The counter and total DAI values are generated and used independently for the 2 groups of carriers. If all carriers within the first group are configured to transfer a maximum of 1 Transport Block then the UE generates 1 acknowledgement for each transmission. If at least 1 carrier within the first group is configured to transfer 2 Transport Blocks then the UE generates 2 acknowledgements for carriers within that group. In the case of carriers configured to use CBG, the number of acknowledgements generated for each carrier is based upon the carrier which is configured with the highest number of CBG. The example in Figure 390, illustrates that carrier 6 has the highest number of CBG (6 CBG), and so the UE generates 6 acknowledgements for all carriers within the group. When a carrier transfers less than the highest number of CBG, the UE generates negative acknowledgements to populate additional entries within the sub-codebook

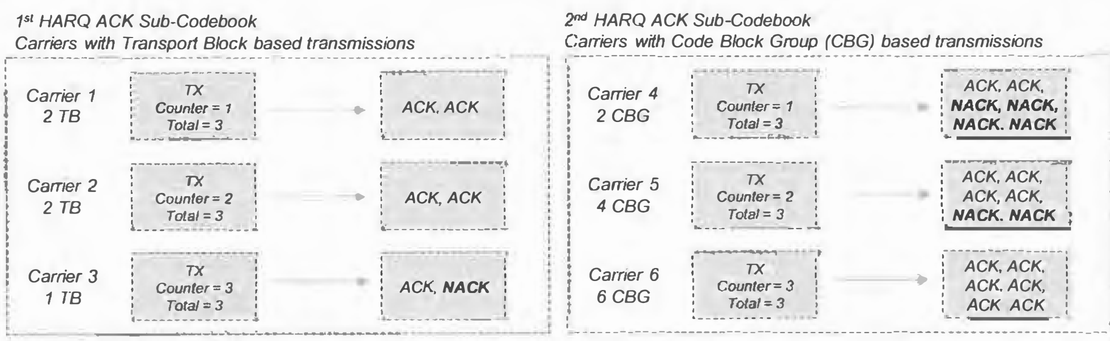


Figure 390 – Sub-codebooks used by dynamic HARQ ACK codebook

13.5.2 UPLINK HARQ

★ Uplink HARQ refers to the transfer of uplink data on the PUSCH with HARQ acknowledgements returned on the PDCCH. Uplink HARQ does not require the use of the codebooks described for the downlink. Instead, acknowledgements are returned individually on the PDCCH

★ Each serving cell has its own HARQ entity and its own set of HARQ processes. A UE is required to support 16 HARQ processes per serving cell:

- in the case of dynamic resource allocations, the Base Station uses PDCCH DCI Format 0_0 or 0_1 to specify the HARQ process associated with a PUSCH transmission. In this case, it is not necessary to configure the UE with a specific number of HARQ processes but the UE assumes that the Base Station can allocate up to 16 processes

- in the case of Configured Grants, the UE does not receive the PDCCH in advance of every PUSCH transmission. The UE is responsible for calculating the HARQ Process Identity associated with each transmission using the following expression:

  HARQ Process ID = [ROUNDDOWN (Current_Symbol / *periodicity*)] MOD *nrofHARQ-Processes*

  where, Current_Symbol = (SFN × SlotsPerFrame × SymbolsPerSlot) + (SlotNumber × SymbolsPerSlot) + SymbolNumber

  in the case of Configured Grants, the Base Station is responsible for configuring the number of HARQ processes and a periodicity. This is done using the *ConfiguredGrantConfig* information presented in Table 289. HARQ re-transmissions for Configured Grants are requested by the Base Station using the PDCCH. In this case, the PDCCH DCI specifies the HARQ process associated with the requested re-transmission

ConfiguredGrantConfig	
nrofHARQ-Processes	1 to 16
periodicity	2, 7, 1x14, 2x14, 4x14, 5x14, 8x14, 10x14, 16x14, 20x14, 32x14, 40x14, 64x14, 80x14, 128x14, 160x14, 256x14, 320x14, 512x14, 640x14, 1024x14, 1280x14, 2560x14, 5120x14, 6, 1x12, 2x12, 4x12, 5x12, 8x12, 10x12, 16x12, 20x12, 32x12, 40x12, 64x12, 80x12, 128x12, 160x12, 256x12, 320x12, 512x12, 640x12, 1280x12, 2560x12 symbols

Table 289 – Subset of the information belonging to *ConfiguredGrantConfig*

★ The PDSCH supports the transmission of up to 2 Transport Blocks using up to 8 layers. In contrast, the PUSCH supports the transmission of 1 Transport Block using up to 4 layers. This means that only a single Transport Block needs to be acknowledged after each transmission

★ Similar to the downlink, each transport block can include multiple Code Block Groups (CBG). Uplink HARQ is responsible for achieving reliable uplink data transfer by managing the re-transmission of transport blocks or the re-transmission of individual Code Block Groups

★ Similar to the downlink, uplink HARQ is asynchronous which means that there is no fixed timing pattern for each HARQ process. Instead, the Base Station must signal the identity of the relevant HARQ process with each uplink resource allocation (except when using Configured Grants). Asynchronous HARQ increases the signalling overhead but also increases flexibility because re-transmissions do not have to be scheduled during specific slots

★ Dynamic uplink resource allocations are provided on the PDCCH using Downlink Control Information (DCI) Formats 0_0 and 0_1. These DCI Formats include key information for the operation of uplink HARQ:

- HARQ Process Number
- New Data Indicator (NDI)
- Redundancy Version (RV)
- CBG Transmission Information (CBGTI)

★ The HARQ process number occupies 4 bits within the DCI providing a range from 0 to 15. The value specifies the HARQ process identity associated with the transmission belonging to the uplink resource allocation

★ The New Data Indicator (NDI) is a 1 bit flag which serves as a HARQ acknowledgement for the previous transmission associated with the specified HARQ Process Number:

- toggling the NDI value relative to its previous value for the specified HARQ Process Number, instructs the UE to initiate a new transmission. This corresponds to a positive acknowledgement for the previous transmission
- using the same NDI value relative to its previous value for the specified HARQ Process Number, instructs the UE to complete a re-transmission. This corresponds to a negative acknowledgement for the previous transmission

★ The Base Station can configure a UE to use Code Block Groups (CBG) on the PUSCH using the *codeBlockGroupTransmission* information element presented in Table 290. In this case, the UE can use the CBG Transmission Information (CBGTI) field within DCI Format 0_1 to determine which CBG require re-transmission. The CBGTI is a bitmap of length 0, 2, 4, 6 or 8 bits, where each bit corresponds to a specific CBG. A '1' indicates that the CBG should be transmitted. For an initial transmission, the UE expects all bits to be set to '1'

PUSCH-ServingCellConfig		
codeBlockGroupTransmission	maxCodeBlockGroupsPerTransportBlock	n2, n4, n6, n8

Table 290 – Information element used to configure Code Block Groups (CBG) on the PUSCH

★ The Redundancy Version (RV) is a set of 2 bits used to instruct the UE to apply a specific puncturing pattern to the PUSCH payload during rate matching. This allows the Base Station to change the puncturing pattern between the initial transmission and any re-transmissions. The Base Station receiver can then benefit from an Incremental Redundancy gain by receiving a different set of Physical layer bits with each transmission

★ 3GPP References: TS 38.331, TS 38.321, TS 38.214, TS 38.213, TS 38.212

13.6 CHANNEL STATE REPORTING

★ The UE reports Channel State Information (CSI) to the Base Station using either the PUSCH or the PUCCH. The Base Station uses the CSI to support its downlink transmissions on the PDSCH and PDCCH

★ Channel State Information (CSI) includes:

- o Channel Quality Indicator (CQI)
- o Rank Indicator (RI)
- o Precoding Matrix Indicator (PMI)
- o SS/PBCH Block Resource Indicator (SSBRI)
- o CSI-RS Resource Indicator (CRI)
- o Layer Indicator (LI)
- o LI-RSRP

★ The Base Station can use this information within its Packet Scheduler and Link Adaptation algorithms, i.e. when the Base Station is selecting UE to receive resource allocations, and when the Base Station is identifying the Modulation and Coding Schemes (MCS) for each PDSCH transmission. In the case of the PDCCH, the Channel State Information can be used when selecting an appropriate Control Channel Element (CCE) aggregation level, i.e. UE in poor coverage are allocated higher aggregation levels

★ Channel State Information is used for open loop and closed loop MIMO transmission schemes. Open loop schemes rely upon the UE reporting CQI and RI, whereas closed loop schemes rely upon the UE reporting CQI, RI and PMI, i.e. closed loop schemes allow the UE to recommend a precoding matrix for downlink transmission. The value of this recommendation depends upon the rate at which the radio environment is changing. Open loop schemes can be more appropriate for rapidly changing radio environments because recommended precoding matrices become invalid before being used. It is also possible to use semi-open loop MIMO which is based upon having partial precoding matrix feedback from the UE, i.e. the UE provides coarse precoding information which is less likely to be changing rapidly over time

★ Channel State Information remains necessary when channel reciprocity exists. The Base Station can take advantage of channel reciprocity to deduce the downlink precoding from uplink measurements. However, uplink measurements do not provide the Base Station with information regarding the downlink signal to noise ratio conditions. Thus, there remains a requirement for the UE to provide feedback in terms of CQI

★ Channel State Information is also used for Beam Management, i.e. the SS/PBCH Block Resource Indicator (SSBRI) and CSI Reference Signal Resource Indicator (CRI) can be used to indicate the preferred SS/PBCH Block and CSI Reference Signal beams. The use of Channel State Information allows rapid and responsive switching between beams. Measurement reports transferred by the RRC layer would be too slow and infrequent for Beam Management purposes

★ In the case of the Phase Tracking Reference Signal (PTRS), Channel State Information can be used to select the best layer for transmission. The PTRS is transmitted using a single logical antenna port and performance is maximised if that antenna port is mapped onto the best transmission layer. A UE can be requested to report a Layer Indicator (LI) which identifies the layer with the best channel conditions. The Base Station can then use this information to map the PTRS onto the appropriate layer

★ The majority of parameters associated with CSI reporting are provided within the *CSI-reportConfig* parameter structure. The first part of this parameter structure is presented in Table 291. Each report configuration is allocated an identity and is linked to a specific serving cell

★ CSI reporting relies upon UE completing downlink measurements and subsequently providing feedback to the Base Station. These measurements are based upon CSI Reference Signal resources. Figure 187 in Section 3.7.4 illustrates the various categories of CSI Reference Signal. The *CSI-reportConfig* parameter structure uses:

- o the *resourcesForChannelMeasurement* information element to specify a Non-Zero Power (NZP) CSI Reference Signal for measuring the propagation channel based upon a 'wanted' signal
- o the *csi-IM-ResourcesForInterference* information element to specify CSI Reference Signal resources which the serving cell does not use for transmission. These resources allow the UE to measure the interference levels generated by neighbouring cells and background noise
- o the *nzp-CSI-RS-ResourcesForInterference* information element to specify CSI Reference Signal resources which the serving cell uses for transmission towards other UE (typically using different downlink beams). These resources allow the UE to measure the interference experienced when using Multi-User MIMO (MU-MIMO), i.e. multiple spatially separated UE sharing the same downlink Resource Blocks

★ The *reportConfigType* allows the CSI measurements to use a periodic, semi-persistent or aperiodic triggering mechanism. The semi-persistent triggering mechanism can be configured specifically for reporting on the PUCCH or for reporting on the PUSCH. Periodic reporting uses the PUCCH, unless a PUSCH resource allocation coincides with the reporting period. Aperiodic reporting always uses the PUSCH

★ In the case of periodic reporting, the UE is configured with *reportSlotConfig* which specifies the reporting period and a slot offset. The reporting period can range from 4 slots up to 320 slots. The minimum period of 4 slots corresponds to 4 ms when using the 15 kHz subcarrier spacing but only 0.5 ms when using the 120 kHz subcarrier spacing. The UE is also configured with the PUCCH resources which are to be used when sending the CSI reports to the Base Station

CSI-reportConfig (Part 1)										
reportConfigId	0 to 47									
carrier	ServCellIndex	0 to 31								
resourcesForChannelMeasurement	CSI-ResourceConfigId	0 to 111								
csi-IM-ResourcesForInterference	CSI-ResourceConfigId	0 to 111								
nzp-CSI-RS-ResourcesForInterference	CSI-ResourceConfigId	0 to 111								
reportConfigType	CHOICE									
	Periodic	reportSlotConfig	4 slots	0 to 3	16 slots	0 to 15	160 slots	0 to 159		
			5 slots	0 to 4	20 slots	0 to 19	320 slots	0 to 319		
			8 slots	0 to 7	40 slots	0 to 39				
			10 slots	0 to 9	80 slots	0 to 79				
		pucch-CSI-ResourceList	SEQUENCE { 1 to 4 instances of PUCCH-CSI-Resource }							
			uplinkBandwidthPartId	0 to 4						
			pucch-Resource	0 to 127						
	semiPersistent OnPUCCH	reportSlotConfig	4 slots	0 to 3	16 slots	0 to 15	160 slots	0 to 159		
			5 slots	0 to 4	20 slots	0 to 19	320 slots	0 to 319		
			8 slots	0 to 7	40 slots	0 to 39				
			10 slots	0 to 9	80 slots	0 to 79				
		pucch-CSI-ResourceList	SEQUENCE { 1 to 4 instances of PUCCH-CSI-Resource }							
			uplinkBandwidthPartId	0 to 4						
			pucch-Resource	0 to 127						
	semiPersistent OnPUSCH	reportSlotConfig	5, 10, 20, 40, 80, 160, 320 slots							
		reportSlotOffsetList	SEQUENCE { 1 to 16 instances of 0 to 32 }							
		p0alpha	0 to 29							
	aperiodic	reportSlotOffsetList	SEQUENCE { 1 to 16 instances of 0 to 32 }							

Table 291 – *CSI-reportConfig* parameter structure (Part 1)

★ In the case of semi-persistent reporting on the PUCCH, the UE is configured using the same format as used for periodic reporting. In the case of semi-persistent reporting on the PUSCH, the UE is configured with a reporting period which ranges between 5 and 320 slots, but the UE is not configured with a specific slot offset. Instead the UE is configured with a list of candidate slot offsets. The number of candidate slot offsets is equal to the number of entries within the *pusch-TimeDomainAllocationList* belonging to the *PUSCH-Config*. This means that the 'Time Domain Resource Assignment' field within the Downlink Control Information (DCI) points towards both a time domain resource allocation and a corresponding slot offset for semi-persistent CSI reporting on the PUSCH. The UE is also configured with a *p0alpha* information element which points towards a specific power control parameter set for the PUSCH

★ In the case of semi-persistent reporting on the PUSCH, 3GPP specified additional reporting periods of 4, 8 and 16 slots within version 15.3 of the specifications. These additional reporting periods are visible at the bottom of Table 293

★ In the case of aperiodic reporting, the UE is only configured with a list of slot offsets (a reporting period is not required because the UE sends only a single report). The number of candidate slot offsets is equal to the number of entries within the *pusch-TimeDomainAllocationList* belonging to the *PUSCH-Config*. Similar to semi-persistent reporting on the PUSCH, the 'Time Domain Resource Assignment' field within the Downlink Control Information (DCI) points towards both a time domain resource allocation and a corresponding slot offset for the aperiodic CSI reporting on the PUSCH

★ Table 291 illustrates that CSI reporting can be periodic, semi-persistent or aperiodic. In addition, the CSI Reference Signal transmissions which are used to derive the CSI measurements can also be periodic, semi-persistent or aperiodic. For example, an aperiodic CSI report can be generated using a periodic CSI Reference Signal transmission. Table 292 summarises each combination of CSI report triggering and CSI Reference Signal transmission triggering

★ Periodic CSI reporting requires periodic CSI Reference Signal transmission. In this case, both the reporting and CSI Reference Signal transmission are configured and initiated using RRC signalling

★ Semi-persistent CSI reporting on the PUCCH and semi-persistent CSI Reference Signal transmission are both triggered using MAC Control Elements, i.e. the 'Semi-Persistent CSI Reporting on PUCCH Activation / Deactivation' and 'Semi-Persistent CSI-RS / CSI-IM Resource Set Activation / Deactivation' MAC Control Elements. In contrast, semi-persistent CSI reporting on the PUSCH is triggered using the 'CSI Request' field within PDCCH Downlink Control Information (DCI) Format 0_1 when the CRC bits have been scrambled using an SP-CSI-RNTI

★ Aperiodic CSI reporting and aperiodic CSI Reference Signal transmission are both triggered using the 'CSI Request' field within DCI Format 0_1

	Periodic CSI Reporting *No dynamic triggering*	Semi-Persistent CSI Reporting on the PUCCH *'SP CSI Reporting on PUCCH Act/Deact' MAC CE*	Semi-Persistent CSI Reporting on the PUSCH *'CSI Request' within DCI Format 0_1*	Aperiodic CSI Reporting *'CSI Request' within DCI Format 0_1*
Periodic CSI Reference Signal *No dynamic triggering*	Supported	Supported	Supported	Supported
Semi-Persistent CSI Reference Signal *'SP CSI-RS / CSI-IM Resource Set Act/Deact' MAC CE*	Not Supported	Supported	Supported	Supported
Aperiodic CSI Reference Signal *'CSI Request' within DCI Format 0_1*	Not Supported	Not Supported	Not Supported	Supported

Table 292 – Triggering of CSI Reporting and CSI Reference Signal Transmission

★ The second part of the *CSI-reportConfig* parameter structure is presented in Table 293. The *reportQuantity* specifies the content of the reports to be provided by the UE. The majority of reports include a CSI Reference Signal Resource Indicator (CRI) which is used for Beam Management purposes, i.e. the UE specifies the best CSI Reference Signal beam to be used for subsequent downlink data transfer. The *reportQuantity* can be configured with the following values:

- '*none*': in this case the UE does not provide the Base Station with a CSI report. This is applicable to scenarios where the UE uses the CSI Reference Signal for its own internal procedures rather than for providing feedback to the Base Station. For example, the 'P3' phase of Beam Management illustrated in Figure 190 (Section 3.7.4.1) involves the Base Station repeating a CSI Reference Signal transmission to allow the UE to attempt reception with each UE beam. The UE is then able to identify the best UE beam and use that beam for subsequent data transfer. The Base Station does not require knowledge of the beam selected by the UE

- '*cri-RI-CQI*': the Rank Indicator (RI) and Channel Quality Indicator (CQI) can be used for an Open Loop MIMO transmission scheme. The Base Station could repetitively cycle through a set of pre-defined precoding matrices. The UE does not require explicit knowledge of these precoding matrices because it can rely upon the Demodulation Reference Signal (DMRS) to deduce the composite impact of the precoding and propagation channel. Alternatively, the '*cri-RI-CQI*' value can be used when there is channel reciprocity and the Base Station is able to determine an appropriate precoding matrix from uplink SRS measurements

- '*cri-RI-PMI-CQI*': the RI, CQI and Precoding Matrix Indicator (PMI) can be used for a Closed Loop MIMO transmission scheme. 3GPP has specified a set of 4 codebook categories for PMI reporting – Type 1 Single Panel and Multi-Panel codebooks for single user MIMO with a maximum rank of 8; Type 2 Single Panel and Port Selection codebooks for multi-user MIMO but restricted to a maximum of rank 2. Type 1 codebooks provide relatively coarse information, whereas Type 2 codebooks provide more detailed information at the cost of an increased signalling overhead

- '*cri-RI-LI-PMI-CQI*': is also applicable to Closed Loop MIMO transmission schemes but also provides the Base Station with Layer Indicator (LI) information. The LI information can be used for mapping specific logical antenna ports onto the best transmission layer, e.g. the antenna port used by the Phase Tracking Reference Signal (PTRS)

- '*cri-RI-i1-CQI*': is applicable to semi-open loop transmission schemes. In this case, the UE does not report complete precoding information (the combination of 'i1' and 'i2') but reports partial precoding information (only 'i1'). This option is used in combination with the Type 1 Single Panel codebook. The UE reports a single wideband PMI result which is assumed to change relatively slowly as a function of time. The Base Station can combine additional open loop precoding with the reported wideband precoding. In general, reported CQI values are 'conditioned' upon the reported PMI values, i.e. the CQI value is valid when the Base Station transmits using the suggested precoding matrix. In this case, the UE is reporting only partial PMI so 3GPP has specified that the UE should assume a random selection of precoding matrix for the remaining PMI. 3GPP also specifies that the UE can assume that precoding is applied to Precoding Resource Block Groups (PRG) which have a size equal to *pdsch-BundleSizeForCSI* (shown in Table 293)

- '*cri-RI-i1*': instructs the UE to report RI and partial PMI but does not instruct the UE to report CQI. This configuration can be used in combination with a second configuration to support a hybrid solution. When configured with 'cri-RI-i1', the UE reports a single wideband partial PMI using the Type 1 Single Panel codebook. This result allows the Base Station to generate a coarse beam towards the UE. The UE can be instructed to provide a second report, for example using '*cri-RI-PMI-CQI*' with the Type 2 Port Selection codebook. This codebook relies upon the use of beamforming when transmitting the CSI Reference Signal. The partial PMI from the first report can be used to beamform the CSI Reference Signal which is then used to generate the complete PMI for the '*cri-RI-PMI-CQI*' report

- '*cri-RSRP*': can be used for Beam Management procedures. The UE can be instructed to report up to four CSI Reference Signal Resource Indicators (CRI) in combination with up to four Layer 1 RSRP measurements. This option can be used for 'Group based Beam Reporting' which allows the UE to report up to two CRI belonging to beams which have been received simultaneously. Group based Beam Reporting is applicable to deployments using multiple Transmit Receive Points (TRP) (see section 13.6.5)

- '*ssb-Index-RSRP*': can also be used for Beam Management procedures. In this case the UE can be instructed to report up to four SS/PBCH Block Resource Indicators (SSBRI) in combination with up to four Layer 1 RSRP measurements. Similar to '*cri-RSRP*', this option can also be used for 'Group based Beam Reporting' when deployments take advantage of multiple TRP

CSI-reportConfig (Part 2)							
reportQuantity	CHOICE						
	none						
	cri-RI-PMI-CQI						
	cri-RI-i1						
	cri-RI-i1-CQI	pdsch-BundleSizeForCSI	2, 4				
	cri-RI-CQI						
	cri-RSRP						
	ssb-Index-RSRP						
	cri-RI-LI-PMI-CQI						
reportFreq Configuration	cqi-FormatIndicator	widebandCQI, subbandCQI					
	pmi-FormatIndicator	widebandPMI, subbandPMI					
	csi-ReportingBand	CHOICE					
		3 subbands	bitstring (3)	9 subbands	bitstring (9)	15 subbands	bitstring (15)
		4 subbands	bitstring (4)	10 subbands	bitstring (10)	16 subbands	bitstring (16)
		5 subbands	bitstring (5)	11 subbands	bitstring (11)	17 subbands	bitstring (17)
		6 subbands	bitstring (6)	12 subbands	bitstring (12)	18 subbands	bitstring (18)
		7 subbands	bitstring (7)	13 subbands	bitstring (13)	19 subbands	bitstring (19)
		8 subbands	bitstring (8)	14 subbands	bitstring (14)		
timeRestrictionForChannelMeasurements	configured, notConfigured						
timeRestrictionForInterferenceMeasurements	configured, notConfigured						
codebookConfig	see Table 298 in section 13.6.3						
groupBasedBeamReporting	CHOICE						
	enabled						
	disabled	nrofReportedRS	1, 2, 3, 4				
cqi-Table	table1, table2, table3						
subbandSize	value1, value2						
non-PMI-PortIndication	SEQUENCE { 1 to 128 instances of PortIndexFor8Ranks }						
	PortIndex For8Ranks	CHOICE					
		portIndex8	rank1, rank2, rank3, rank4, rank5, rank6, rank7, rank8				
		portIndex4	rank1, rank2, rank3, rank4				
		portIndex2	rank1, rank2				
		portIndex1	NULL				
semiPersistentOnPUSCH-v1530	reportSlotConfig-v1530	4, 8, 16 slots					

Table 293 – *CSI-reportConfig* parameter structure (Part 2)

★ The *cqi-FormatIndicator* and *pmi-FormatIndicator* are used to instruct the UE to provide either wideband or sub-band information. Wideband information is applicable to the complete Bandwidth Part specified within the *CSI-ResourceConfig* associated with the *resourcesForChannelMeasurement* (see Table 291). Sub-band reporting divides the Bandwidth Part into a set of sub-bands according to the *subbandSize* information element. The *csi-ReportingBand* information element indicates the specific set of sub-bands for which the UE should generate reports. Sub-band reporting is described in greater detail in section 13.6.1

★ The *timeRestrictionForChannelMeasurements* and *timeRestrictionForInterferenceMeasurements* are used to indicate whether or not the UE should use a specific time window when completing its channel (wanted signal) and interference measurements

★ The *codebookConfig* defines a relatively large parameter structure which is applicable to PMI reporting. This parameter structure is presented in Table 298 (section 13.6.3). The use of *groupBasedBeamReporting* is described in section 13.6.5

★ The *cqi-Table* specifies which of the 3 tables presented in section 13.6.1 are used for CQI reporting (64QAM table, 256QAM table or Low Spectral Efficiency table

★ The *non-PMI-PortIndication* is applicable when the UE is configured with *reportQuantity* set to 'cri-RI-CQI'. In general, CQI values are generated based upon the reported PMI value but in this case the UE does not report a PMI value. 3GPP specifies that for this case, the UE should assume an identity matrix for precoding, with the set of layers (according to the reported rank) mapped onto the set of CSI Reference Signal ports according to the information provided by the *non-PMI-PortIndication*

13.6.1 CHANNEL QUALITY INDICATOR

- Channel Quality Indicator (CQI) values allow a UE to quantify and report its downlink radio channel conditions within a specific Bandwidth Part. CQI values can be reported to the Base Station using either the PUCCH or the PUSCH
- The Base Station can use the CQI reports within its packet scheduling and link adaptation algorithms. If a Proportional Fair packet scheduler is used then UE reporting high CQI values relative to their average CQI values are more likely to be selected for resource allocation. Link adaptation is more likely to allocate high throughputs to UE reporting high CQI values
- CQI values represent a signal to interference plus noise ratio rather than a signal strength. This means a UE must complete both 'wanted' signal power measurements and interference plus noise power measurements
    - 'wanted' signal measurements are completed using a Non Zero Power (NZP) CSI Reference Signal. The relevant NZP CSI Reference Signal is identified by the *resourcesForChannelMeasurement* information element within the *CSI-reportConfig*
    - interference plus noise measurements are completed using a CSI Interference Measurement resource and/or an NZP CSI Reference Signal for Interference Measurement resource. These resources are identified by the *csi-IM-ResourcesForInterference* and *nzp-CSI-RS-ResourcesForInterference* information elements within the *CSI-reportConfig*
- 3GPP TS 38.214 specifies three CQI tables which correspond to the set of three PDSCH MCS tables, i.e. there is a 64QAM table, a 256QAM table and a Low Spectral Efficiency table. The three CQI tables are presented in Table 294, while the corresponding MCS tables are presented in Table 91, Section 3.6.1
- CQI values are signalled using a set of 4 bits which provide a range from 0 to 15. High CQI values indicate that the UE is able to receive high order modulation with a high coding rate, i.e. relatively little channel coding redundancy. The 'Efficiency' figures provide a measure of spectral efficiency and are given by the modulation order multiplied by the coding rate (modulation orders are QPSK: 2, 16QAM: 4, 64QAM: 6, 256QAM: 8)

	CQI Table 1 (64QAM Table)			CQI Table 2 (256QAM Table)			CQI Table 3 (Low Spectral Efficiency Table)		
	Transport Block Error Probability = 0.1			Transport Block Error Probability = 0.1			Transport Block Error Probability = 0.00001		
CQI Index	Modulation	Coding Rate	Efficiency	Modulation	Coding Rate	Efficiency	Modulation	Coding Rate	Efficiency
0	Out-of-Range			Out-of-Range			Out-of-Range		
1	QPSK	0.076	0.1523	QPSK	0.076	0.1523	QPSK	0.029	0.0586
2	QPSK	0.117	0.2344	QPSK	0.188	0.3770	QPSK	0.049	0.0977
3	QPSK	0.188	0.3770	QPSK	0.438	0.8770	QPSK	0.076	0.1523
4	QPSK	0.301	0.6016	16QAM	0.369	1.4766	QPSK	0.117	0.2344
5	QPSK	0.438	0.8770	16QAM	0.479	1.9141	QPSK	0.188	0.3770
6	QPSK	0.588	1.1758	16QAM	0.602	2.4063	QPSK	0.301	0.6016
7	16QAM	0.369	1.4766	64QAM	0.455	2.7305	QPSK	0.438	0.8770
8	16QAM	0.479	1.9141	64QAM	0.554	3.3223	QPSK	0.588	1.1758
9	16QAM	0.602	2.4063	64QAM	0.650	3.9023	16QAM	0.369	1.4766
10	64QAM	0.455	2.7305	64QAM	0.754	4.5234	16QAM	0.479	1.9141
11	64QAM	0.554	3.3223	64QAM	0.853	5.1152	16QAM	0.602	2.4063
12	64QAM	0.650	3.9023	256QAM	0.694	5.5547	64QAM	0.455	2.7305
13	64QAM	0.754	4.5234	256QAM	0.778	6.2266	64QAM	0.554	3.3223
14	64QAM	0.853	5.1152	256QAM	0.864	6.9141	64QAM	0.650	3.9023
15	64QAM	0.926	5.5547	256QAM	0.926	7.4063	64QAM	0.754	4.5234

Table 294 – CQI Tables for 64QAM, 256QAM and Low Spectral Efficiency

- The Base Station can request the UE to report either wideband or sub-band CQI values. This instruction is provided to the UE using the *cqi-FormatIndicator* within the *CSI-reportConfig* (Table 293). A wideband CQI provides a result which is derived from the complete Bandwidth Part. In contrast, a sub-band CQI provides a result which is derived from a specific section of the Bandwidth Part. The identity of the relevant Bandwidth Part is not immediately visible within the *CSI-reportConfig*. It is specified by the *bwp-Id* within the *CSI-ResourceConfig* which is identified by the *resourcesForChannelMeasurement* information element. The *CSI-ResourceConfig* parameter structure is presented in Table 116 (section 3.7.4)
- When using sub-band reporting, the Base Station uses the *subbandSize* information element within the *CSI-reportConfig* to select between a pair of sub-band sizes. These sub-band sizes (presented in Table 295) also depend upon the size of the Bandwidth Part

Bandwidth Part Size (Physical Resource Blocks)	Sub-band Size 1 (Physical Resource Blocks)	Sub-band Size 1 (Physical Resource Blocks)
< 24	Sub-band Reporting Not Applicable	
24 to 72	4	8
73 to 144	8	16
145 to 275	16	32

Table 295 – Sub-band sizes as a function of the Bandwidth Part size

★ Sub-bands are positioned using the Common Resource Block numbering that belongs to the overall channel bandwidth. This means that the first and last sub-bands belonging to a Bandwidth Part may be partial sub-bands. This depends upon the length of the Bandwidth Part and the position of the Bandwidth Part relative to the overall channel bandwidth. Examples of sub-bands within a series of Bandwidth Parts are illustrated in Figure 391

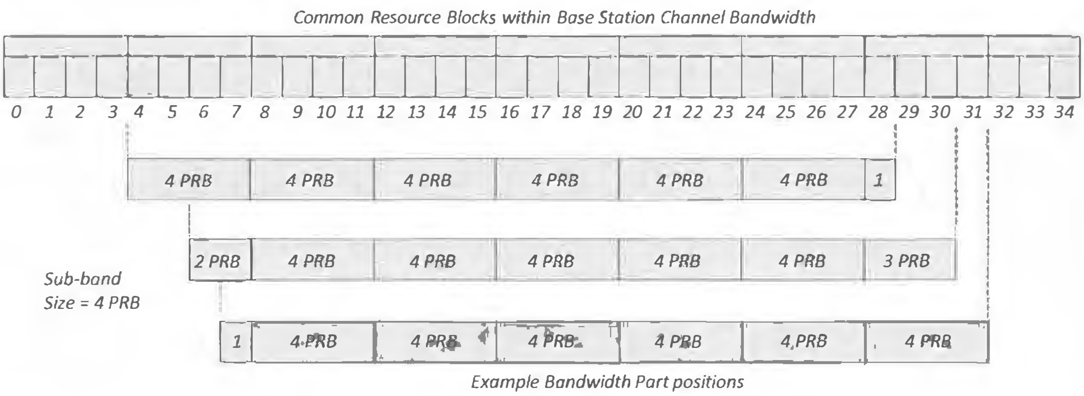


Figure 391 – Sub-bands belonging to a series of example Bandwidth Parts

★ A Bandwidth Part can include up to 19 sub-bands (72 / 4 = 18, plus 1 in case the Bandwidth Part is not aligned with the sub-band boundaries). This would create a signalling payload size of 19 × 4 × 2 = 152 bits if absolute CQI values were signalled for each sub-band associated with 2 codewords, i.e. when reporting a rank higher than 4. 3GPP has specified the use of differential CQI values for sub-band reporting. These differential values require only 2 bits rather than 4 bits so the signalling payload size is reduced by a factor of 2. Differential sub-band CQI values are defined relative to the wideband CQI value using the following expression:

Differential Sub-band CQI = Sub-band CQI Offset = Sub-band CQI   Wideband CQI

★ The mapping between CQI offset and the reported differential CQI value is presented in Table 296

Sub-band Differential CQI Value	Sub-band CQI Offset
0	0
1	1
2	≥ 2
3	≤ -1

Table 296 – Mapping for Differential CQI values

★ The Base Station can instruct the UE to report only a subset of the sub-bands within the Bandwidth Part. This is done using the *csi-ReportingBand* information element within the *CSI-reportConfig* (Table 293). *csi-ReportingBand* provides a bit string where each bit corresponds to a specific sub-band. The bit string can have a length which ranges from 3 to 19 bits, corresponding to the minimum and maximum number of sub-bands within a Bandwidth Part. The right-most bit within the bit string corresponds to the lowest sub-band within the Bandwidth Part

★ 3GPP TS 38.214 specifies that the CQI values reported by the UE are conditioned upon the reported Precoding Matrix Indicator (PMI), Rank Indicator (RI) and CSI Reference Signal Resource Indicator (CRI). This means that the reported CQI values assume that the Base Station applies the requested precoding, rank and CSI Reference Signal selection. It also means that a specific UE can report different CQI values even when the radio conditions are identical if the options for precoding are changed, i.e. the UE may report a higher CQI if the precoding options are improved (potentially using a Type 2 codebook rather than a Type 1 codebook). In addition, there are scenarios where the UE is requested to report CQI values without a PMI value, or with only a partial PMI value, i.e. *reportQuantity* set equal to 'cri-RI-CQI' or 'cri-RI-i1-CQI'. In these cases, 3GPP TS 38.214 provides additional rules regarding the precoding that the UE should assume when generating its CQI values

- UE report the CQI value which corresponds to the largest Transport Block size that can be received with a Transport Block error rate which does not exceed 10 % when using the 64QAM or 256QAM tables, or which does not exceed 0.001 % when using the Low Spectral Efficiency table. The CQI tables do not explicitly specify a Transport Block size for each CQI value but they allow the UE to calculate a Transport Block size based upon the modulation order, the coding rate and an assumed 'CSI Reference Resource'
- In the frequency domain, the 'CSI Reference Resource' corresponds to the set of Physical Resource Blocks within either the complete Bandwidth Part (if the UE is reporting a wideband CQI), or a sub-band belonging to the Bandwidth Part (if the UE is reporting a sub-band CQI)
- In the time domain, the 'CSI Reference Resource' corresponds to a single downlink slot. It is assumed that the first 2 symbols are allocated for control signalling, while the remaining 12 symbols are available for the PDSCH and DMRS. The DMRS is assumed to be 'front loaded' with the number of DMRS symbols equal to the value of *maxLength* within *DMRS-DownlinkConfig*. Additional DMRS symbols are assumed according to the value of *dmrs-AdditionalPosition*
- This indicates that the DMRS configuration may impact the reported CQI values. An increased DMRS overhead will lead to a smaller Transport Block size associated with each CQI value (although the coding rate for each CQI value will remain constant). A UE is likely to be capable of receiving higher coding rates for increased DMRS overheads due to the improved channel estimation. Thus, an increased DMRS overhead could lead to higher reported CQI values but potentially reduced throughputs due to the increased overhead (unless the performance benefit of the DMRS outweighs the increased overhead)
- It is also assumed that the Reference Resource uses the same subcarrier spacing as the PDSCH, and that no Resource Elements are occupied by the Synchronisation Signals, PBCH, NZP CSI Reference Signal nor ZP CSI Reference Signal
- As an example, consider a UE configured with 2×2 MIMO while reporting rank 2 with a wideband CQI value of 14 within the 64QAM CQI table. Assume a Bandwidth Part which includes 273 Resource Blocks, with a single front loaded DMRS symbol and no additional DMRS symbols. In this case, the approximate Transport Block size can be calculated as 2 MIMO layers × 273 Resource Blocks × 12 subcarriers × 11 symbols × 6 bits per modulation symbol × 873/1024 coding rate = 368 665 bits. If the subcarrier spacing is 30 kHz, the slot duration is 0.5 ms so the Physical layer throughput during a single downlink slot is 737 Mbps
- 3GPP References: TS 38.214

13.6.2 RANK INDICATOR

- Rank Indicators (RI) are applicable to both open loop and closed loop transmission schemes. The UE uses the Rank Indicator to request a specific number of MIMO layers
- In general, a Base Station is expected to generate the number of layers requested by the UE. However, there may be scenarios where the Base Station decides to use a different number of layers. For example, the Base Station may generate a reduced number of layers if the downlink buffer is relatively empty and there is insufficient data to justify the use of the requested number of layers
- When channel reciprocity exists, the Base Station may be able to deduce the downlink Rank using uplink measurements
- Rank Indicators are reported when the *reportQuantity* within the *CSI-reportConfig* is set to either 'cri-RI-PMI-CQI', 'cri-RI-i1', 'cri-RI-i1-CQI', 'cri-RI-CQI' or 'cri-RI-LI-PMI-CQI'
- The reported Rank Indicator is based upon the reported CSI Reference Signal Resource Indicator (CRI)
- The number of useful layers depends upon the propagation channel conditions. Transferring a high number of layers requires a corresponding high number of uncorrelated propagation paths between the transmitter and receiver
- 3GPP References: TS 38.214

13.6.3 PRECODING MATRIX INDICATOR

- The Precoding Matrix Indicator (PMI) allows the UE to report its preferred precoding for downlink transmissions on the PDSCH. The PMI is applicable to closed loop and semi-open loop transmission schemes. In the case of semi-open loop transmission schemes a partial PMI report is provided to the Base Station
- In the case of smaller antenna configurations, e.g. a single cross polar panel antenna, the PMI can indicate the preferred precoding for MIMO. In the case of larger antenna configurations, e.g. a 64 transceiver active antenna, the PMI can indicate the preferred precoding for both MIMO and beamforming
- It is not mandatory for the Base Station to apply the precoding indicated by the PMI, and the Base Station does not provide the UE with explicit information regarding the precoding which has been applied. Instead, the UE relies upon using the Demodulation Reference Signal (DMRS) when decoding the PDSCH. The DMRS is precoded in the same way as the PDSCH so it can be used to determine the composite impact of the propagation channel and the Base Station precoding
- The release 15 version of the 3GPP specifications relies upon 'implicit' Channel State Information. This means that the UE reports its preferred precoding for the current propagation channel conditions, but the UE does not explicitly specify the propagation channel which has been measured. 'Explicit' Channel State Information involves the UE reporting the actual propagation channel measurements, e.g. a set of multi-path components with a range of delays and amplitudes. It is likely that 'explicit' Channel State Information will be introduced within a later version of the 3GPP specifications
- The precoding matrices specified by 3GPP are based upon a specific set of assumed antenna configurations. These antenna configurations are specified by defining the number of rows and columns of cross polar antenna elements. For example, a smaller antenna may have 1 row and 2 columns of cross polar antenna elements, supporting a total of 4 transceivers. A larger antenna could have 4 rows and 4 columns of cross polar antenna elements, supporting a total of 32 transceivers. The set of antenna configurations assumed by 3GPP does not restrict live network deployments from using other configurations. The maximum antenna configuration assumed by 3GPP supports a total of 32 transceivers and is thus able to transmit 32 CSI Reference Signals. An actual network deployment could use an active antenna with 64 transceivers but for the purposes of CSI reporting it could transmit CSI Reference Signals using up to 32 of its transceivers
- The release 15 version of 3GPP TS 38.214 defines four solutions for PMI reporting. These solutions are summarised in Table 297 and are described in greater detail within the following sub-sections

	Type 1 Single Panel	*Type 1 Multi Panel*	*Type 2 Single Panel*	*Type 2 Port Selection*
Primary Utilisation	Single User MIMO		Multi-User MIMO	
MIMO Ranks	1 to 8	1 to 4	1 to 2	
Resolution	Normal		High	
Reporting Stages	Dual Stage reporting of Wideband and Sub-band information			
Reporting Content	Beam selection and co-phasing phase shifts		Weighted combination of beams with relative amplitudes and co-phasing phase shifts	
CSI RS Ports	2, 4, 8, 12, 16, 24, 32	8, 16, 32	4, 8, 12, 16, 24, 32	
Solution Type	Standalone			Hybrid, or combined with information from Beam Management or Channel Reciprocity
CSI RS Beamforming	CSI RS typically transmitted without Beamforming			CSI RS Beamformed

Table 297 – Solutions for PMI Reporting

- The 'Type 1 Single Panel' solution includes support for basic 2×2 MIMO without beamforming, e.g. when using a single cross polar panel antenna. It also provides support for 4×4 and 8×8 MIMO using larger antenna configurations which are also able to support beamforming. The 'Type 1 Multi-panel' solution provides support for Non-Uniform Antenna Arrays, i.e. the antenna element spacing between antenna panels is not equal to the antenna element spacing within a panel
- Both of the Type 1 solutions support PMI reporting in 2 stages. The first stage provides wideband information which does not change rapidly over time. This can involve beam selection, or beam group selection. The second stage provides sub-band information which changes more rapidly over time. This can involve beam selection from within a group and phase shift selection for co-phasing between polarisations, layers and antenna panels
- The Type 2 solutions focus upon providing more detailed Channel State Information for the purposes of Multi-User MIMO. They support a maximum Rank of 2 corresponding to a maximum of 2 layers per UE. The maximum number of layers per cell is likely to be higher to allow multiple UE to use 2×2 MIMO simultaneously while sharing a common Resource Block allocation
- Type 2 reports are based upon selecting a set of beams and then specifying relative amplitudes and phases to generate a weighted combination of beams for each layer of transmission. The 'Type 2 Port Selection' solution relies upon the Base Station having some advance information to allow beamforming of the CSI Reference Signal transmissions. This advance information can originate from uplink measurements if channel reciprocity is available. Otherwise it can originate from Beam Management reports or it can use the wideband reports from a different PMI reporting solution (this is known as a hybrid solution when a combination of PMI reporting solutions is used)

★ The majority of parameters associated with PMI reporting are configured using the *CodebookConfig* parameter structure presented in Table 298. This parameter structure uses the combination of *codebookType* and *subtype* to identify the relevant PMI reporting solution. The following sub-sections describe each of these PMI reporting solutions and the relevant parameter sets

★ In the case of the 'Type 1 Single Panel' codebook, the Base Station specifies the use of two antenna ports, or more than 2 antenna ports. If only 2 antenna ports are used then the codebook provides precoding for MIMO. If more than 2 antenna ports are used then the codebook provides precoding for both MIMO and beamforming. When using more than 2 antenna ports, the Base Station specifies the 'n1-n2' antenna configuration to be assumed by the UE (described in the next sub-section)

★ Each 'n1-n2' antenna configuration has an associated bit string which is used for codebook subset restriction (these bit strings are not shown in Table 298). For example, the '2-1' configuration uses a bit string of length 8 to specify its codebook subset restrictions. These restrictions can be used to limit the set of beams available for selection by the UE. 3GPP specifies an 'Oversampling' factor of 4 to increase the number of beams available for selection. This means that a '2-1' antenna configuration supports a total of $2 \times 4 = 8$ beams and these 8 beams correspond to the bit string of length 8. As a second example, the '4-4' configuration uses a bit string of length 256 to specify its codebook subset restrictions. In this case, the 'Oversampling' factor of 4 leads to a total of $(4 \times 4) \times (4 \times 4) = 256$ beams and these 256 beams correspond to the bit string of length 256. Note that in the first example, the number of beams was given by 2×4 and was not given by $(2 \times 4) \times (1 \times 4)$. This is because beamforming in the elevation direction is not possible when 'n2' = 1

★ The *CodebookConfig* specifies a second codebook subset restriction for the 'Type 1 Single Panel' codebook using the *typeI-SinglePanel-codebookSubsetRestriction-i2* information element. In this case, the restriction refers to 'i2' which corresponds to the second stage of PMI reporting (the first stage is based upon beam selection and generates 'i1'). The second stage of PMI reporting can be used to select 1 beam from a group of 4 beams (when using *codebookMode* = 2) and can also be used to select 1 phase shift from a set of 4 phase shifts. This leads to 16 combinations available for selection and thus a bit string of length 16 has been specified for the codebook subset restriction

★ In addition, it is possible to restrict the rank values reported by the UE. The 'Type 1 Single Panel' codebook supports up to rank 8 and so a bit string of length 8 has been specified

CodebookConfig							
codebookType	CHOICE						
	type1	subType	CHOICE				
			typeI-SinglePanel	nrOfAntennaPorts	CHOICE		
					two	twoTX-CodebookSubsetRestriction	
					moreThanTwo	n1-n2	CHOICE
							2-1, 2-2, 4-1, 3-2, 6-1, 4-2, 8-1, 4-3, 6-2, 12-1, 4-4, 8-2, 16-1
						typeI-SinglePanel-codebookSubset Restriction-i2	BIT STRING {SIZE 16}
				typeI-SinglePanel-ri-Restriction		BIT STRING {SIZE 8}	
			typeI-MultiPanel	ng-n1-n2	CHOICE		
					2-2-1, 2-4-1, 4-2-1, 2-2-2, 2-8-1, 4-4-1, 2-4-2, 4-2-2		
				ri-Restriction	BIT STRING {SIZE 4}		
		codebookMode		1, 2			
	type2	subType	CHOICE				
			typeII	n1-n2-codebookSubsetRestriction	CHOICE		
					2-1, 2-2, 4-1, 3-2, 6-1, 4-2, 8-1, 4-3, 6-2, 12-1, 4-4, 8-2, 16-1		
				typeII-RI-Restriction	BIT STRING {SIZE 2}		
			typeII-PortSelection	portSelectionSamplingSize	1, 2, 3, 4		
				typeII-PortSelectionRI-Restriction	BIT STRING {SIZE 2}		
		phaseAlphabetSize		4, 8			
		subbandAmplitude		True, False			
		numberOfBeams		2, 3, 4			

Table 298 – *CodebookConfig* parameter structure

13.6.3.1 TYPE 1 SINGLE PANEL CODEBOOK

- 'Type 1' codebooks are primarily intended for Single User MIMO (SU-MIMO) with support for both high and low order transmissions, i.e. 8×8, 4×4 and 2×2 MIMO. The single panel version is based upon the assumption that the UE receives its downlink transmissions from a single antenna panel
- The Type 1 Single Panel codebook is configured using the *CodebookConfig* within the *CSI-reportConfig*. The *codebookType* must be set to 'type1', while the *subtype* must be set to 'typeI-SinglePanel'
- The Base Station is then expected to transmit CSI Reference Signals from a specific number of antenna ports. The number of antenna ports is configured using the *nrofPorts* information element within the *CSI-RS-ResourceMapping*. The UE uses the CSI Reference Signals to identify its preferred precoding, i.e. the UE selects the precoding weights which it would like the Base Station to apply in order to maximise the downlink signal quality
- If the CSI Reference Signal is configured with 2 antenna ports {3000, 3001} then it is assumed that the Base Station is configured with a single column cross polar panel antenna, i.e. the Base Station is not capable of beamforming. In this case, the UE selects a codebook index from the set of values presented in Table 299. This table includes two columns of precoding matrices. The first column is applicable if the UE is reporting a Rank Indicator (RI) = 1, whereas the second column is applicable if the UE is reporting a Rank Indicator = 2. The precoding matrices represent the set of preferred phase shifts between layers transmitted by each antenna element

	1 Layer	2 Layers
Codebook Index 0	$\frac{1}{\sqrt{2}}\begin{bmatrix}1\\1\end{bmatrix}$	$\frac{1}{2}\begin{bmatrix}1 & 1\\1 & -1\end{bmatrix}$
Codebook Index 1	$\frac{1}{\sqrt{2}}\begin{bmatrix}1\\j\end{bmatrix}$	$\frac{1}{2}\begin{bmatrix}1 & 1\\j & -j\end{bmatrix}$
Codebook Index 2	$\frac{1}{\sqrt{2}}\begin{bmatrix}1\\-1\end{bmatrix}$	Not Applicable
Codebook Index 3	$\frac{1}{\sqrt{2}}\begin{bmatrix}1\\-j\end{bmatrix}$	Not Applicable

Table 299 – Codebooks for 1 and 2 layer CSI Reporting when CSI Reference Signal uses antenna ports 3000 and 3001

- Figure 392 illustrates the precoding which corresponds to the single layer column of Table 299. The Layer Mapping function is transparent and modulation symbols are passed directly to the precoding. All codebook entries have a '1' in the upper position so antenna port 1 transmits the Layer 1 modulation symbols directly (after scaling the amplitude by $1/\sqrt{2}$). Each codebook entry has a different value in the lower position and these different values correspond to phase shifts of 0, 90, 180 and 270 degrees. The selected phase shift is applied to the Layer 1 modulation symbols before transmission using antenna port 2

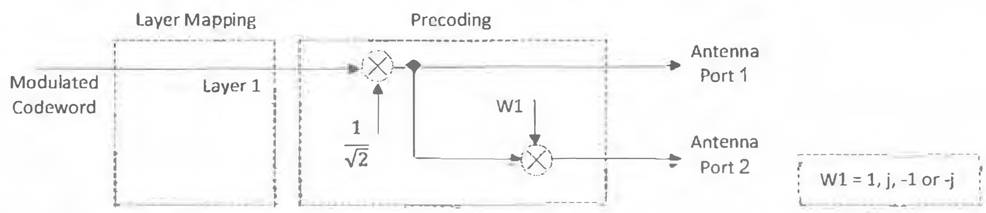


Figure 392 – Single layer precoding applicable when CSI Reference Signal uses antenna ports 3000 and 3001

- Figure 393 illustrates the precoding which corresponds to the dual layer column of Table 299. In this case, the Layer Mapping function generates two layers from a single codeword by distributing alternate modulation symbols between the two layers. Both codebook entries have a '1 1' in the upper row so antenna port 1 transmits a simple summation of the two layers (after scaling the amplitude by 1/2). The two codebook entries have different values in their lower rows which correspond to phase shifts of (0, 180) degrees and (90, 270) degrees. The selected pair of phase shifts is applied before transmission using antenna port 2

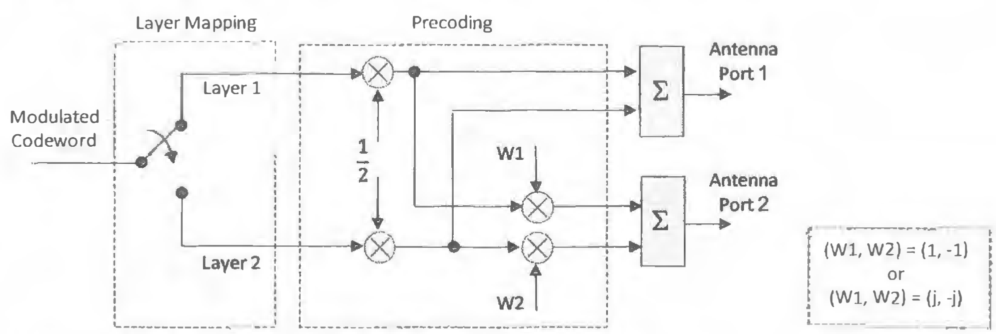


Figure 393 – Dual layer precoding applicable when CSI Reference Signal uses antenna ports 3000 and 3001

★ The amplitude scaling factors within Table 299 are used to normalise the total transmit power. Power is proportional to $amplitude^2$ so in the single layer case, the amplitude scaling factor of $1/\sqrt{2}$ generates a power of $1/\sqrt{2} \times 1/\sqrt{2} = 1/2$ at each antenna port and a total power of '1'. In the dual layer case, the amplitude scaling factor of 1/2 generates a power of $1/2 \times 1/2 = 1/4$ at the input to the summation for each antenna port. A total of 4 signals are summed so the total power is also '1'

★ The Base Station can restrict the set of codebook indices which are available for selection. This may be done if some entries are not useful for the current channel conditions or antenna configuration. Codebook restriction is configured using the bitmap of length 6 bits defined by the *twoTX-CodebookSubsetRestriction* information element shown in Table 298. The first 4 bits correspond to the set of 4 single layer precoding matrices, whereas the last 2 bits correspond to the set of 2 dual layer precoding matrices

★ If the CSI Reference Signal is configured with more than 2 antenna ports, then it is assumed that the Base Station is configured with a larger antenna which is capable of beamforming. In this case, PMI selection corresponds to a combination of beam selection and cross polarisation phase shift selection

★ 3GPP TS 38.214 specifies precoding matrices for a specific set of antenna configurations. These antenna configurations are presented in Table 300. The N_1 variable defines the number of cross polar antenna element columns, whereas the N_2 variable defines the number of cross polar antenna element rows. The number of CSI Reference Signal antenna ports is always equal to $2 \times N_1 \times N_2$ because each row and column is assumed to include 2 polarisations

★ The O_1 and O_2 variables define oversampling factors which determine the number of beams available for selection. The product of N_1 and O_1 defines the number of beams available for selection across each row of cross polar antenna elements. Whereas, the product of N_2 and O_2 defines the number of beams available for selection across each column of cross polar antenna elements. O_2 is always set equal to 1 for antenna configurations which have a single row of antenna elements (in this case it is not possible to provide beamforming in the elevation direction). Otherwise, the oversampling factors are set equal to 4

Number of CSI RS Antenna Ports	(N_1, N_2)	(O_1, O_2)
4	(2, 1)	(4, 1)
8	(2, 2)	(4, 4)
	(4, 1)	(4, 1)
12	(3, 2)	(4, 4)
	(6, 1)	(4, 1)
16	(4, 2)	(4, 4)
	(8,1)	(4, 1)

Number of CSI RS Antenna Ports	(N_1, N_2)	(O_1, O_2)
24	(4, 3)	(4, 4)
	(6, 2)	(4, 4)
	(12, 1)	(4, 1)
32	(4, 4)	(4, 4)
	(8, 2)	(4, 4)
	(16,1)	(4, 1)

Table 300 – Supported Antenna Panel and Oversampling configurations

★ Figure 394 illustrates some example antenna configurations with their corresponding set of beams. The first example is based upon the first entry within Table 300, i.e. 2 columns of cross polar antenna elements and a single row of cross polar antenna elements. There is a total of 4 antenna elements which correspond to the 4 CSI Reference Signals. The oversampling factor of 4 leads to a set of 8 candidate beams distributed across the single row of antenna elements. PMI selection involves selection amongst those 8 beams

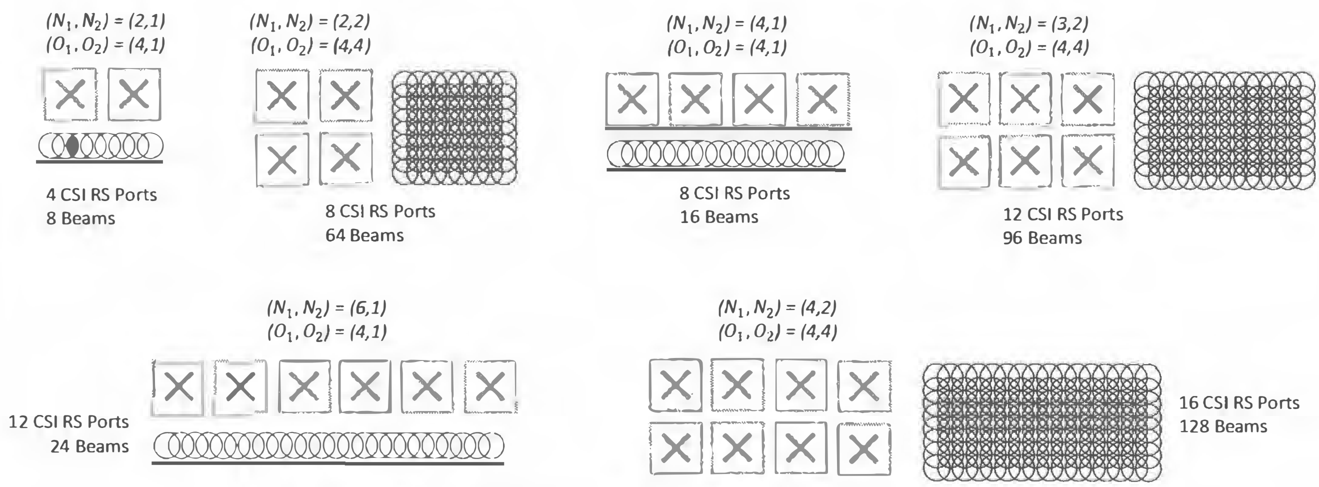


Figure 394 – Example antenna configurations with corresponding beam sets

★ The second example in Figure 394 is based upon the second entry within Table 300, i.e. 2 columns of cross polar antenna elements and 2 rows of cross polar antenna elements. There is a total of 8 antenna elements which correspond to the 8 CSI Reference Signals. The oversampling factor of 4 in both dimensions leads to a set of $8 \times 8 = 64$ candidate beams distributed across the two rows and two columns of antenna elements. PMI selection involves selection amongst those 64 beams

★ It should be noted that the antenna configurations specified in Table 300 and illustrated in Figure 394 represent the transceiver connectivity to the antenna. They do not represent the total set of physical antenna elements. This concept is illustrated in Figure 395. The first example illustrates that the actual physical antenna has 2 columns of cross polar antenna elements but only a single row of transceivers. The second example illustrates that the actual antenna has 2 columns of cross polar antenna elements and 2 rows of transceivers

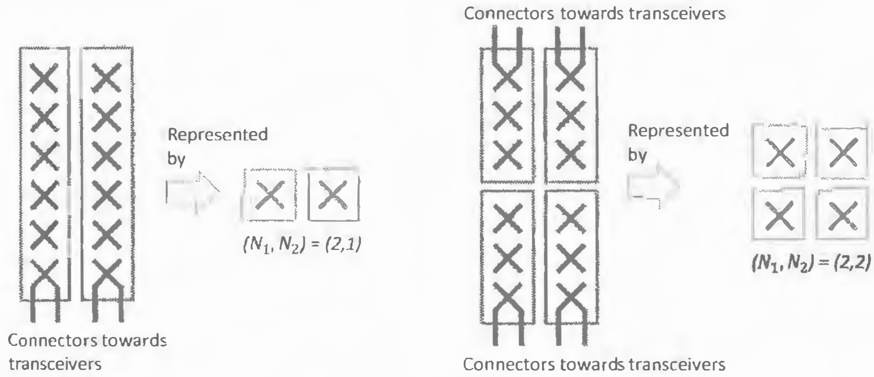


Figure 395 – Examples of physical antenna elements connected to transceivers

★ In the case of 1 or 2 transmission layers, 3GPP has specified 2 modes of operation when selecting the precoding matrix. The Base Station uses the *codebookMode* information element to instruct the UE to apply a specific mode of operation. The *codebookMode* information element is visible within Table 298. Both modes of operation are based upon a 2-stage PMI reporting procedure, but the information reported during each stage differs

Codebook Mode = 1 (1 or 2 transmission layers)

★ Figure 396 illustrates an example assuming single layer transmission from an antenna with 2 rows and 2 columns of cross polar antenna elements. Stage 1 involves selecting a specific beam from the set of 64 beams, whereas stage 2 involves selecting a specific phase shift from a set of 4 phase shifts (0, 90, 180 and 270 degrees). When codebook mode 1 is used for the transmission of 2 layers then stage 2 involves selecting a specific phase shift from a set of 2 phase shifts (0 and 90 degrees)

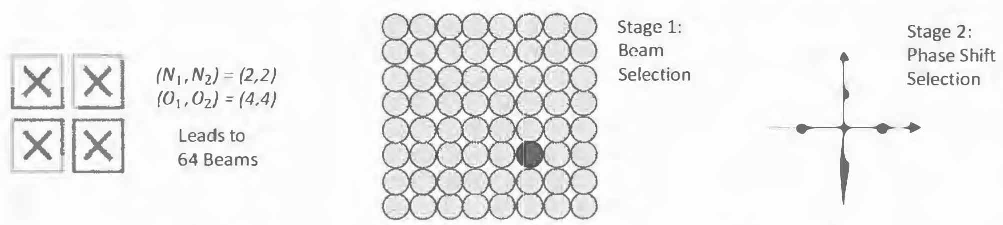


Figure 396 – Example of Codebook Mode 1 for single layer transmission

Codebook Mode = 2 (1 or 2 transmission layers)

★ Figure 397 illustrates an example assuming single layer transmission from an antenna with 2 rows and 2 columns of cross polar antenna elements. In this case, the 64 beams are divided into 16 groups and stage 1 involves selecting one of these groups. Stage 2 involves selecting a specific beam from within the group and also selecting a phase shift from a set of 4 phase shifts (0, 90, 180 and 270 degrees). When codebook mode 2 is used for the transmission of 2 layers then only the 0 and 90 degree phase shifts are available for selection

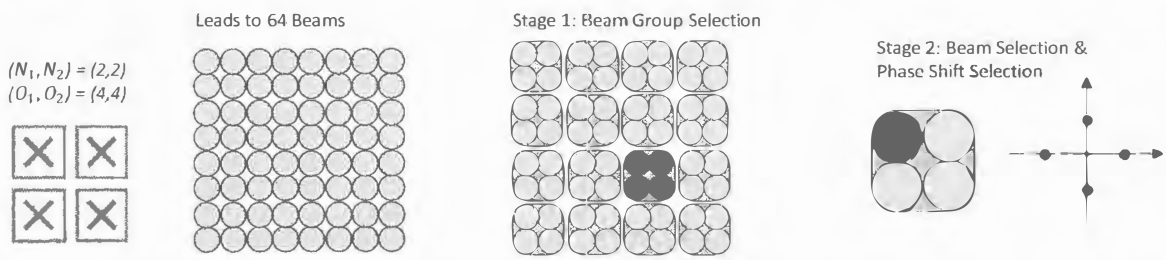


Figure 397 – Example of Codebook Mode 2 for single layer transmission (multiple rows of cross polar antenna elements)

★ Figure 397 illustrates the grouping of 4 beams in a 2×2 grid. Beam groups always include 4 beams but the layout of the group is not always a 2×2 grid. If the antenna has a single row of antenna elements then beamforming in the elevation direction is not possible so beams form a single row and grouping is applied across that row. Figure 398 illustrates an example of this grouping

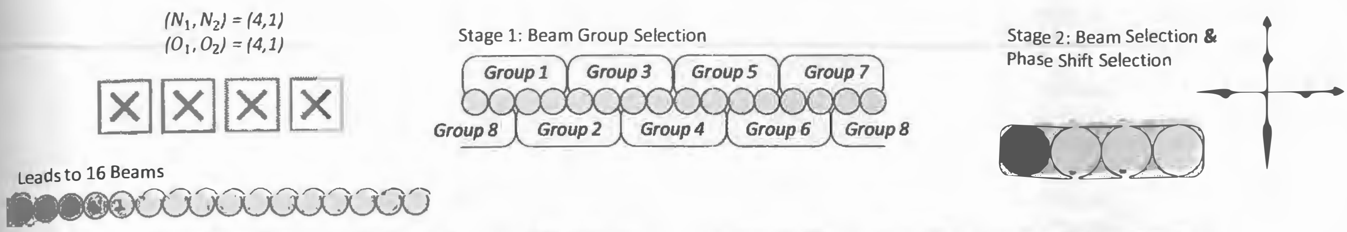


Figure 398 – Example of Codebook Mode 2 for single layer transmission (single row of cross polar antenna elements)

- In this case the groups overlap so there are 8 groups distributed across the 16 beams
- When selecting a PMI for 2 layers, it is possible to select different beams for each layer. The first stage of reporting involves providing a value for $i_{1,1}$ which identifies the beam or group of beams in the horizontal direction, $i_{1,2}$ which identifies the beam or group of beams in the vertical direction, and $i_{1,3}$ which specifies an offset between the beams selected for each layer. This offset may be '0' indicating that both layers use the same beam (1 layer per polarisation), or the offset may be a multiple of the oversampling factor (a multiple of 4 beams) in either the horizontal and/or vertical directions. The second stage of reporting involves providing a value for $i_{1,3}$ which identifies a phase shift when using Codebook Mode 1, and which identifies a beam within a group plus a phase shift when using Codebook Mode 2
- For both Codebook Mode 1 and Codebook Mode 2, the first stage of reporting is treated as wideband and relatively long term, whereas the second stage of reporting is treated as frequency selective and short term. The means that stage 1 reporting provides a single result which is applicable to the complete bandwidth and this result does not require very frequent updates. In contrast, stage 2 reporting provides a result for each sub-band and these results are updated relatively frequently
- Codebook Mode 1 provides an advantage in terms of reducing the payload size associated with the frequent stage 2 reports (because it only requires the phase shift to be reported for each sub-band). However, this may have a negative impact upon performance because there is less scope for fine tuning the selected beam, i.e. the same beam is assumed to be appropriate for the whole bandwidth, and that beam is updated less frequently
- When transferring 1 or 2 layers, there is a one-to-one mapping between the number of layers and the number of polarisations. In this case, a beam can be generated by each polarisation to support the transmission of the 2 layers. When transferring more than 2 layers, it becomes necessary to use more than a single beam per polarisation. In these cases, the Codebook Mode does not have any impact and both modes apply the same selection procedure
- Figure 399 illustrates the general concept of using multiple beams to support higher order MIMO. This means that multiple layers are transmitted by each polarisation but those layers are separated spatially by using different beams. These beams are pointing in different directions so the UE has to rely upon reflections and scattering to ensure that all layers can be received. The number of beams required is given by: ROUNDUP (Reported Rank / 2)

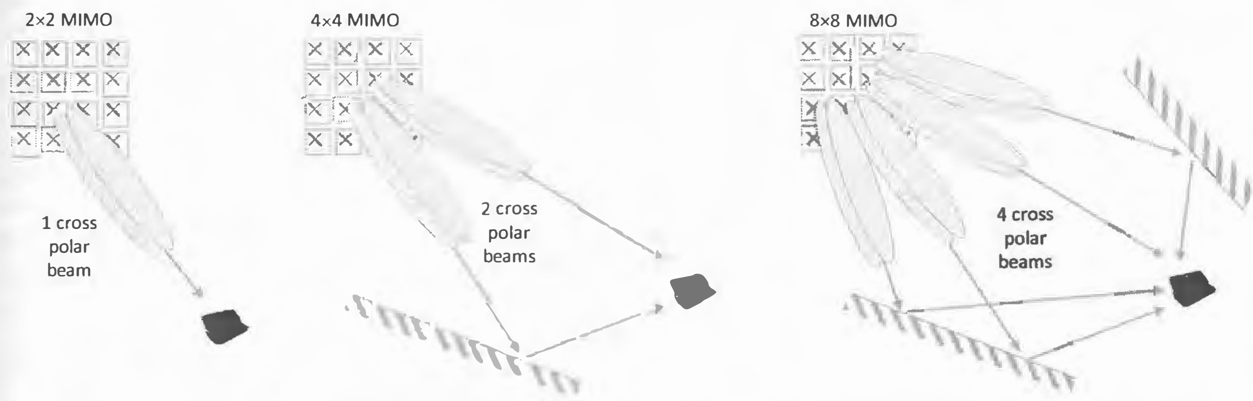


Figure 399 – Multiple cross polar beams used to support 4×4 and 8×8 MIMO

- When selecting multiple beams to transfer more than 2 layers, the UE is not free to select any combination of beams. The selected beams must be separated by multiples of the Oversampling Factors, O_1 and O_2. This helps to ensure that the beams have sufficient spatial separation and are effectively orthogonal
- When transferring more than 2 layers, beam groups are no longer used and the first stage of reporting always identifies a specific beam rather than a group of beams
- Figure 400 illustrates the selection of 2 beams when using 4×4 MIMO with a range of example antenna configurations. The first example is based upon a single row of 8 beams. The pair of beams must be separated by 4 positions so there is only a single candidate for the second beam once the first beam has been selected. The second example is based upon a single row of 16 beams. In this case, there is an increased number of candidate secondary beams after selecting the first beam. The third example is based upon a grid of 8×8 beams. The candidate secondary beams are separated from the first beam by 4 positions in the horizontal and/or vertical directions

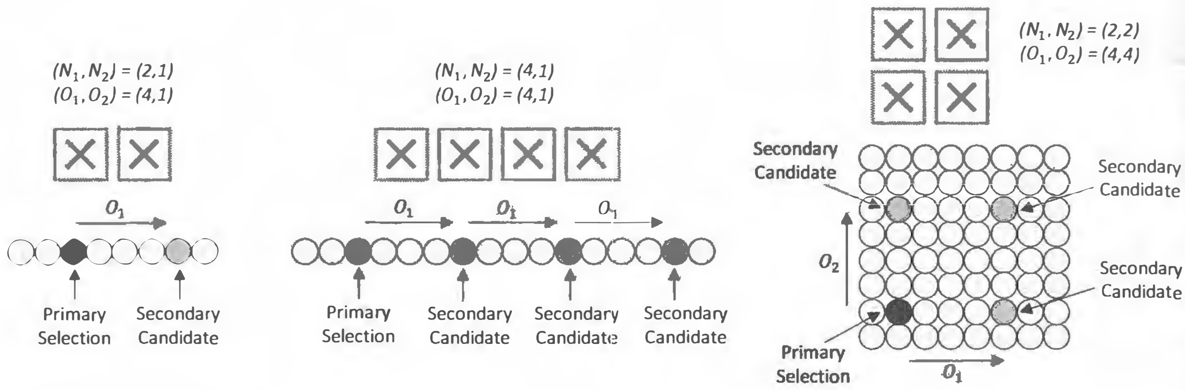


Figure 400 – Example selection of 2 cross polar beams for 4×4 MIMO

★ When transferring more than 4 layers (requiring 3 or 4 beams), the positions of the 2[nd], 3[rd] and 4[th] beams are fixed relative to the position of the first beam. Examples of this concept are illustrated in Figure 401. The antenna configuration with a single row of 8 beams is unable to support the set of 3 beams so this configuration is excluded from Figure 401 (N_1 must be greater than 2, if $N_2 = 1$)

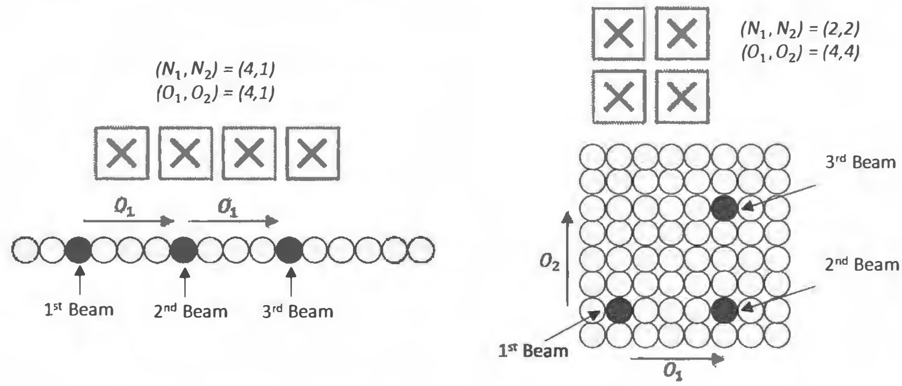


Figure 401 – Example selection of 3 cross polar beams for 8×8 MIMO with Rank 6

★ Finally, there is a special case when transferring either 3 or 4 layers using antenna configurations which support ≥ 16 CSI Reference Signals. In this case, the antenna elements belonging to each polarisation are divided into 2 groups so there are effectively 4 groups of antenna elements (+45° group 1, +45° group 2, -45° group 1, -45° group 2). The UE then selects a single beam and that single beam is transmitted by each of the 4 groups of antenna elements. Each group transmits the beam with a different phase shift to provide differentiation. This scenario is compared with the 'normal' scenario in Figure 402. The horizontal beamwidth increases by a factor of 2 because the number of antenna elements used to generate each beam in the horizontal direction decreases by a factor of 2

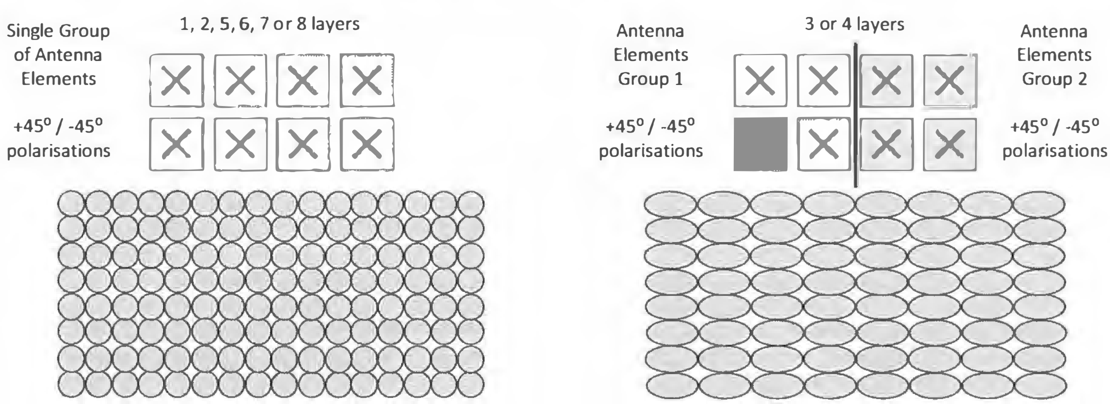


Figure 402 – Use of 2 groups of antenna elements to transfer 3 or 4 layers

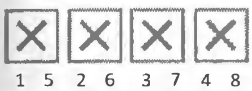
★ The solution in Figure 402 is only applied when transferring 3 or 4 layers with a relatively large antenna configuration. Smaller antenna configurations have less antenna elements so are less capable of creating directional beams after dividing the total set of elements into two groups. Transferring 1 or 2 layers does not require this grouping because the 1 or 2 layers can be simply transferred using the 2 polarisations. Applying this concept to more than 4 layers would require the total set of antenna elements to be divided into 3 or more groups. In this case, the number of elements per group would become smaller and each group would be less capable of generating a directional beam

- In addition to restricting the use of specific PMI indices, the Base Station can also restrict the use of specific Rank Indicator (RI) values. This is done using the *typeI-SinglePanel-ri-Restriction* bitmap within *CodebookConfig*

- Within 3GPP TS 38.214, PMI are specified using matrix notation. Interpretation of these matrices is not immediately obvious but the main points can be deduced by inspection. Figure 403 illustrates the fundamental principles of matrix multiplication within the context of beamforming. This example is based upon an antenna which has a single row of 4 cross polar antenna elements. This antenna is used to generate one beam from each polarisation. As described in section 1.21, a beam is generated by applying a series of phase shifts to the duplicated signals transmitted by each antenna element. In this example, a beam is generated using 4 antenna elements so a series of 4 phase shifts is required. The phase shifts are stacked to generate a beamforming vector. The first phase shift is zero so the first entry within the beamforming vector is '1'. The phase shift difference between adjacent entries within the beamforming vector determine the direction of the beam. When the UE selects a beam for its PMI, the UE is selecting a phase shift difference between adjacent entries within the beamforming vector

- Figure 403 assumes that the same beamforming vector is applied to both polarisations so both sets of antenna elements generate a beam in the same direction. The beamforming vectors for the two polarisations form the leading diagonal entries within the matrix multiplication. Layer 1 symbols are multiplied by the first beamforming vector, while layer 2 symbols are multiplied by the second beamforming vector. This generates the set of 8 outputs which are mapped onto the set of 8 antenna elements. Based upon this description, the first layer is transmitted by a first beam generated by the first polarisation, and the second layer is transmitted by a second beam generated by the second polarisation. In reality, both layers are transmitted by the first beam and both layers are transmitted by the second beam. The paragraph below Figure 403 extends the description to explain how this is achieved

- The matrix which includes the beamforming vectors can be simplified if each beamforming vector is represented by 'v' and the entries within the output vector are represented by 'Tx'. The example illustrated in Figure 403 is based upon a single row of cross polar antenna elements. In this case, a 1 dimensional beamforming vector is applicable. If the example had been based upon an antenna with multiple rows and multiple columns of antenna elements then the 1 dimensional beamforming vector would become a 2 dimensional beamforming matrix (generated using a multiplication of 2 beamforming vectors, with 1 vector transposed)



$$v = \begin{bmatrix} 1 \\ e^{j\frac{m\pi}{8}} \\ e^{j\frac{2m\pi}{8}} \\ e^{j\frac{3m\pi}{8}} \end{bmatrix}$$

Beamforming Vector applied to each polarisation

Beamforming Vector for first polarisation

$$\begin{bmatrix} tx1 \\ tx2 \\ tx3 \\ tx4 \\ tx5 \\ tx6 \\ tx7 \\ tx8 \end{bmatrix} = \begin{bmatrix} 1 & 0 \\ e^{j\frac{\pi}{8}} & 0 \\ e^{j\frac{2\pi}{8}} & 0 \\ e^{j\frac{3\pi}{8}} & 0 \\ 0 & 1 \\ 0 & e^{j(\frac{\pi}{8})} \\ 0 & e^{j(\frac{2\pi}{8})} \\ 0 & e^{j(\frac{3\pi}{8})} \end{bmatrix} \begin{bmatrix} Layer\ 1 \\ Layer\ 2 \end{bmatrix}$$

Modulation symbols belonging to Layers 1 and 2

8 outputs for 8 antenna elements

Beamforming Vector for second polarisation

Simplified expression

$$[Tx] = \begin{bmatrix} v & 0 \\ 0 & v \end{bmatrix} \begin{bmatrix} Layer\ 1 \\ Layer\ 2 \end{bmatrix}$$

Beamforming Vector

Figure 403 – Fundamental matrices for a beamforming precoder

- The beamforming matrix in Figure 403 includes '0's, whereas the PMI matrices within 3GPP TS 38.214 do not include any zeros. Figure 403 has applied precoding for beamforming but has not applied any precoding for MIMO. Typical MIMO precoding is presented in Figure 393. The inclusion of a MIMO precoding matrix is shown in Figure 404. The MIMO matrix provides the short term, frequency selective precoding while the beamforming matrix provides the longer term wideband precoding. In this case, the MIMO precoding generates a first output which is the sum of the two layers, and a second output which is the sum of phase shifted versions of the two layers. The beamforming precoding matrix can be multiplied by the MIMO precoding matrix to generate a composite matrix. This matrix is now in the same format as that which appears within 3GPP TS 38.214 when considering the transmission of 2 layers

$$[Tx] = \underbrace{\begin{bmatrix} v & 0 \\ 0 & v \end{bmatrix}}_{\text{Beamforming Precoding}} \underbrace{\begin{bmatrix} 1 & 1 \\ e^{j\beta} & e^{-j\beta} \end{bmatrix}}_{\text{MIMO Precoding}} \begin{bmatrix} Layer\ 1 \\ Layer\ 2 \end{bmatrix}$$

$$[Tx] = \underbrace{\begin{bmatrix} v & v \\ ve^{j\beta} & ve^{-j\beta)} \end{bmatrix}}_{\text{Composite Precoding Matrix}} \begin{bmatrix} Layer\ 1 \\ Layer\ 2 \end{bmatrix}$$

Figure 404 – Composite Precoding Matrix generated by combining the Beamforming and MIMO matrices

13.6.3.2 TYPE 1 MULTI PANEL CODEBOOK

★ The Type 1 Multi-Panel codebook provides support for Base Station configurations using either 2 or 4 antenna panels. In contrast to the Type 1 Single Panel codebook which supports ranks 1 to 8, the Multi-Panel codebook supports ranks 1 to 4

★ 3GPP TS 38.214 specifies precoding matrices for a specific set of antenna configurations. These antenna configurations are presented in Table 301. The N_g variable defines the number of antenna panels, whereas the N_1 and N_2 variables define the number of cross polar antenna element columns and rows respectively. The number of CSI Reference Signal antenna ports is equal to $2 \times N_g \times N_1 \times N_2$ because each row and column is assumed to include 2 polarisations

★ Similar to the Single Panel scenario, the O_1 and O_2 variables define oversampling factors which determine the number of beams available for selection. The number of beams available for selection is not given by $N_g \times (N_1 \times O_1) \times (N_2 \times O_1)$, but is given by $(N_1 \times O_1) \times (N_2 \times O_1)$

Number of CSI RS Antenna Ports	(N_g, N_1, N_2)	(O_1, O_2)
8	(2, 2, 1)	(4, 1)
16	(2, 4, 1)	(4, 1)
	(4, 2, 1)	(4, 1)
	(2, 2, 2)	(4, 4)

Number of CSI RS Antenna Ports	(N_g, N_1, N_2)	(O_1, O_2)
32	(2, 8, 1)	(4, 1)
	(4, 4, 1)	(4, 1)
	(2, 4, 2)	(4, 4)
	(4, 2, 2)	(4, 4)

Table 301 – Supported Multi Antenna Panel and Oversampling configurations

★ Figure 405 illustrates some example antenna configurations with their corresponding set of beams. The first example is based upon the first entry within Table 301, i.e. 2 antenna panels with 2 columns of cross polar antenna elements per panel and a single row of cross polar antenna elements per panel. There is a total of 8 antenna elements which correspond to the 8 CSI Reference Signals. The oversampling factor of 4 leads to a set of 8 candidate beams distributed across the single row of antenna elements. PMI selection involves selection amongst those 8 beams. In the case of multi panel configurations, PMI selection also involves the selection of co-phasing phase shifts between both polarisations and antenna panels

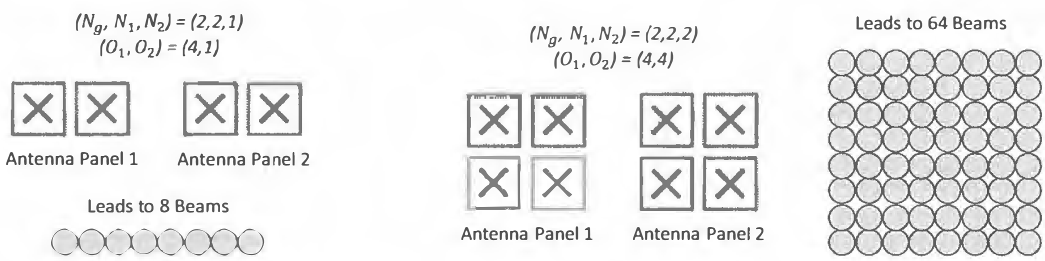


Figure 405 – Beams available for selection for example multi panel antenna configurations

★ The second example in Figure 405 is based upon the fourth entry within Table 301, i.e. 2 antenna panels with 2 columns of cross polar antenna elements per panel and 2 rows of cross polar antenna elements per panel. There is a total of 16 antenna elements which correspond to the 16 CSI Reference Signals. The oversampling factor of 4 in both dimensions leads to a set of 8 × 8 = 64 candidate beams. PMI selection involves selection amongst those 64 beams

★ Figure 406 illustrates the beams associated with the transmission of 1 to 4 layers. The UE selects a single beam when reporting rank 1. That single beam is transmitted by each polarisation of each antenna panel, i.e. the pair of antenna panels radiate 2 cross polar beams. Similarly, the UE can select a single beam when reporting rank 2. In this case, each individual polarisation beam transmits a precoded combination of the 2 layers

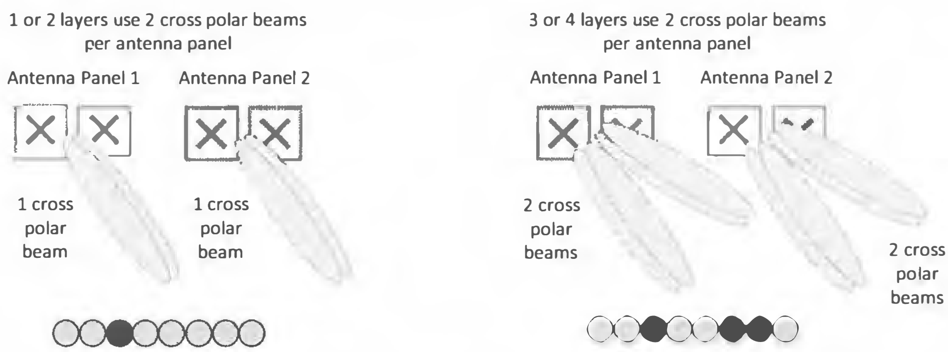


Figure 406 – Beams transmitted by each antenna panel for the transmission of 1 to 4 layers

★ The UE selects 2 beams which are separated by the oversampling factor when reporting rank 3 or rank 4. Each polarisation of each antenna panel transmits these 2 beams so there is a total of 4 cross polar beams. Each individual polarisation beam transmits a precoded combination of the 3 or 4 layers

★ 3GPP has specified 2 modes of operation when selecting the precoding matrix. The Base Station uses the *codebookMode* information element to instruct the UE to apply a specific mode of operation (this information element is applicable to both single panel and multi panel Type 1 codebooks). In the case of the multi panel codebook, the operating mode impacts the reporting of the inter-panel and inter-polarisation co-phasing phase shifts:

- o Codebook Mode = 1: supports both 2 and 4 antenna panels
  - Stage 1 Reporting: if 2 antenna panels are configured, the UE reports 1 wideband phase shift for inter-panel co-phasing. If 4 antenna panels are configured, the UE reports 3 wideband phase shifts for inter-panel co-phasing. The beam selection is also reported during stage 1
  - Stage 2 Reporting: the UE reports 1 phase shift per sub-band for inter-polarisation co-phasing
- o Codebook Mode = 2: supports only 2 antenna panels
  - Stage 1 Reporting: the UE reports 2 wideband phase shifts for a combination of inter-panel and inter-polarisation co-phasing. The beam selection is also reported during stage 1
  - Stage 2 Reporting: the UE reports a set of 3 phase shifts per sub-band for a combination of inter-panel and inter-polarisation co-phasing

★ Codebook Mode 2 benefits from an increased quantity of sub-band reporting but this generates an increased signalling overhead. In addition, Codebook Mode 2 is restricted to 2 antenna panels

13.6.3.3 TYPE 2 SINGLE PANEL CODEBOOK

★ 'Type 2' codebooks are intended for Multi User MIMO (MU-MIMO) with support for a maximum of 2 layers, i.e. 2×2 MIMO. They provide more accurate Channel State Information than Type 1 codebooks but also generate a larger signalling overhead. Rank 1 and Rank 2 PMI indices belonging to a Type 1 codebook identify a preferred beam and an inter-polarisation co-phasing phase shift. PMI indices belonging to a Type 2 codebook identify a set of beams and a set of amplitude coefficients. These amplitude coefficients are used to generate a weighted combination of beams. The Type 2 codebook also identifies a phase shift for co-phasing between beams

★ The Type 2 Single Panel codebook is configured using the *CodebookConfig* within the *CSI-reportConfig*. The *codebookType* must be set to 'type2', while the *subtype* must be set to 'typeII'

★ The Base Station is expected to transmit non-precoded CSI Reference Signals from a specific number of antenna ports. The number of antenna ports is configured using the *nrofPorts* information element within the *CSI-RS-ResourceMapping*. The UE uses the CSI Reference Signals to identify its preferred precoding, i.e. the UE selects the precoding weights which it would like the Base Station to apply in order to maximise the downlink signal quality

★ Similar to the Type 1 codebooks, 3GPP TS 38.214 specifies Type 2 precoding matrices for a specific set of antenna configurations. Type 2 Single Panel codebooks have been specified to use the same antenna configurations as Type 1 Single Panel codebooks. These configurations are repeated in Table 302. The N_1 variable defines the number of cross polar antenna element columns, whereas the N_2 variable defines the number of cross polar antenna element rows. The number of CSI Reference Signal antenna ports is always equal to $2 \times N_1 \times N_2$ because each row and column is assumed to include 2 polarisations

★ The O_1 and O_2 variables define oversampling factors which determine the number of beams available for selection. The product of N_1 and O_1 defines the number of beams available for selection across each row of cross polar antenna elements. Whereas, the product of N_2 and O_2 defines the number of beams available for selection across each column of cross polar antenna elements

Number of CSI RS Antenna Ports	(N_1, N_2)	(O_1, O_2)
4	(2, 1)	(4, 1)
8	(2, 2)	(4, 4)
	(4, 1)	(4, 1)
12	(3, 2)	(4, 4)
	(6, 1)	(4, 1)
16	(4, 2)	(4, 4)
	(8, 1)	(4, 1)

Number of CSI RS Antenna Ports	(N_1, N_2)	(O_1, O_2)
24	(4, 3)	(4, 4)
	(6, 2)	(4, 4)
	(12, 1)	(4, 1)
32	(4, 4)	(4, 4)
	(8, 2)	(4, 4)
	(16, 1)	(4, 1)

Table 302 – Supported Antenna Panel and Oversampling configurations

★ Similar to Type 1 codebooks, PMI reporting is completed in 2 stages. The first stage provides wideband information and is assumed to change relatively slowly as a function of time, whereas the second stage provides sub-band information and is assumed to change more rapidly as a function of time

★ The first stage of PMI reporting (wideband information) is summarised in Figure 407. This figure assumes a single antenna panel which has 4 columns and 2 rows of cross polar antenna elements. The Oversampling factors of 4 in both dimensions lead to a pool of 16 × 8 = 128 beams

★ The *CodebookConfig* parameter structure uses the *numberOfBeams* information element to specify the number of beams which the UE must select. This information element can be configured with values of 2, 3 or 4. It is mandatory to configure a value of 2 when there are only 4 CSI Reference Signals, i.e. the antenna panel is relatively small and there are only 8 beams within the pool. Figure 407 assumes that *numberOfBeams* = 4

★ The total pool of beams is divided into groups, where the number of groups in a specific dimension equals the number of cross polar pairs in that dimension. The example in Figure 407 has 4 × 2 = 8 groups because there are 4 × 2 cross polar antenna element pairs. Beam selection is then done in 2 steps. The first step selects a beam position within a group, while the second step selects the groups. This means that only a single beam can be selected per group, which helps to ensure that there is orthogonality between the selected beams. It also means that each of the selected beams occupies the same position within a group, which helps to reduce the signalling overhead. The selected beams are common for both polarisations and both layers (if rank 2 is being reported, otherwise there is only a single layer)

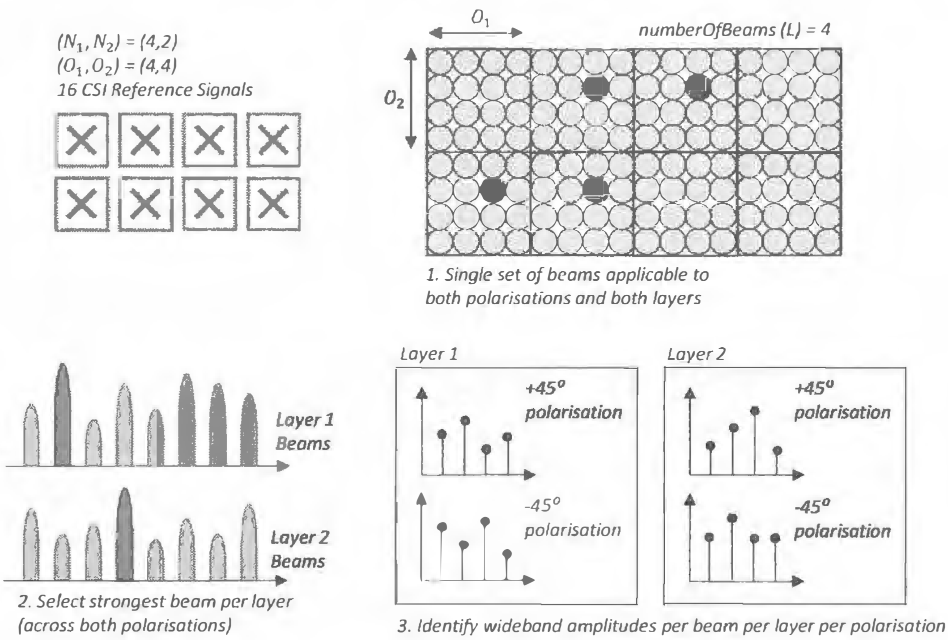


Figure 407 – Stage 1 of PMI reporting for Type 2 Single Panel Codebook

★ The UE then proceeds to identify the strongest beam for each layer. Figure 407 assumes rank 2 so a strongest beam is identified for layer 1 and a strongest beam is identified for layer 2. The beams associated with each polarisation are considered to be independent so the strongest beam is selected from a set of 8 beams (rather than from a set of 4 beams)

★ After identifying the strongest beam for each layer, the UE selects a wideband amplitude coefficient for each of the remaining beams. This wideband amplitude coefficient quantifies the power of a beam relative to the strongest beam. 3GPP TS 38.214 specifies power ratios of 1, 1/2, 1/4, 1/8, 1/16, 1/32, 1/64 and 0, i.e. a set of 8 power levels which require 3 bits within the signalling payload

★ The second stage of PMI reporting involves providing information per sub-band:

- o phase shifts are reported for each beam relative to the phase of the strongest beam. The example illustrated in Figure 407 is based upon 8 beams per layer, so the UE reports 7 phase shifts per layer. The Base Station uses the *phaseAlphabetSize* information element within the *CodebookConfig* to specify the use of either QPSK or 8PSK when selecting phase shifts. The use of 8PSK provides increased angular resolution but requires 3 bits of signalling payload rather than 2 bits

- o the Base Station can instruct the UE to either include or exclude sub-band amplitude information using the *subbandAmplitude* information element within the *CodebookConfig* parameter structure. Sub-band amplitude information uses a lower resolution than wideband amplitude information to help reduce the signalling payload size. Wideband amplitude values are selected from a set of 8 values (requiring 3 bits), whereas sub-band amplitude values are selected from a set of 2 values (requiring only 1 bit). The sub-band amplitude values are used to scale the wideband amplitude

★ The information from the first and second stages of PMI reporting is combined to generate a weighted combination of beams for each sub-band, layer and polarisation

13.6.3.4 TYPE 2 PORT SELECTION CODEBOOK

- The 'Type 2 Port Selection' codebook is a special type of codebook which assumes that the Base Station already has at least some knowledge of the propagation channel between itself and the UE. The Base Station uses this information to generate CSI Reference Signal beams towards the UE, i.e. the 'Type 2 Port Selection' codebook relies upon the transmission of CSI Reference Signals which have already been precoded for beamforming. The UE is able to use these CSI Reference Signal beams to provide refined Channel State Information. There are three general scenarios:
  - the Base Station uses channel reciprocity to obtain the initial propagation channel information. This allows the Base Station to generate the CSI Reference Signal beamforming vectors for transmission towards the UE
  - the Base Station uses reports from the Beam Management procedure to obtain information regarding the preferred beamforming direction. The Base Station can then use this information to generate the CSI Reference Signal beams towards the UE
  - the Base Station uses a 2-step hybrid CSI reporting solution. This involves the Base Station configuring the UE to use a combination of two PMI codebooks. The UE is instructed to use the first codebook to generate and report the long term, wideband channel information. These first reports provide the Base Station with sufficient information to generate the beamforming vectors for CSI Reference Signal transmission towards the UE. The UE is then instructed to use the 'Type 2 Port Selection' codebook to provide the short term, higher resolution Channel State Information. The codebook used during the first step could be the 'Type I Single Panel' codebook. The Base Station uses the *reportQuantity* information element within the *CSI-reportConfig* (Table 293) to instruct the UE to provide only the wideband information when using the first codebook, i.e. by configuring a value of 'cri-RI-i1' or cri-RI-i1-CQI'. The 'i1' variable refers to the wideband Channel State Information provided during the first stage of PMI reporting ('i2' refers to the sub-band Channel State Information provided during the second stage of PMI reporting). The general sequence of events is illustrated in Figure 408

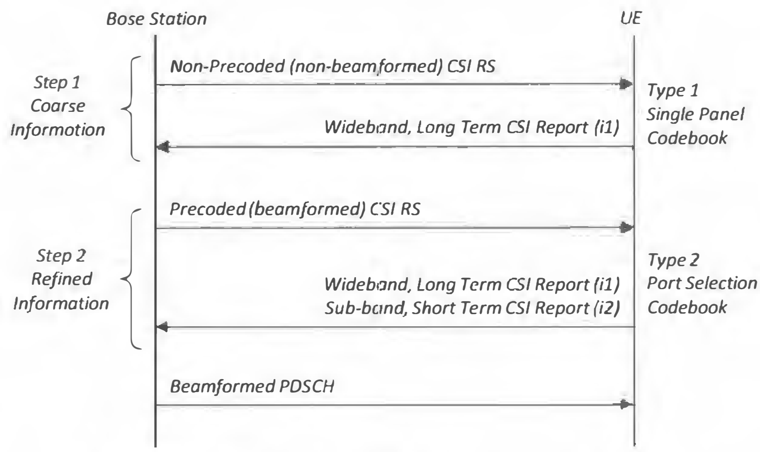


Figure 408 – Hybrid CSI reporting using 2-step procedure

- Similar to the 'Type 2 Single Panel' codebook, the 'Type 2 Port Selection' codebook is intended for Multi User MIMO (MU-MIMO) with support for a maximum of 2 layers, i.e. 2×2 MIMO. The PMI indices belonging to both Type 2 codebooks define a weighted combination of beams
- The 'Type 2 Port Selection' codebook is configured using the *CodebookConfig* within the *CSI-reportConfig*. The *codebookType* must be set to 'type2', while the *subtype* must be set to 'typeII-PortSelection'. The number of antenna ports used for CSI Reference Signal transmission is configured using the *nrofPorts* information element within the *CSI-RS-ResourceMapping*
- At a high level, the CSI reports generated for 'Type 2 Port Selection' are similar to those generated for 'Type 2 Single Panel'. In both cases, the UE selects a set of beams, identifies the strongest beam and then quantifies the amplitude of each of the remaining beams relative to the strongest beam. These amplitudes are used to generate the weighted combination of beams. In addition, the UE identifies a set of phase shifts to co-phase each beam
- However, the beam selection procedure differs between the two codebooks. 'Type 2 Port Selection' does not involve the use of Oversampling factors. Other codebooks use Oversampling factors to generate intermediate beam positions between a pair of spatially separated orthogonal beams. In these cases, oversampling increases the resolution of the beam selection procedure. In the case of 'Type 2 Port Selection', beam selection is based upon the set of actual beamformed CSI Reference Signal transmissions, rather than a set of hypothetical beam positions. Figure 409 illustrates some examples of beam selection for the 'Type 2 Port Selection' codebook
- The UE is configured to receive a specific number of CSI Reference Signals. These CSI Reference Signals span both polarisations so the number of cross polar beams available for selection is half the number of CSI Reference Signals. Figure 409 illustrates examples of 32, 16, 8 and 4 CSI Reference Signals which are used to generate 16, 8, 4 and 2 cross polar beams respectively. The preferred beams are assumed to be the same for each polarisation (and each layer when rank 2 is reported), so the UE makes a single selection which is then valid for both polarisations (and both layers when rank 2 is reported)

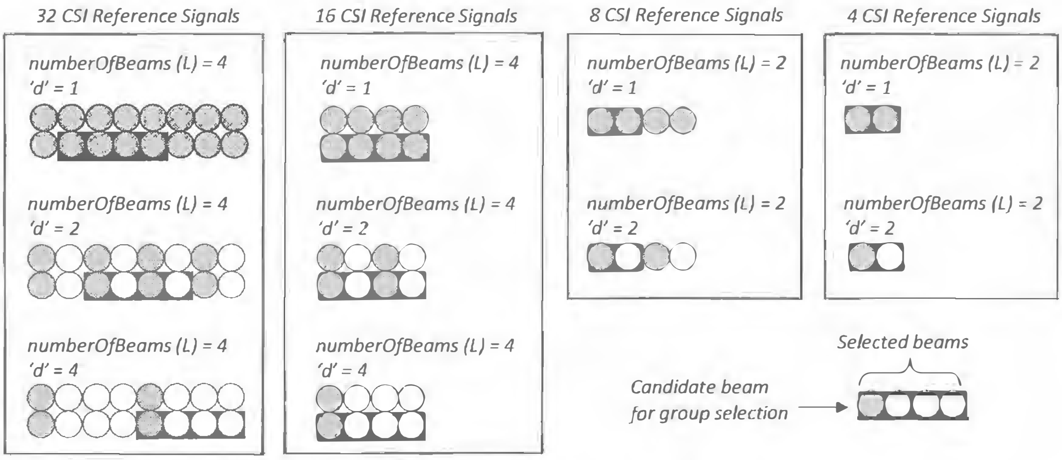


Figure 409 – Beam selection for the Type 2 Port Selection codebook

- The *CodebookConfig* parameter structure uses the *numberOfBeams* information element to specify the number of beams which the UE must select (shown as 'L' within Figure 409). This information element can be configured with values of 2, 3 or 4. It is mandatory to configure a value of 2 when there are only 4 CSI Reference Signals. In the case of 'Type 2 Port Selection', there is no oversampling so the set of selected beams are adjacent to one another, rather than being separated by the Oversampling factor

- When using the 'Type 2 Port Selection' codebook, the *CodebookConfig* parameter structure also specifies the *portSelectionSampling Size* information element (shown as 'd' within Figure 409). This information element specifies the spacing between candidate beam selections. Values of 1, 2, 3 and 4 can be configured. A low value allows beam selection with increased resolution but increases the signalling payload size. The selected beam identifies the first beam within the selected group of beams. All beams within the selected group are consecutive and follow the first beam

- The UE then proceeds to identify the strongest beam for each layer from within the selected group of beams. At this stage, the beams associated with each polarisation are considered to be independent so the strongest beam is selected from all beams across both polarisations

- After identifying the strongest beam for each layer, the UE selects a wideband amplitude coefficient for each of the remaining beams. This wideband amplitude coefficient quantifies the power of a beam relative to the strongest beam. 3GPP TS 38.214 specifies power ratios of 1, 1/2, 1/4, 1/8, 1/16, 1/32, 1/64 and 0, i.e. a set of 8 power levels which require 3 bits within the signalling payload

- The UE then generates the sub-band Channel State Information according to:

  - phase shifts are reported for each beam relative to the phase of the strongest beam. For example, the UE reports 7 phase shifts per layer if 8 beams have been selected. The Base Station uses the *phaseAlphabetSize* information element within the *CodebookConfig* to specify the use of either QPSK or 8PSK when selecting phase shifts. The use of 8PSK provides increased angular resolution but requires 3 bits of signalling payload rather than 2 bits

  - the Base Station can instruct the UE to either include or exclude sub-band amplitude information using the *subbandAmplitude* information element within the *CodebookConfig* parameter structure. Sub-band amplitude information uses a lower resolution than wideband amplitude information to help reduce the signalling payload size. Wideband amplitude values are selected from a set of 8 values (requiring 3 bits), whereas sub-band amplitude values are selected from a set of 2 values (requiring only 1 bit). The sub-band amplitude values are used to scale the wideband amplitude

- The information from the wideband and sub-band stages of PMI reporting is combined to generate a weighted combination of beams for each sub-band, layer and polarisation

13.6.4 LAYER INDICATOR

- MIMO allows the transmission of multiple layers. It is likely that the quality of each layer will be different. In some cases, it is useful for the Base Station to know which layer is received with the highest quality

- The Layer Indicator (LI) identifies the strongest layer from the set of layers indicated by the reported Rank Indicator (RI). For example, if the UE reports Rank 4 then the Layer Indicator identifies the strongest of those 4 layers. If the UE is reporting CQI values for two codewords (applicable to more than 4 layers) then the UE reports the strongest layer belonging to the codeword with the highest reported CQI. If the two CQI values are equal then the UE reports the strongest layer belonging to the first codeword

- The Base Station can take advantage of the Layer Indicator when transmitting the Phase Tracking Reference Signal (PTRS). The performance of the PTRS is maximised if it is transmitted using the layer with the best channel conditions. If the PTRS is transmitted using port 1000, while the UE reports that layer 3 has the best channel conditions, then the Base Station can map antenna port 1000 onto layer 3

13.6.5 SSBRI, CRI AND L1-RSRP

★ The SS/PBCH Block Resource Indicator (SSBRI) is reported when *reportQuantity* within *CSI-reportConfig* is configured with a value of 'ssb-Index-RSRP'. The SSBRI is reported in combination with a Layer 1 RSRP measurement recorded from the Secondary Synchronisation Signal (SSS)

★ The SSBRI can be used during Beam Management procedures when identifying the best downlink beam(s). The use of Channel State Information allows rapid and responsive switching between beams. Measurement reports transferred by the RRC layer would be too slow and infrequent for Beam Management procedures

★ The Base Station can either enable or disable the use of Group based Beam Reporting when configuring a UE to provide SSBRI reports. This is done using the *groupBasedBeamReporting* information element within *CSI-reportConfig* (presented in Table 303)

extract from *CSI-reportConfig*			
groupBasedBeamReporting	CHOICE		
	enabled	disabled	
		nrofReportedRS	1, 2, 3, 4

Table 303 – Configuration of Group based Beam Reporting

★ If Group based Beam Reporting is disabled, the *nrofReportedRS* information element specifies the number of SS/PBCH Block measurements within a single report. A UE can be requested to include up to 4 measurements per report.

★ If Group based Beam Reporting is enabled, the UE includes up to 2 measurements recorded from SS/PBCH Blocks which have been received simultaneously. The primary objective of Group based Beam Reporting is to provide support for deployment scenarios involving multiple Transmit Receive Points (TRP). Examples of these scenarios are illustrated in Figure 410. The first scenario is based upon a single Base Station which manages a pair of antenna panels acting as independent TRP. The second scenario is based upon a pair of Base Stations which act as independent TRP. In both cases, Group based Beam Reporting allows the UE to report the best beam from each TRP, i.e. providing Beam Management information to allow downlink transmission from both TRP

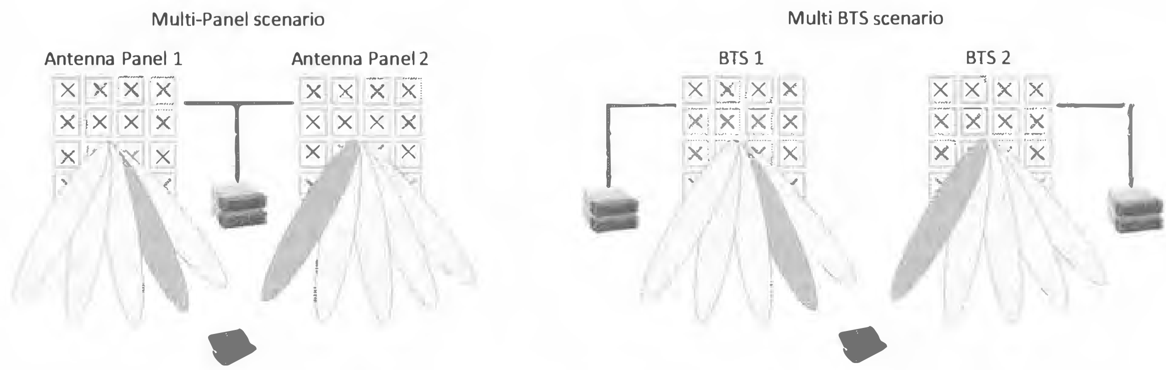


Figure 410 – Deployment scenarios using Group based Beam Reporting

★ The structure of an 'ssb-Index-RSRP' report is illustrated in Figure 411. The report starts with up to four SSBRI values which identify the SS/PBCH Blocks which have been measured. Each value occupies $LOG_2\ (K_s^{SSB})$ bits within the signalling payload, where K_s^{SSB} is the number of SS/PBCH Blocks available for measurement. The SSBRI values are followed by the Layer 1 RSRP measurements. 3GPP has specified the reporting of Differential RSRP values to help reduce the signalling payload size. A single absolute RSRP measurement result is reported, while the remaining measurement results are reported as differential values relative to the absolute value. The absolute value occupies 7 bits whereas the differential values occupy 4 bits. The mapping used for the absolute and differential values are presented in section 10.1

CRI or SSBRI #1
CRI or SSBRI #2
CRI or SSBRI #3
CRI or SSBRI #4
RSRP #1
Differential RSRP #2
Differential RSRP #3
Differential RSRP #4

Figure 411 – Reporting format for CRI / SSBRI with Layer 1 RSRP measurements

- ★ The CSI Reference Signal Resource Indicator (CRI) is reported in combination with a Layer 1 RSRP measurement when *reportQuantity* within *CSI-reportConfig* is configured with a value of 'cri-RSRP'. In this case, the RSRP measurement is recorded from the CSI Reference Signal
- ★ The CRI is also reported in combination with other Channel State Information when *reportQuantity* is configured with a value of 'cri-RI-PMI-CQI', 'cri-RI-i1', 'cri-RI-i1-CQI', 'cri-RI-CQI' or 'cri-RI-LI-PMI-CQI'
- ★ Similar to the SSBRI, the CRI can be used during Beam Management procedures when identifying the best downlink beam(s). The CRI allow the Base Station to switch between CSI Reference Signal beams which are typically more directional than SS/PBCH beams
- ★ The concept of Group based Beam Reporting is also applicable to CSI Reference Signal transmissions so the beams illustrated in Figure 410 could be either SS/PBCH Block beams, or CSI Reference Signal beams
- ★ The reporting structure illustrated in Figure 411 is also applicable to reporting CRI in combination with RSRP measurements. Each CRI occupies $LOG_2\ (K_s^{CSI-RS})$ bits within the signalling payload, where K_s^{CSI-RS} is the number of CSI Reference Signals available for measurement
- ★ 3GPP References: TS 38.214, TS 38.212, TS 38.133

13.7 UPLINK RESOURCE REQUEST

★ The Base Station packet scheduler is responsible for allocating resources to transfer uplink data. In some cases, it is not necessary for the UE to request those resources:

  o the Base Station may allocate resources in a proactive manner, i.e. provide the UE with capacity on the PUSCH before it is actually requested. This approach helps to reduce latency because the UE is able to transmit uplink data without having to request resources and subsequently wait for those resources to be allocated. Proactive scheduling is generally applicable to cells which are not heavily loaded. Cells transferring a lot of data may not have sufficient capacity to allocate resources which may not be required, i.e. proactive scheduling grants are typically given low priority by the packet scheduler. 'Proactive Grants' are described in section 7.4.4.4

  o the Base Station may provide the UE with 'Configured Grants' to allow uplink transmission on the PUSCH without having to receive individual resource allocations on the PDCCH. A UE configured in this way is not free to transmit on any Resource Block at any time, but is configured to allow periodic transmission on a specific set of Resource Blocks. This type of resource allocation is also known as 'Grant Free' resource allocation and is analogous to Sem-Persistent Scheduling (SPS) in the downlink. 'Configured Grants' are described in section 7.4.4.3

★ Otherwise, a UE can request uplink resources using the following mechanisms:

  o Scheduling Request (section 13.7.1)

  o Buffer Status Reporting (section 13.7.2)

  o Random Access procedure (section 13.1)

★ A UE can use the Random Access procedure to request uplink resources if it has not been configured with the appropriate PUCCH resources to send a Scheduling Request. This results in the UE completing the Random Access procedure while in RRC Connected mode. The Buffer Status Reporting (BSR) procedure allows the UE to report its buffer occupancy, i.e. providing the Base Station with information regarding the requirement for additional resources. Buffer Status Reports are transmitted on the PUSCH so the UE must already have at least one uplink resource allocation. A Scheduling Request can be used to request uplink resources for a Buffer Status Report if they are not already available

13.7.1 SCHEDULING REQUEST

★ A UE uses the Scheduling Request (SR) procedure as a mechanism to request air-interface resources for a new uplink transmission

★ Figure 412 illustrates the sequence of events associated with the transmission of a Scheduling Request. Uplink data belonging to a specific Logical Channel is queued for transmission within the UE buffer. This uplink data triggers the UE to send a Scheduling Request using PUCCH resources which have been configured specifically for the Logical Channel which has the uplink data ready for transmission. The Base Station receives the Scheduling Request and is able to deduce the Logical Channel (or group of Logical Channels if multiple Logical Channels have been linked to the same set of PUCCH resources). Knowledge of the Logical Channel helps the Base Station to prioritise the Scheduling Request

★ The Base Station then proceeds to allocate uplink resources on the PUSCH using a PDCCH transmission. The UE uses those resources to send a Buffer Status Report (BSR) in combination with at least some of the buffered data. The Buffer Status Report provides the Base Station with information regarding the volume of data waiting to be transferred. Alternatively, if the UE buffer can be emptied using the initial uplink resource allocation, the UE can exclude the Buffer Status Report and send only the uplink data

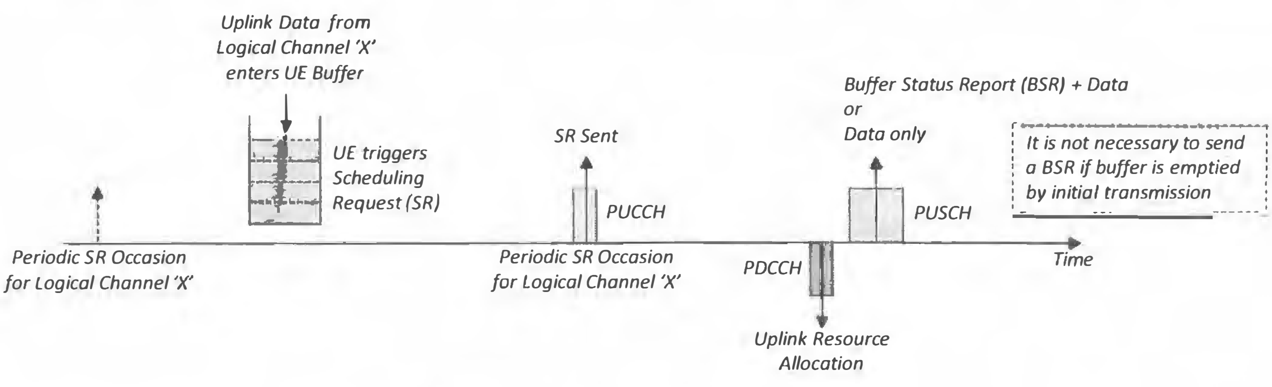


Figure 412 –Scheduling Request transmission

★ Once a Scheduling Request has been triggered, it is categorised as 'pending' until it is 'cancelled', i.e. a Scheduling Request remains categorised as 'pending' after it has been transmitted. A Scheduling Request is 'cancelled' after the UE has received an uplink resource allocation and has sent a Buffer Status Report, or after the UE has received an uplink resource allocation and has been able to empty its transmission buffers

★ Scheduling Requests are sent using the PUCCH physical channel. All PUCCH Formats can accommodate a Scheduling Request, i.e. Formats 0, 1, 2, 3 and 4 described in section 7.3. However, Scheduling Request resources are always configured using either PUCCH Format 0 or PUCCH Format 1. Other PUCCH formats can be used when PUCCH transmissions coincide, e.g. a Scheduling Request transmission using PUCCH Format 0 coincides with a CSI Reporting transmission using PUCCH Format 3. In that case, both the Scheduling Request and CSI Report can be transferred using PUCCH Format 3

★ A UE is not free to transmit a Scheduling Request at any instant in time. Instead, the Base Station provides the UE with timing information which defines the time instants that a UE is permitted to transmit a Scheduling Request. This timing information includes the *SR-periodicity* and *SR-offset*. The *SR-periodicity* is the most important parameter from the perspective of balancing the trade-off between network load and end-user latency. A short periodicity creates a high load because the UE has PUCCH resources reserved more frequently (PUCCH resources are dedicated to a specific UE so those resources cannot be re-used once allocated). The benefit of a short periodicity is the reduced latency provided by the lower average waiting time for a Scheduling Request opportunity

★ Table 304 presents the *SchedulingRequestResourceConfig* parameter structure which configures both the *SR-periodicity* and *SR-offset* using the *periodicityAndOffset* information element. The period can be as short as 2 symbols for very low latency applications. Alternatively, the period can be up to 640 slots for delay tolerant applications

SchedulingRequestResourceConfig								
schedulingRequestResourceId	1 to 8							
schedulingRequestId	0 to 7							
periodicityAndOffset	CHOICE							
	2 symbols	-	4 slots	0 to 3	16 slots	0 to 15	160 slots	0 to 159
	6 or 7 sym	-	5 slots	0 to 4	20 slots	0 to 19	320 slots	0 to 320
	1 slot	-	8 slots	0 to 7	40 slots	0 to 39	640 slots	0 to 639
	2 slots	0, 1	10 slots	0 to 9	80 slots	0 to 79		
PUCCH-ResourceId	0 to 127							

Table 304 – Scheduling Request Resource Configuration parameter structure

★ The numerology and cyclic prefix duration determine the set of allowed Scheduling Request periodicities. Table 305 presents the values allowed for each combination. The higher subcarrier spacings support higher periodicities in terms of slots but the upper value remains constant when expressed in terms of ms, i.e. 80 slots for the 15 kHz subcarrier spacing corresponds to 80 ms, while 640 slots for the 120 kHz subcarrier spacing also corresponds to 80 ms

Subcarrier Spacing	Cyclic Prefix	Scheduling Request Periodicity
15 kHz ($\mu = 0$)	Normal	2, 7 symbols, 1, 2, 4, 5, 8, 10, 16, 20, 40, 80 slots
30 kHz ($\mu = 1$)	Normal	2, 7 symbols, 1, 2, 4, 8, 10, 16, 20, 40, 80, 160 slots
60 kHz ($\mu = 2$)	Normal	2, 7 symbols, 1, 2, 4, 8, 16, 20, 40, 80, 160, 320 slots
60 kHz ($\mu = 2$)	Extended	2, 6 symbols, 1, 2, 4, 8, 16, 20, 40, 80, 160, 320 slots
120 kHz ($\mu = 3$)	Normal	2, 6 symbols, 1, 2, 4, 8, 16, 40, 80, 160, 320, 640 slots

Table 305 – Scheduling Request periodicities for each numerology and cyclic prefix duration

★ If the *SR-periodicity* is less than 1 slot (2 or 7 symbols when using the normal cyclic prefix; 2 or 6 symbols when using the extended cyclic prefix), the Scheduling Request opportunities start at symbols which satisfy the following expression:

$$\left(SR_{START\_SYM} - \left(PUCCH_{START\_SYM}\ mod\ SR\text{-}periodicity\right)\right)\ mod\ SR\text{-}periodicity = 0$$

★ SR_{START_SYM} is the symbol during which the Scheduling Request opportunity starts, whereas $PUCCH_{START\_SYM}$ is the value of *startingSymbolIndex* configured for the PUCCH (see Figure 253 in section 7.3). For example, if *SR-periodicity* = 7 symbols, while $PUCCH_{START\_SYM} = 4$, then Scheduling Request opportunities start within each slot during symbols 4 and 11

★ If the *SR-periodicity* is 1 slot, the Scheduling Request opportunities start within each slot at the symbol specified by the PUCCH configuration parameter: *startingSymbolIndex*

★ If the *SR-periodicity* is greater than 1 slot, the Scheduling Request opportunities occur during slots which satisfy:

$$\left(SFN \times N_{slot}^{frame,\mu} + SR_{SLOT} - SR\text{-}offset\right)\ mod\ SR\text{-}periodicity = 0$$

★ SR_{SLOT} is the slot during which the Scheduling Request opportunity occurs. For example, if *SR-periodicity* = 16 slots, *SR-offset* = 12, and the 30 kHz subcarrier spacing is used (20 slots per radio frame), the Scheduling Request opportunities occur during slots {SFN 0, slot 12}, {SFN 1, slot 8}, {SFN 2, slot 4}, {SFN 3, slot 0}, {SFN 3, slot 16}, etc. Within each slot, the Scheduling Request opportunities start at the symbol specified by the PUCCH configuration parameter: *startingSymbolIndex*

★ Returning to Table 304, each *SchedulingRequestResourceConfig* is associated with a *schedulingRequestResourceId*. This identity is simply used as a reference to address a specific instance of the parameter structure when setting up or releasing Scheduling Request resources within the parent *PUCCH-Config* parameter structure

★ In contrast, the *schedulingRequestId* represents a pointer towards an additional set of parameters associated with the Scheduling Request resources. These additional parameters are presented in Table 306

SchedulingRequestConfig		
schedulingRequestToAddModList	SEQUENCE {1 to 8 instances}	
	schedulingRequestId	0 to 7
	sr-ProhibitTimer	1, 2, 4, 8, 16, 32, 64, 128 ms
	sr-TransMax	4, 8, 16, 32, 64
schedulingRequestToReleaseList	SEQUENCE {1 to 8 instances}	
	schedulingRequestId	0 to 7

Table 306 – Scheduling Request Configuration parameter structure

★ *sr-ProhibitTimer* defines the minimum time between consecutive Scheduling Requests, i.e. this timer is started after sending a Scheduling Request and the UE must wait for this timer to expire before sending another Scheduling Request

★ *sr-TransMax* specifies the maximum number of Scheduling Requests which can be sent to the Base Station. If the number of Scheduling Requests reaches this upper limit before receiving an uplink resource allocation, the UE releases its PUCCH and SRS resources and initiates the random access procedure

★ Figure 413 illustrates a first Scheduling Request being sent after uplink data arrives within the UE buffer. This example assumes that the UE does not immediately receive an uplink resource allocation from the Base Station. Instead, it is assumed that an additional 2 Scheduling Request transmissions are required, with each transmission separated by a minimum period of *sr-ProhibitTimer*

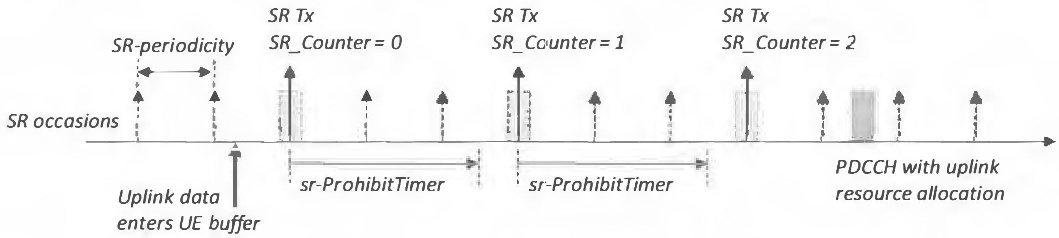


Figure 413 – Re-transmission of Scheduling Request until reception of uplink resource allocation

★ Figure 414 illustrates that each Logical Channel can be linked to a specific Scheduling Request configuration. This means that different Logical Channels can be configured with different values for *sr-ProhibitTimer* and *sr-TransMax*. In addition, it means that each Logical Channel can be linked to a specific Scheduling Request Resource configuration and a specific PUCCH resource (the PUCCH resource is identified using the *PUCCH-ResourceId* within Table 304)

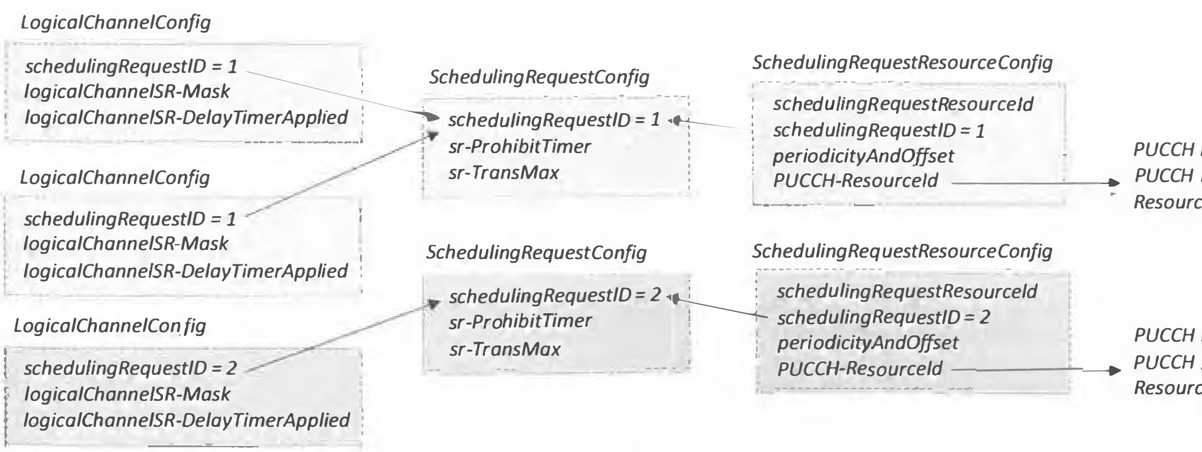


Figure 414 – Mapping of Logical Channels onto Scheduling Request Configurations and PUCCH resources

★ Linking different Logical Channels to different PUCCH resources allows the Base Station to identify the Logical Channel which has triggering the Scheduling Request. This is useful information when prioritising the Scheduling Request. For example, if the Logical Channel is responsible to transferring data for a low latency application then the Base Station can allocate higher priority to the Scheduling Request. The drawback associated with allocating different PUCCH resources to different logical channels is an increased PUCCH resource requirement, i.e. the UE requires multiple sets of PUCCH resources rather than a single set

★ Table 307 presents the set of parameters within *LogicalChannelConfig* which are applicable to the transmission of Scheduling Requests. *schedulingRequestID* is used as the pointer towards the Scheduling Request configuration

extract from *LogicalChannelConfig*	
schedulingRequestID	0 to 7
logicalChannelSR-Mask	BOOLEAN
logicalChannelSR-DelayTimerApplied	BOOLEAN

Table 307 – Scheduling Request Identity within the *LogicalChannelConfig*

★ *logicalChannelSR-Mask* is a flag which is used to indicate whether or not the Logical Channel is permitted to trigger Scheduling Requests when using a Type 1 or Type 2 'Configured Grant' (Configured Grants are described in section 7.4.4.3). This may be appropriate for a connection using 'Configured Grants' because the UE already has regular periodic uplink resource allocations, i.e. it may not be necessary for the UE to send a Scheduling Request. Some Logical Channels may be permitted to trigger Scheduling Requests when 'Configured Grants' are being used, if for example those Logical Channels have low latency requirements while the 'Configured Grants' are using a relatively long period between resource allocations

★ *logicalChannelSR-DelayTimerApplied* is a flag which activates a timer used to delay the transmission of a Scheduling Request. The actual value of the timer is configured using *logicalChannelSR-DelayTimer* belonging to BSR-Config (presented in Table 309 in the section below). The timer is started when there is a requirement to send a 'Regular' Buffer Status Report for a logical channel which has the flag set tot 'True'. The corresponding Scheduling Request must wait for the timer to expire before being sent. The objective of this timer is to provide a solution for managing low priority Logical Channels at busy cells. It can also be used as a solution for voice service packet aggregation, i.e. the timer can be set to 40 ms so the UE requests uplink capacity after 2 packets have been received from the codec (assuming the voice codec generates packets every 20 ms)

★ 3GPP References: TS 38.213, TS 38.321, TS 38.331

13.7.2 BUFFER STATUS REPORTING

★ A UE uses Buffer Status Reporting (BSR) to provide the Base Station within information regarding the volume of uplink data waiting to be transferred. Buffer Status Reports are sent on the PUSCH using a MAC Control Element. The provision of a Buffer Status Report helps the Base Station to allocate an appropriate quantity of air-interface resources

★ Both the PDCP and RLC layers provide the MAC layer with data volume figures so the UE is able to signal the total buffered data volume to the Base Station

★ Buffer Status Reports are sent per 'Logical Channel Group' (LCG) rather than per 'Logical Channel' (although it is possible for an LCG to include only a single Logical Channel). In general, Logical Channels with similar priority are linked to the same LCG. This allows the Base Station to differentiate between the volume of high priority data and the volume of lower priority data. For example, Logical Channels used for signalling may be linked to a first LCG, while Logical Channels transferring conversational data could be linked to a second LCG, and Logical Channels transferring Non-Real Time (NRT) data could be linked to a third LCG. A UE can be configured with up to 8 LCG so the Base Station has reasonable flexibility when grouping the set of Logical Channels

★ A Logical Channel is linked to an LCG using the *logicalChannelGroup* information element shown in Table 308. This information element belongs to the *LogicalChannelConfig* parameter structure

extract from *LogicalChannelConfig*	
logicalChannelGroup	0 to 7

Table 308 – Logical Channel Group within the *LogicalChannelConfig*

★ The remaining parameters associated with Buffer Status Reporting are configured using the *BSR-Config* shown in Table 309

BSR-Config	
periodicBSR-Timer	1, 5, 10, 16, 20, 32, 40, 64, 80, 128, 160, 320, 640, 1280, 2560 subframes, infinity
retxBSR-Timer	10, 20, 40, 80, 160, 320, 640, 1280, 2560, 5120, 10240 subframes
logicalChannelSR-DelayTimer	20, 40, 64, 128, 512, 1024, 2560 subframes

Table 309 – Buffer Status Report Configuration parameter structure

★ There are three categories of triggering mechanism for Buffer Status Reports (BSR):

- o Regular BSR triggering is applicable if:
  - new uplink data becomes available for transmission, and that uplink data belongs to a Logical Channel which has higher priority than the Logical Channels associated with the previously available uplink data
  - new uplink data becomes available for transmission after having no uplink data available for transmission
  - the *retxBSR-Timer* expires when there is uplink data waiting to be transferred. The *retxBSR-Timer* has been specified to help avoid the deadlock situation which occurs when the Base Station fails to receive a Buffer Status Report while the UE believes that reception has been successful, i.e. the UE fails to receive the request for a re-transmission. In this situation the UE waits for an uplink resource allocation but the Base Station does not provide any resources because it failed to receive the Buffer Status Report. The *retxBSR-Timer* helps to resolve the situation by triggering a re-transmission of the report
- o Periodic BSR triggering is applicable if:
  - the *periodicBSR-Timer* expires. This timer can be set to 'infinity' so periodic Buffer Status Reports are optional. The periodic timer is re-started after each Buffer Status Report transmission unless the 'truncated' report format is used
- o Padding BSR triggering is applicable if:
  - uplink resources have been allocated such that the number of padding bits equals or exceeds the size of a Buffer Status Report. In this case, a Buffer Status Report is included within the uplink packet to reduce the quantity of padding, i.e. taking advantage of the unused uplink capacity

★ Four formats have been specified for the Buffer Status Report: Short BSR, Short Truncated BSR, Long BSR and Long Truncated BSR. Selection between these four formats is based upon the procedure illustrated in Figure 415

★ If the BSR is triggered using either the Regular or Periodic mechanisms then either a Long or Short BSR is generated. The Long BSR is designed to accommodate information regarding multiple LCG so this format is generated if more than a single LCG has uplink data to transfer. Otherwise, a Short BSR is generated to provide information regarding a single LCG

★ If the BSR is triggered using the Padding mechanism then the BSR format depends upon the quantity of padding which is available to accommodate the BSR. It is assumed that the quantity of padding is always at least as large as a Short BSR otherwise the Padding BSR would not have been triggered. If there is sufficient padding to accommodate a Long BSR then a Long BSR is generated. Otherwise, if only a single LCG has data to transfer then a Short BSR is generated. Otherwise, if multiple LCG have data to transfer but the size of the padding can only accommodate a Short BSR then Short Truncated BSR is generated for the LCG with the highest priority Logical Channel. Otherwise, a Long Truncated BSR is generated for the LCG with the highest priority Logical Channels

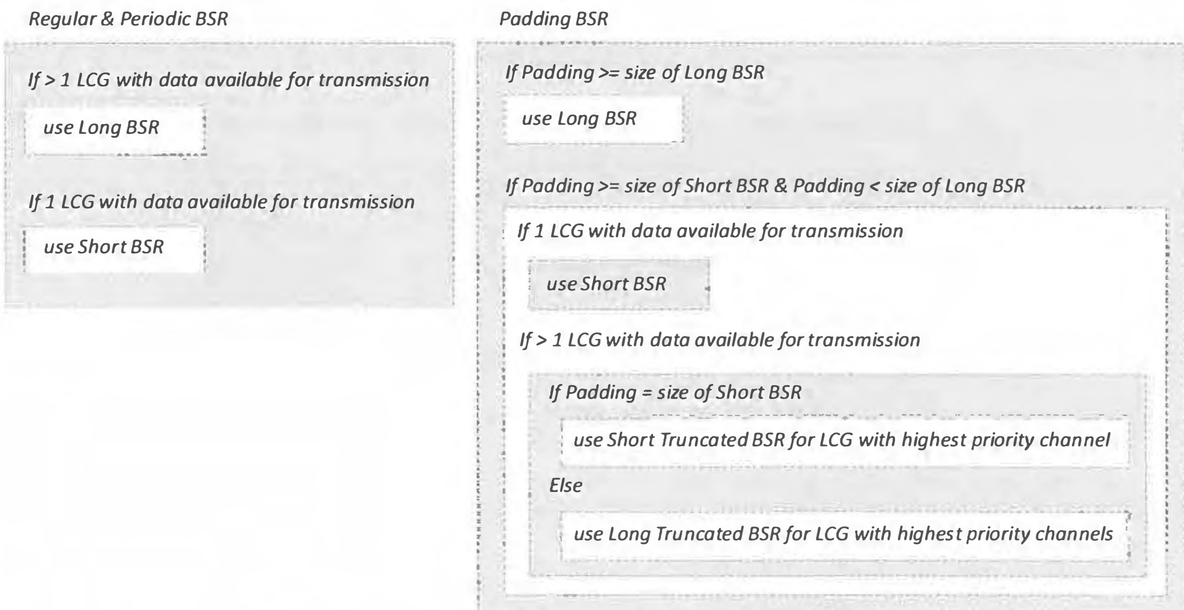


Figure 415 – Selection between the four Buffer Status Report formats

★ The structure of a Short BSR and a Short Truncated BSR is illustrated in Figure 416. These MAC Control Elements have the same format and have a fixed size. The actual payload of the MAC Control Element is 1 Byte. An additional 1 Byte subheader is included to identify the payload of the MAC Control Element. An LCID value of 61 is used to identify a Short BSR, whereas an LCID value of 59 is used to identify a Short Truncated BSR (LCID stands for Logical Channel Identity but within this context it is used to identify a MAC CE rather than a Logical Channel)

Figure 416 – Structure of a Short and Short Truncated Buffer Status Report

★ The size and structure of a Short and Short Truncated BSR are the same. The only difference is that the Short BSR provides information when only a single LCG has data to transfer, whereas the Short Truncated LCG provides information regarding the LCG which includes the highest priority Logical Channel when multiple LCG have data to transfer

★ The 5 bits used to quantify the Buffer Size act as a pointer towards an entry within a 3GPP standardised look-up table (Table 310). The values within this table have units of Bytes

Index	BS Value	Index	BS Value	Index	BS Value	Index	BS Value
0	0	8	≤ 102	16	≤ 1446	24	≤ 20 516
1	≤ 10	9	≤ 142	17	≤ 2014	25	≤ 28 581
2	≤ 14	10	≤ 198	18	≤ 2806	26	≤ 39 818
3	≤ 20	11	≤ 276	19	≤ 3909	27	≤ 55 474
4	≤ 28	12	≤ 384	20	≤ 5446	28	≤ 77 284
5	≤ 38	13	≤ 535	21	≤ 7587	29	≤ 107 669
6	≤ 53	14	≤ 745	22	≤ 10 570	30	≤ 150 000
7	≤ 74	15	≤ 103	23	≤ 14 726	31	> 150 000

Table 310 – Buffer Size (BS) values for Short and Short Truncated Buffer Status Reports

★ The structure of a Long BSR and a Long Truncated BSR is illustrated in Figure 417. These MAC Control Elements have the same format but have a variable size. The Long BSR includes 'Buffer Size' fields for all LCG which have data available to transfer, whereas the Long Truncated BSR includes 'Buffer Size' fields for a subset of the LCG which have data available to transfer. The subset is selected according to the priority of the Logical Channels belonging to each LCG

★ An additional subheader is included to identify the payload and length of the MAC Control Element. An LCID value of 62 is used to identify a Long BSR, whereas an LCID value of 60 is used to identify a Long Truncated BSR

★ In the case of the Long BSR, the first byte of the payload includes a series of flags to indicate which LCG have Buffer Size fields included within the BSR. The number of Buffer Size fields equals the number of flags set to '1'

★ In the case of the Long Truncated BSR, the first byte of the payload includes a series of flags to indicate which LCG have data available to transfer. In this case, the number of Buffer Size fields is less than the number of LCG flags set to '1'

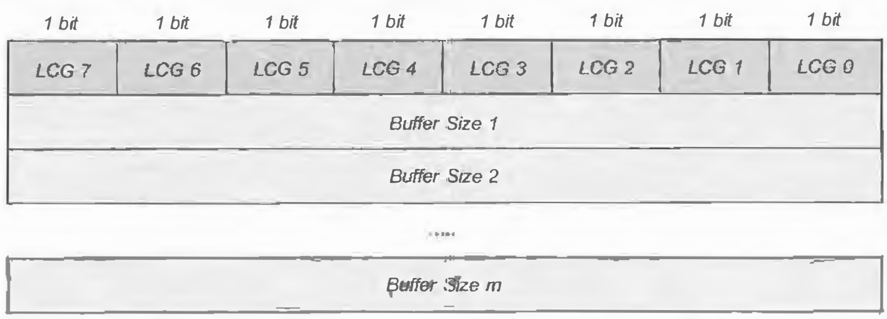


Figure 417 – Structure of a Long and Long Truncated Buffer Status Report

★ The Long BSR and Long Truncated BSR use 8 bits rather than 5 bits to quantify the Buffer Size. This allows the use of a larger look-up table which includes values up to 81 338 368 Bytes. This larger look-up table can be found within 3GPP TS 38.321

★ 3GPP References: TS 38.321, TS 38.331

13.8 POWER HEADROOM REPORTING

★ The UE sends Power Headroom (PHR) reports to the Base Station using MAC Control Elements which are transmitted on the PUSCH. The Base Station can use these reports within its Packet Scheduler and Link Adaptation algorithms. The Packet Scheduler is responsible for identifying the number of Resource Blocks to be allocated to the PUSCH, whereas Link Adaptation is responsible for identifying the Modulation and Coding Scheme (MCS). It may be necessary to restrict the number of allocated Resource Blocks or the allocated MCS if the UE is reporting a low Power Headroom

★ Power Headroom reports can also be used within other areas of Radio Resource Management. A Base Station can use the reports to calculate the path loss towards the UE. These path loss results can then be used to enable/disable specific functionality. For example, a UE may be configured with uplink Carrier Aggregation when the path loss is low, and the configuration can be subsequently released if the path loss becomes high, i.e. the UE may benefit from focusing its uplink transmit power across a single carrier rather than across multiple carriers when the path loss is high

★ Power Headroom reports are configured using the *PHR-Config* presented in Table 311. This parameter structure belongs to the *MAC-CellGroupConfig*

PHR-Config	
phr-PeriodicTimer	10, 20, 50, 100, 200, 500, 1000 subframes, infinity
phr-ProhibitTimer	0, 10, 20, 50, 100, 200, 500, 1000 subframes
phr-Tx-PowerFactorChange	1, 3, 6 dB, infinity
multiplePHR	True, False
phr-Type2OtherCell	True, False
phr-ModeOtherCG	real, virtual

Table 311 – Power Headroom Configuration parameter structure

★ Power Headroom reports do not trigger Scheduling Requests. This means that Power Headroom reports are only sent when the UE has already been allocated PUSCH resources for another reason, e.g. to transfer uplink data

★ The *phr-PeriodicTimer* can be used to instruct the UE to send periodic Power Headroom reports. Configuring a value of 'infinity' disables periodic reporting. Otherwise, the period is defined in terms of subframes, i.e. units of 1 ms

★ The *phr-Tx-PowerFactorChange* can be used to instruct the UE to send a Power Headroom report when the path loss has changed by more than the value of the parameter. Configuring a value of 'infinity' disables path loss based reporting. Otherwise, path loss changes of 1, 3 or 6 dB can be used to trigger a Power Headroom report

★ A Power Headroom report can also be triggered if the UE changes its transmit power back-off requirement (Maximum Power Reduction (MPR)) by more than the value of *phr-Tx-PowerFactorChange*. The MPR tends to increase when a UE uses higher order modulation schemes or when using Resource Blocks towards the edge of the channel bandwidth. The MPR may also increase if there is a requirement to satisfy more stringent out-of-band emissions or spurious emissions

★ Power Headroom reports are also triggered when a Secondary Cell is activated, when a Primary Secondary Cell Group (SCG) Cell is added, and when Power Headroom reporting is first configured or reconfigured

★ The *phr-ProhibitTimer* is used to prevent the UE from sending Power Headroom reports too frequently. The prohibit timer is started after sending a report and subsequent reports triggered by path loss changes or power back-off changes cannot be sent until the timer has expired

★ The *multiplePHR* information element instructs the UE to use either the 'Single Entry' or 'Multiple Entry' MAC Control Element. 3GPP TS 38.331 specifies that this information element should be set to 'True' when using Multi-RAT Dual Connectivity (MR-DC) and for NR Uplink Carrier Aggregation. Otherwise it should be set to 'False'. This means that the 'Multiple Entry' MAC Control Element is used for the Non-Standalone EN-DC Base Station configuration

★ The 'Single Entry' MAC Control Element is presented in Figure 418. The Logical Channel Identity (LCID) used to identify this MAC Control Element within its subheader is '57'. The 'R' fields are reserved and are populated with '0'

R	R	Power Headroom (Type 1, PCell)
R	R	$P_{CMAX,f,c}$

Figure 418 – Single Entry Power Headroom MAC Control Element

★ The Power Headroom value occupies a set of 6 bits providing a range from 0 to 63. These 64 signalled values are mapped onto actual Power Headroom results using the look-up table presented as Table 312. Note that a step size of 1 dB is used for lower reported values, while a step size of 2 dB is used for higher reported values

Reported Value	Actual Value (dB)	Reported Value	Actual Value (dB)
POWER_HEADROOM_0	PH < -32	POWER_HEADROOM_56	24 ≤ PH < 26
POWER_HEADROOM_1	-32 ≤ PH < -31	POWER_HEADROOM_57	26 ≤ PH < 28
POWER_HEADROOM_2	-31 ≤ PH < -30	POWER_HEADROOM_58	28 ≤ PH < 30
… …	…	POWER_HEADROOM_59	30 ≤ PH < 32
POWER_HEADROOM_52	19 ≤ PH < 20	POWER_HEADROOM_60	32 ≤ PH < 34
POWER_HEADROOM_53	20 ≤ PH < 21	POWER_HEADROOM_61	34 ≤ PH < 36
POWER_HEADROOM_54	21 ≤ PH < 22	POWER_HEADROOM_62	36 ≤ PH < 38
POWER_HEADROOM_55	22 ≤ PH < 24	POWER_HEADROOM_63	PH ≥ 38

Table 312 – Power Headroom Report mapping

- Figure 418 indicates that a 'Type 1' Power Headroom report for the primary serving cell is included within the 'Single Entry' MAC Control Element. A 'Type 1' report quantifies the difference between the nominal UE maximum transmit power and the PUSCH transmit power requirement. The expression used to calculate the Power Headroom is presented in Figure 419. This expression is based upon the standard PUSCH power control equation described in section 13.3.1. It can generate a negative result if the calculated transmit power requirement exceeds the maximum UE transmit power

Maximum UE Transmit Power | *Subcarrier Spacing* | *Allocated Resource Blocks* | *Path Loss Measurement* | *Closed Loop Power Control Component*

$$PH_{TYPE1,b,f,c}(i,j,q_d,l) = P_{CMAX,f,c}(i) - \left\{P_{O\_PUSCH,b,f,c}(j) + 10 \times LOG\left(2^{\mu} \times M^{PUSCH}_{RB,b,f,c}(i)\right) + \alpha_{b,f,c}(j) \times PL_{b,f,c}(q_d) + \Delta_{TF,b,f,c}(i) + f_{b,f,c}(i,l)\right\}$$

Nominal UE Transmit Power (can include compensation for Supplemental Uplink) | *Fractional Power Control Multiplier* | *Modulation and Coding Scheme Offset*

Figure 419 – Type 1 Power Headroom calculation based upon actual PUSCH transmission

- The 'Single Entry' report also includes the $P_{CMAX,f,c}(i)$ value which was used to calculate the Power Headroom. This allows the Base Station to calculate the Path Loss, i.e. the Base Station has knowledge of all other variables within the power control equation. The $P_{CMAX,f,c}(i)$ value occupies a set of 6 bits within the report providing a range from 0 to 63. These 64 signalled values are mapped onto actual values using the look-up table presented as Table 313

Reported Value	Actual Value (dBm)	Reported Value	Actual Value (dBm)
PCMAX_C_0	$P_{CMAX,c,f}$ < -29	PCMAX_C_60	30 ≤ $P_{CMAX,c,f}$ < 31
PCMAX_C_1	-29 ≤ $P_{CMAX,c,f}$ < -28	PCMAX_C_61	31 ≤ $P_{CMAX,c,f}$ < 32
PCMAX_C_2	-28 ≤ $P_{CMAX,c,f}$ < -27	PCMAX_C_62	32 ≤ $P_{CMAX,c,f}$ < 33
… …	…	PCMAX_C_63	33 ≤ $P_{CMAX,c,f}$

Table 313 – $P_{CMAX,f,c}(i)$ mapping

- The 'Multiple Entry' MAC Control Element is presented in Figure 420. The Logical Channel Identity (LCID) used to identify this MAC Control Element is '56' when the MAC Control Element starts with a set of 7 flags (C1 to C7), and is '54' when the MAC Control Element starts with a set of 31 flags (C1 to C31). Figure 420 illustrates the MAC Control Element which starts with 7 flags
- The flags are used to indicate which serving cells have Power Headroom reports included within the MAC Control Element. Flag C1 corresponds to the serving cell with *ServCellIndex* = 1, flag C2 corresponds to the serving cell with *ServCellIndex* = 2, etc.
- Figure 420 illustrates that the first Power Headroom result within the MAC Control Element is 'Type 2'. Inclusion of this result depends upon the configuration of the *phr-Type2OtherCell* information element within Table 311. The release 15 version of the 3GPP specifications does not define a 'Type 2' result for NR but allows the MAC Control Element to include a 'Type 2' result for LTE. Thus, the 'Type 2' result is generated based upon the rules within 3GPP TS 36.213 (Physical Layer Procedures for E-UTRA). The 'Type 2' result quantifies the Power Headroom when the UE transmits both the PUSCH and PUCCH simultaneously. The release 15 version of the specifications does not permit simultaneous transmission of the PUSCH and PUCCH using NR so it is not meaningful to generate a 'Type 2' result for NR
- The 'V' field indicates whether the Power Headroom result is based upon a real transmission or a reference format (also known as a virtual transmission). It also indicates whether or not a $P_{CMAX,f,c}$ figure follows the Power Headroom result, i.e. a $P_{CMAX,f,c}$ figure is only included when the Power Headroom result is based upon a real transmission

C7	C6	C5	C4	C3	C2	C1	R
P	V	Power Headroom (Type 2, Pcell)					
R	R	$P_{CMAX,f,c}$ 1					
P	V	Power Headroom (Type 1, PCell)					
R	R	$P_{CMAX,f,c}$ 2					
P	V	Power Headroom (Type X, Serving Cell 1)					
R	R	$P_{CMAX,f,c}$ 3					
...	...	...					
P	V	Power Headroom (Type X, Serving Cell n)					
R	R	$P_{CMAX,f,c}$ m					

Figure 420 – Multiple Entry Power Headroom MAC Control Element

- When the Power Headroom result is applicable to another Cell Group, e.g. an LTE Cell Group when using EN-DC Dual Connectivity, the *phr-ModeOtherCG* information element within Table 311 determines whether or not a $P_{CMAX,f,c}$ figure can be included. Configuring *phr-ModeOtherCG* with a value of 'real' indicates that a $P_{CMAX,f,c}$ figure can be included
- The 'P' field indicates whether or not the $P_{CMAX,f,c}$ figure includes a power back-off due to a permitted Maximum Power Reduction (MPR). The 'P' field is set to '1' if the UE has applied a power back-off
- The second Power Headroom result within the Multiple Entry MAC Control Element is a 'Type 1' result for the primary serving cell. This result is based upon an actual PUSCH transmission if a transmission is available for the calculation. Otherwise, it is based upon a reference PUSCH transmission. The expression shown in Figure 421 is used to calculate the 'Type 1' result based upon a reference PUSCH transmission. In this case, the power control equation excludes the term dependent upon the subcarrier spacing and Resource Block allocation. This means that the reference PUSCH transmission corresponds to a single Resource Block with a subcarrier spacing equal to 15 kHz. The MCS dependent term is also excluded so the calculation assumes a 0 dB MCS boost

Maximum UE Transmit Power · *Path Loss Measurement* · *Closed Loop Power Control Component*

$$PH_{TYPE1,b,f,c}(i,j,q_d,l) = \tilde{P}_{CMAX,f,c}(i) - \{P_{O\_PUSCH,b,f,c}(j) + \alpha_{b,f,c}(j) \times PL_{b,f,c}(q_d) + f_{b,f,c}(i,l)\}$$

Nominal UE Transmit Power · *Fractional Power Control Multiplier*

Figure 421 – Type 1 Power Headroom calculation based upon Reference PUSCH transmission

- The subsequent Power Headroom results within Figure 420 are labelled as 'Type X'. These results can be either 'Type 1' or 'Type 3'. A 'Type 3' result is based upon the Sounding Reference Signal (SRS) rather than the PUSCH. A 'Type 1' result based upon an actual transmission is included whenever possible. A 'Type 3' result is included if an actual SRS transmission is available while an actual PUSCH transmission is not available
- Figure 422 presents the expression used to calculate a 'Type 3' result based upon an actual SRS transmission. This expression uses the standard SRS power control equation described in section 13.3.3

Maximum UE Transmit Power · *Subcarrier Spacing* · *Allocated Resource Blocks* · *Path Loss Measurement*

$$PH_{TYPE3,b,f,c}(i,q_s) = P_{CMAX,f,c}(i) - \{P_{O\_SRS,b,f,c}(q_s) + 10 \times LOG(2^{\mu} \times M_{SRS,b,f,c}(i)) + \alpha_{SRS,b,f,c}(q_s) \times PL_{b,f,c}(q_d) + h_{b,f,c}(i,l)\}$$

Nominal UE Transmit Power · *Fractional Power Control Multiplier* · *Closed Loop Power Control Component*

Figure 422 – Type 3 Power Headroom calculation based upon actual SRS transmission

- The MAC Control Element does not include an explicit indication of the result type so the Base Station is required to apply the same logic as the UE when identifying a Power Headroom result as either 'Type 1' or 'Type 3'
- 3GPP References: TS 38.321, TS 38.213, TS 38.331, TS 36.213

13.9 RADIO LINK MONITORING

★ 3GPP specifies Radio Link Monitoring procedures for the UE. The Base Station is also likely to support Radio Link Monitoring but the implementation will depend upon the network vendor. For example, the Base Station can detect radio link failure if it stops receiving periodic Channel State Information (CSI) reports from the UE. This section focuses upon the UE procedures specified by 3GPP

★ 3GPP specifies that the UE applies Radio Link Monitoring to the Primary serving Cell (PCell) of the Master Cell Group (MCG). If the UE is configured with a Secondary Cell Group (SCG), then the UE also applies Radio Link Monitoring to the Primary SCG Cell (PSCell). Radio Link Monitoring is only applied to the active Bandwidth Parts, i.e. the UE is not required to monitor Bandwidth Parts which are inactive

★ Measurements for Radio Link Monitoring are completed by the Physical layer. Measurement results are passed to both the MAC and RRC layers. The RRC layer is responsible for detecting Radio Link Failure (RLF) while the MAC layer is responsible for detecting Beam Failure. These responsibilities are summarised in Figure 423

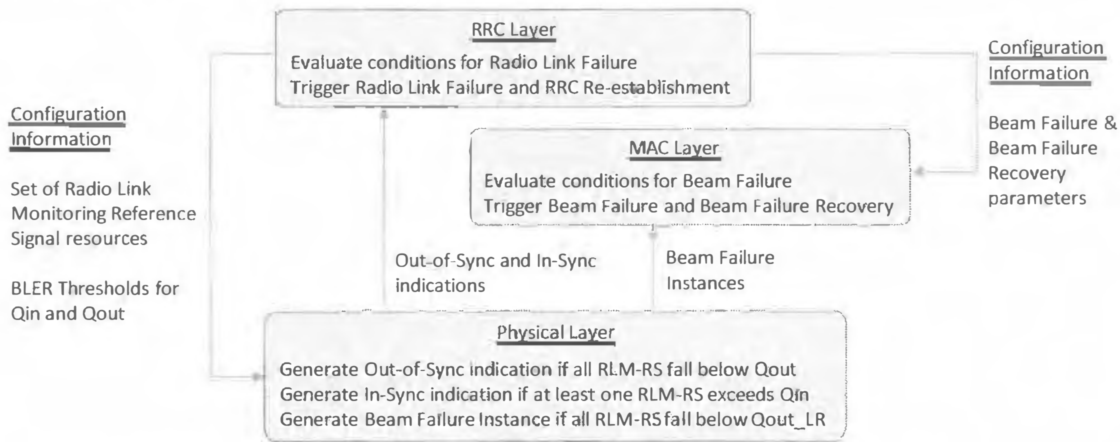


Figure 423 – Radio Link Monitoring within the RRC and MAC layers based upon Physical layer measurements

★ A Base Station can use RRC signalling to configure a UE with a set of Radio Link Monitoring Reference Signal (RLM-RS) resources. The RRC layer within the UE passes this information to the Physical layer within the UE. The resources can be:

- o SS/PBCH Blocks (SSB), or
- o Channel State Information Reference Signals (CSI-RS), or
- o a combination of SSB and CSI-RS

★ Figure 424 illustrates the general concept of these RLM-RS resources. 3GPP TS 38.133 specifies the maximum number of RLM-RS resources which a UE is expected to be capable of monitoring. When using Frequency Range 1 carrier frequencies ≤ 3GHz, a UE must be capable of monitoring 2 resources. When using Frequency Range 1 carrier frequencies > 3GHz, a UE must be capable of monitoring 4 resources. When using Frequency Range 2 carrier frequencies, a UE must be capable of monitoring 8 resources

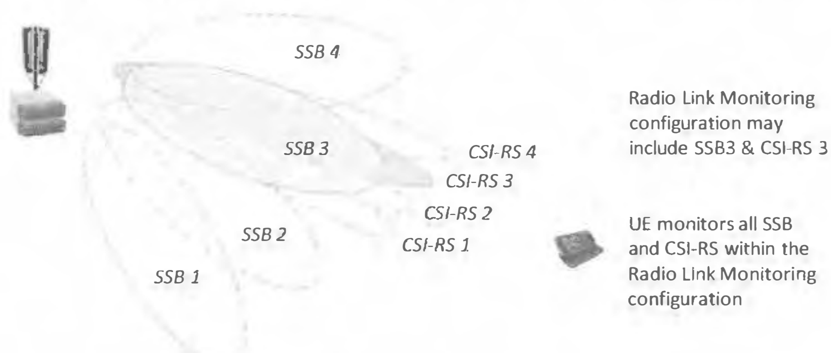


Figure 424 – SSB and CSI-RS used as Radio Link Monitoring Reference Signal (RLM-RS) resources

★ The Base Station can use the *RadioLinkMonitoringConfig* parameter structure presented in Table 314 to configure a set of RLM-RS resources. Each Radio Link Monitoring Reference Signal (RLM-RS) is linked to a *Purpose* which instructs the UE to use the Reference Signal for Beam Failure Detection, Radio Link Monitoring or both Beam Failure Detection and Radio Link Monitoring. A maximum of 2 RLM-RS can be configured for Beam Failure Detection, i.e. the number of RLM-RS with *Purpose* set equal to 'beamFailure' or 'both' should not exceed 2

RadioLinkMonitoringConfig				
failureDetectionResources ToAddModList	SEQUENCE {1 to 10 instances}			
	RadioLinkMonitoringRS	RadioLinkMonitoringRS-Id	0 to 9	
		Purpose	beamFailure, rlf, both	
		detectionResource	CHOICE	
			ssb-Index	csi-RS-Index
			0 to 63	0 to 191
failureDetectionResources ToReleaseList	SEQUENCE {1 to 10 instances}			
	RadioLinkMonitoringRS-Id	0 to 9		
beamFailureInstanceMaxCount	1, 2, 3, 4, 5, 6, 8, 10			
beamFailureDetectionTimer	1, 2, 3, 4, 5, 6, 8, 10 Beam Failure Detection Periods			

Table 314 – *RadioLinkMonitoringConfig* parameter structure

★ It is possible that the Base Station does not configure any Reference Signals within the *failureDetectionResourcesToAddModList*. In this case, the UE monitors Reference Signals which are linked to active Transmission Configuration Indicator (TCI) States for the Control Resource Sets (CORESET) that the UE is monitoring to receive the PDCCH. These Reference Signals have a Quasi Co-Location (QCL) relationship with the PDCCH

13.9.1 BEAM FAILURE

★ Under normal operating conditions, Beam Management procedures allow a UE to switch between beams as the radio conditions change over time, i.e. a UE which is moving around a cell can switch between beams by reporting a CSI Reference Signal Resource Indicator (CRI) or SS/PBCH Block Resource Indicator (SSBRI). These indicators provide the Base Station with information regarding the preferred beam at any point in time

★ A UE can experience Beam Failure if the radio conditions change such that existing beams become unreliable before the UE has been able to switch to a new beam. This could be caused by the end-user stepping around a corner or a vehicle causing an obstruction. Operating bands within Frequency Range 2 are more vulnerable to Beam Failure due to the characteristics of radio wave propagation at high frequencies. The reduced diffraction and increased shadowing means that beams can rapidly disappear as UE move around a cell

★ UE must be capable of detecting Beam Failure, selecting a new beam and recovering the connection with minimal delay. This is achieved by allowing these procedures to be completed using a combination of the Physical and MAC layers without any higher layer signalling, i.e. these procedures are transparent to the RRC layer

★ The Physical layer uses a quality threshold to trigger failure indications to the MAC layer. 3GPP TS 38.133 specifies that Q_{out_LR} corresponds to a quality at which the Block Error Rate (BLER) belonging to a hypothetical PDCCH transmission is 10 %, i.e. PDCCH reception is not reliable. The hypothetical PDCCH is assumed to be transferring DCI Format 1_0 with a Control Channel Element (CCE) aggregation level of 8 and the CORESET spanning 2 symbols

★ The Physical layer generates a '*Beam Failure Instance*' when the radio link quality belonging to all of the monitored Reference Signals is worse than Q_{out_LR}. This '*Beam Failure Instance*' is then used as an input for Beam Failure detection at the MAC layer. The MAC layer uses these indications in combination with the *beamFailureInstanceMaxCount* and *beamFailureDetectionTimer* information elements shown in Table 314

★ Figure 425 illustrates Beam Failure detection at the MAC layer. The MAC layer maintains *BFI_COUNTER* which is initially set to '0'. If the MAC layer receives a 'Beam Failure Instance' from the Physical layer, *BFI_COUNTER* is incremented by '1' and the *beamFailureDetectionTimer* is re-started. If *beamFailureDetectionTimer* expires then *BFI_COUNTER* is reset to '0'. Beam Failure is detected if *BFI_COUNTER* ≥ *beamFailureInstanceMaxCount*, i.e. Beam Failure detection requires the 'Beam Failure Instances' to be generated at a rate which does not allow the *beamFailureDetectionTimer* to expire

★ The *beamFailureDetectionTimer* is configured using units of 'Beam Failure Detection Periods'. The duration associated with a Beam Failure Detection Period depends upon the Connected Mode DRX configuration:

$T_{BFD\_PERIOD} = MAX(2\ ms,\ T_{BFD-RS})$ if DRX is disabled

$T_{BFD\_PERIOD} = MAX(1.5 \times DRX\_Cycle,\ 1.5 \times T_{BFD-RS})$ if DRX is enabled AND DRX_Cycle ≤ 320 ms

$T_{BFD\_PERIOD} = DRX\_Cycle$ if DRX is enabled AND DRX_Cycle > 320 ms

where, T_{BFD-RS} is the minimum period of the Reference Signal resources used for Beam Failure detection

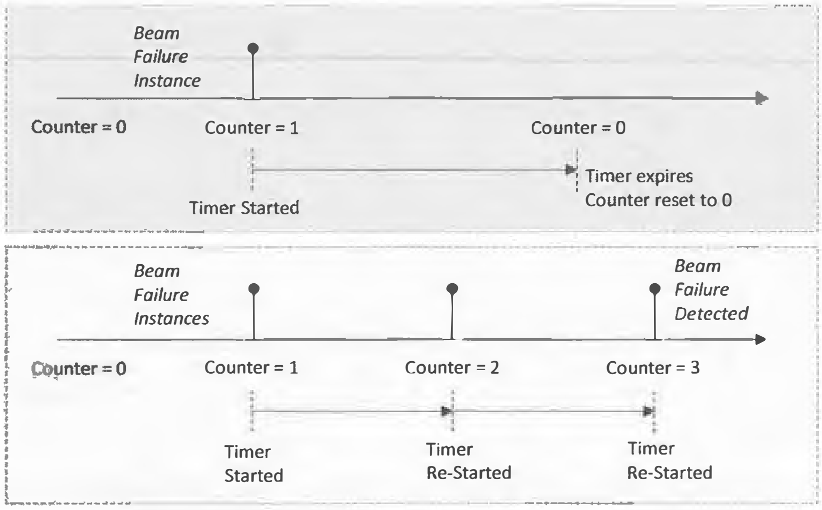


Figure 425 – Beam Failure detection at MAC layer

★ A CSI Reference Signal can be configured with a period between 4 and 640 slots, whereas an SS/PBCH can be configured with a period between 5 and 160 ms. In general, the Beam Failure Detection Period will be shorter when DRX is disabled and the UE remains continuously DRX active. A shorter period will allow faster Beam Failure detection but will also make the procedure more sensitive and may increase the number of Beam Failures

★ Once Beam Failure has been detected, the UE attempts to recover by initiating a Random Access procedure. The Base Station can use the *BeamFailureRecoveryConfig* presented in Table 315 to provide the UE with a set of resources for the recovery procedure

BeamFailureRecoveryConfig					
rootSequenceIndex-BFR	0 to 137				
rach-ConfigBFR	prach-ConfigurationIndex	0 to 255			
	msg1-FDM	1, 2, 4, 8			
	msg1-FrequencyStart	0 to 274			
	zeroCorrelationZoneConfig	0 to 15			
	preambleReceivedTargetPower	-202 to -60, step 2 dBm			
	preambleTransMax	3, 4, 5, 6, 7, 8, 10, 20, 50, 100, 200			
	powerRampingStep	0, 2, 4, 6 dB			
	ra-ResponseWindow	1, 2, 4, 8, 10, 20, 40, 80 slots			
rsrp-ThresholdSSB	0 to 127				
candidateBeamRSList	SEQUENCE {1 to 16 instances}				
	PRACH-Resource DedicatedBFR	CHOICE			
		ssb		csi-RS	
		ssb	0 to 63	csi-RS	0 to 191
		ra-PreambleIndex	0 to 63	ra-OccasionList	SEQUENCE {1 to 64 instances}
					0 to 511
				ra-PreambleIndex	0 to 63
ssb-perRACH-Occasion	1/8, 1/4, 1/2, 1, 2, 4, 8, 16				
ra-ssb-OccasionMaskIndex	0 to 15				
recoverySearchSpaceId	0 to 39				
ra-Prioritization	powerRampingStepHighPriority	0, 2, 4, 6 dB			
	scalingFactorBI	0, 0.25, 0.5, 0.75			
beamFailureRecoveryTimer	10, 20, 40, 60, 80, 100, 150, 200 ms				
msg1-SubcarrierSpacing-v1530	15, 30, 60, 120 kHz				

Table 315 – Beam Failure Recovery Configuration

★ Before transmitting a PRACH preamble, the UE must identify a new target beam. The *candidateBeamRSList* provides a list of up to 16 SS/PBCH Block and/or CSI Reference Signal beams. Each beam is allocated a specific dedicated PRACH preamble so the Base Station can use the preamble transmission to deduce which beam the UE has selected

- The UE measures the RSRP of the candidate beam before selecting it for recovery. If the candidate beam is associated with an SS/PBCH Block then the RSRP must exceed the mapped value of *rsrp-ThresholdSSB*. If the candidate beam is associated with a CSI Reference Signal then the RSRP must exceed the mapped value of *rsrp-ThresholdSSB* + *powerControlOffsetSS*. The latter parameter is provided using *NZP-CSI-RS-Resource* rather than *BeamFailureRecoveryConfig*

- Once a candidate beam has been selected for recovery, the UE uses the relevant *ra-PreambleIndex* in combination with the *rootSequenceIndex-BFR* and the *zeroCorrelationZoneConfig* to generate the PRACH preamble. The Root Sequence Index has a range from 0 to 137 which indicates that a short PRACH preamble is to be used for this procedure (long PRACH preambles use root sequence indices which range from 0 to 838). In addition, the UE is provided with *msg1-SubcarrierSpacing-v1530* which is allocated a value of 15, 30, 60 or 120 kHz. These subcarrier spacings correspond to values used by short PRACH preambles rather than long PRACH preambles (long PRACH preambles use subcarrier spacings of 1.25 and 5 kHz)

- The UE then identifies a time and frequency resource to transmit the PRACH preamble using the *prach-ConfigurationIndex*, *msg1-FDM* and *msg1-FrequencyStart* parameters. The *preambleReceivedTargetPower* is used as an input when calculating the transmit power of the PRACH preamble. *preambleTransMax* defines the maximum number of PRACH preambles which can be transmitted and *powerRampingStep* defines the power ramping step size between transmissions. *ra-ResponseWindow* defines the time duration that the UE waits for a response on the PDCCH after each PRACH preamble transmission

- The random access procedure for Beam Failure recovery can take advantage of 'Prioritised Random Access', as described in section 13.1.3. Prioritised Random Access is achieved by increasing the rate at which the PRACH preamble transmit power is increased during power ramping, i.e. by increasing the step size. It also allows a reduction of the Back-off Indicator included within MSG2, i.e. allowing the UE to re-attempt PRACH preamble transmission sooner. The value of *powerRampingStepHighPriority* replaces the value of *powerRampingStep*, while the value of *scalingFactorBI* is multiplied by the value of the Back-off Indicator within MSG2

- The *recoverySearchSpaceId* specifies the Search Space that the UE monitors for a PDCCH transmission in response to its PRACH preamble. The Beam Failure recovery is categorised as successful as soon as the UE receives a PDCCH with the CRC bits scrambled by the UE's C-RNTI. Figure 366 in section 13.1.2 illustrates the random access procedure for Beam Failure recovery

- The *BeamFailureRecoveryConfig* also provides a *beamFailureRecoveryTimer* which is started when the UE initiates the Beam Failure recovery procedure based upon the parameter set within *BeamFailureRecoveryConfig*. If the timer expires before the UE has completed the procedure, the UE attempts recovery using the contention based Random Access procedure rather than using the dedicated preambles within *BeamFailureRecoveryConfig*

13.9.2 RADIO LINK FAILURE

- Under normal operating conditions, a UE maintains its connection towards a primary serving cell and completes a handover to change the primary serving cell when necessary. The Base Station instructs the UE to return RRC: Measurement Reports when the conditions for handover are satisfied. This allows the Base Station to take a handover decision and subsequently initiate the handover procedure

- A UE can experience Radio Link Failure (RLF) if a handover procedure fails or if a handover procedure is not initiated when it is required. The former could result from congestion at the target cell or a change in radio conditions which leads to poor target cell coverage. The latter could result from a missing neighbour relationship or a triggering threshold which initiates the handover procedure too late. A UE can also experience Radio Link Failure if the 5G coverage becomes weak and the UE is unable to complete an inter-system handover

- A UE which has experienced Radio Link Failure must switch off its transmit power with minimal delay to ensure that the UE does not generate uplink interference while its connection has been lost. 3GPP TS 38.133 specifies a UE must switch off its transmit power within 40 ms of detecting Radio Link Failure. A Base Station should also be capable of detecting Radio Link Failure to avoid allocating resources and transmitting towards a UE when the UE is unable to receive

- The Base Station configures the UE with a pair of Block Error Rate (BLER) targets. $BLER_{out}$ corresponds to a quality level (Q_{out}) at which the radio link is categorised as being unreliable. $BLER_{in}$ corresponds to a quality level (Q_{in}) at which the radio link is categorised as being reliable. 3GPP has catered for two sets of values within the RRC signalling protocol although only a single set is currently specified (presented in Table 316)

Configuration	$BLER_{out}$	$BLER_{in}$
0	10 %	2 %
1	Currently not specified	

Table 316 – Block Error Rates (BLER) associated with Q_{out} and Q_{in}

- The Base Station uses the *rlmInSyncOutOfSyncThreshold* information element within *SpCellConfig* (presented in Table 317) to specify the appropriate pair of BLER values. Excluding this information element from the parameter structure indicates that configuration '0' should be used, whereas including the information element indicates that configuration '1' should be used

SpCellConfig		
servCellIndex	0 to 31	
reconfigurationWithSync	ReconfigurationWithSync	
rlf-TimersAndConstants	t310	0, 50, 100, 200, 500, 1000, 2000, 4000, 6000 ms
	n310	1, 2, 3, 4, 6, 8, 10, 20
	n311	1, 2, 3, 4, 5, 6, 8, 10
	t311-v1530	1000, 3000, 5000, 10 000, 15 000, 20 000, 30 000 ms
rlmInSyncOutOfSyncThreshold	1	
spCellConfigDedicated	ServingCellConfig	

Table 317 – *SpCellConfig* parameter structure

★ 3GPP TS 38.133 specifies that Q_{out} corresponds to a quality at which the BLER belonging to a hypothetical PDCCH transmission is worse than $BLER_{out}$, i.e. PDCCH reception is not reliable. The hypothetical PDCCH is assumed to be transferring DCI Format 1_0 with a Control Channel Element (CCE) aggregation level of 8 and the CORESET spanning 2 symbols

★ The Physical layer of the UE generates an '*Out-of-Sync*' indication which is forwarded to the RRC layer when the radio link quality belonging to all of the monitored Reference Signals is worse than Q_{out}

★ Similarly, 3GPP TS 38.133 specifies that Q_{in} corresponds to a quality at which the BLER belonging to a hypothetical PDCCH transmission is better than $BLER_{in}$, i.e. PDCCH reception is reliable. In this case, the hypothetical PDCCH is assumed to be transferring DCI Format 1_0 but with a CCE aggregation level of 4 and the CORESET spanning 2 symbols. Assuming an aggregation level of 4 rather than 8 helps to ensure that downlink reception is reliable

★ The Physical layer of the UE generates an '*In-Sync*' indication which is forwarded to the RRC layer when the radio link quality belonging to at least one of the monitored Reference Signals is better than Q_{in}

★ The RRC layer uses the '*Out-of-Sync*' and '*In-Sync*' indications in combination with N310, T310 and N311 to detect Radio Link Failure. The timer T310 is started if the RRC layer receives N310 consecutive '*Out-of-Sync*' indications. The timer T310 is stopped and reset if the RRC layer subsequently receives N311 consecutive '*In-Sync*' indications. Radio Link Failure is detected if T310 expires. Figure 426 illustrates two examples based upon N310 = 3 and N311 = 2

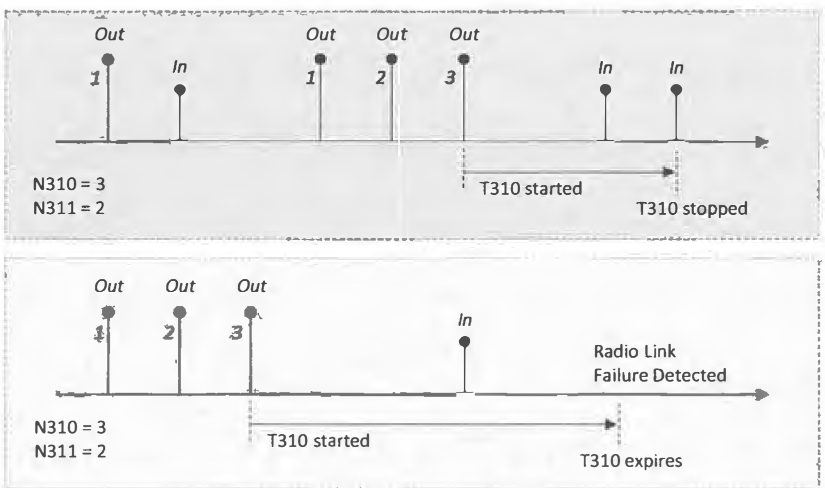


Figure 426 – Radio Link Failure detection at the RRC layer

★ The Base Station can configure the UE with values for N310, T310 and N311 using the *rlf-TimersAndConstants* presented in Table 317. Alternatively, the UE can receive values within the *UE-TimersAndConstants* section of SIB1 (presented in Table 147, section 6.2)

★ The rate at which the UE can generate '*Out-of-Sync*' and '*In-Sync*' indications depends upon the Connected Mode DRX configuration:

$T_{RLF\_PERIOD} = MAX(10\,ms,\ T_{RLF-RS})$ if DRX is disabled

$T_{RLF\_PERIOD} = MAX(10\,ms, 1.5 \times DRX\_Cycle,\ 1.5 \times T_{RLF-RS})$ if DRX is enabled AND DRX_Cycle ≤ 320 ms

$T_{RLF\_PERIOD} = DRX\_Cycle$ if DRX is enabled AND DRX_Cycle > 320 ms

where, T_{RLF-RS} is the minimum period of the Reference Signal resources used for Radio Link Failure detection

- In some scenarios, the '*Out-of-Sync*' and '*In-Sync*' indications for Radio Link Failure detection will be generated at the same rate as the '*Beam Failure Instance*' indications for Beam Failure detection, e.g. when DRX is configured with a cycle duration > 320 ms. In other scenarios, the '*Out-of-Sync*' and '*In-Sync*' indications for Radio Link Failure detection will be generated at a slower rate, e.g. when DRX is disabled and the Reference Signals for Beam Failure detection have a minimum period which is less than 10 ms

- A UE does not necessarily generate an '*Out-of-Sync*' or '*In-Sync*' indication after every evaluation period. For example, the UE will not generate an indication if the monitored Reference Signals have a quality which is between Q_{out} and Q_{in}

- If Radio Link Failure is detected at the primary serving cell (at the Master Cell Group (MCG) when using Dual Connectivity) then the UE actions depend upon the state of the connection:

  - if the Security Mode procedure has not been completed then the UE releases itself to RRC Idle mode using cause 'other'

  - if the Security Mode procedure has been completed but SRB2 and at least one Data Radio Bearer (DRB) have not been setup then the UE releases itself to RRC Idle using cause 'RRC Connection Failure'

  - else, the UE initiates the RRC Connection Re-establishment procedure to recover its connection. In the case of the EN-DC Non-Standalone Base Station architecture, the MCG belongs to an LTE Base Station so the RRC Connection Re-establishment is completed using LTE. RRC Connection Re-establishment involves the UE initiating the Random Access procedures and sending an *RRCConnectionReestablishmentRequest* as MSG3 if using LTE, or an *RRCReestablishmentRequest* as MSG3 if using NR. If re-establishment is completed at a new target Base Station, the UE context is retrieved from the original Base Station with X2 signalling if using LTE, or with Xn signalling if using NR

- If Radio Link Failure is detected at a primary Secondary Cell Group (SCG) cell then the UE initiates the 'SCG Failure Information' procedure to report the Radio Link Failure to the MCG, i.e. Radio Link Failure at the SCG does not cause the UE to release itself to RRC Idle mode, nor does it trigger the RRC Connection Re-establishment procedure. When using the EN-DC Non-Standalone Base Station architecture, the UE sends an RRC: *SCGFailureInformationNR* message to the LTE Base Station. This message belongs to the LTE RRC signalling protocol so is specified by 3GPP TS 36.331 rather than TS 38.331

- Figure 427 illustrates an example of the signalling which can follow the transmission of the RRC: *SCGFailureInformationNR* message. The Master Node uses the X2 Application Protocol to forward an *SGNB Modification Request* to the Secondary Node. This message includes a 'MeNB to SgNB Container' which encapsulates the *CG-ConfigInfo* parameter structure. This parameter structure provides the Secondary Node with information from the RRC: *SCGFailureInformation* message, i.e. it includes the 'Failure Type' and a set of SCG Measurements reported by the UE (the *MeasResultSCG-Failure* is extracted directly from the *SCGFailureInformation* message)

- The Secondary Node forwards downlink data received from the Serving Gateway (S-GW) across the X2 interface towards the Master Node. The Master Node is then able to transfer the downlink data towards the UE

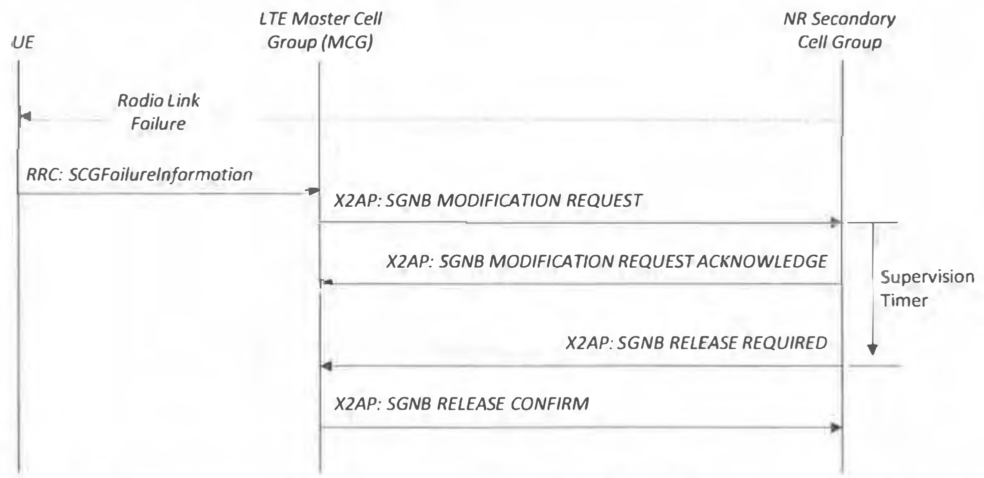


Figure 427 – *SCGFailureInformation* forwarded within X2AP: *SGNB Modification Request* (EN-DC Base Station architecture)

- The Secondary Node may be able to use the SCG measurements to identify a new Secondary Cell for the EN-DC connection. In this case, resources are requested and the UE is subsequently instructed to add the new Secondary Cell. Figure 427 illustrates a scenario where the UE measurements do not identify a new target cell. In this case, the Secondary Node uses the X2AP: *SGNB Release Required* message to inform the Master Node that it plans to release its resources for the UE

- In addition to receiving '*out-of-sync*' indications from the Physical layer, a UE can also trigger Radio Link Failure if the maximum number of RLC re-transmissions is reached, or if a Random Access procedure fails due to reaching the maximum number of preamble transmissions

- 3GPP References: TS 38.331, TS 38.133, TS 36.423, TS 36.133, TS 38.213

13.10 DISCONTINUOUS RECEPTION

★ Discontinuous Reception (DRX) is used in RRC Idle mode when monitoring for paging messages. It avoids the UE having to monitor all PDCCH transmission opportunities and helps to conserve UE battery power. The Paging Frames and Paging Occasions defined for RRC Idle mode DRX are described in section 12.4

★ DRX can also be used in RRC Connected mode to help conserve UE battery power. Connected Mode DRX takes advantage of periods of inactivity by allowing the UE to enter a 'sleep' state during which the UE is not required to monitor the PDCCH. The UE periodically wakes to monitor the PDCCH in case there is a requirement to receive a downlink resource allocation. The UE is permitted to interrupt its 'sleep' state to send a Scheduling Request and thus initiate uplink data transfer

★ Long DRX cycles increase UE battery power savings but they also increase latency. The Base Station is unable to forward downlink data to the UE, while the UE is in its 'sleep' state (DRX Inactive). The Base Station is required to wait for the UE to become 'DRX Active' before allocating resources and forwarding downlink data. The average waiting time increases for long DRX cycle durations

★ In general, the transfer of uplink data is not delayed by the DRX cycle because the UE is permitted to interrupt its 'sleep' state to send a Scheduling Request. However, the Base Station may align the timing of the Scheduling Request period with the timing of the DRX cycle, i.e. restricting the UE to sending Scheduling Requests only when the UE is DRX Active (or just prior to becoming DRX Active). In this case, the UE and Base Station will have similar average waiting periods when there is a requirement to transfer data

★ Connected Mode DRX can also have an impact upon the performance of Timing Advance. Timing Advance relies upon uplink transmissions from the UE which allow the Base Station to measure the existing uplink transmission timing and to make adjustments when necessary. For example, the Base Station may use periodic Channel State Information (CSI) reports on the PUCCH to measure the uplink transmission timing. The UE does not interrupt 'DRX Inactive' periods to transmit periodic CSI reports on the PUCCH so the number of uplink transmissions received by the Base Station is likely to decrease when using Connected Mode DRX. Ultimately, the Base Station may not receive sufficient uplink transmissions to maintain uplink synchronisation. The '*timeAlignmentTimer*' will expire if the Base Station is unable to generate Timing Advance Commands. The UE will then move into the 'out-of-synchronisation' state and the UE will be required to complete the Random Access procedure before transferring further data

★ The general concept of Connected Mode DRX is illustrated in Figure 428

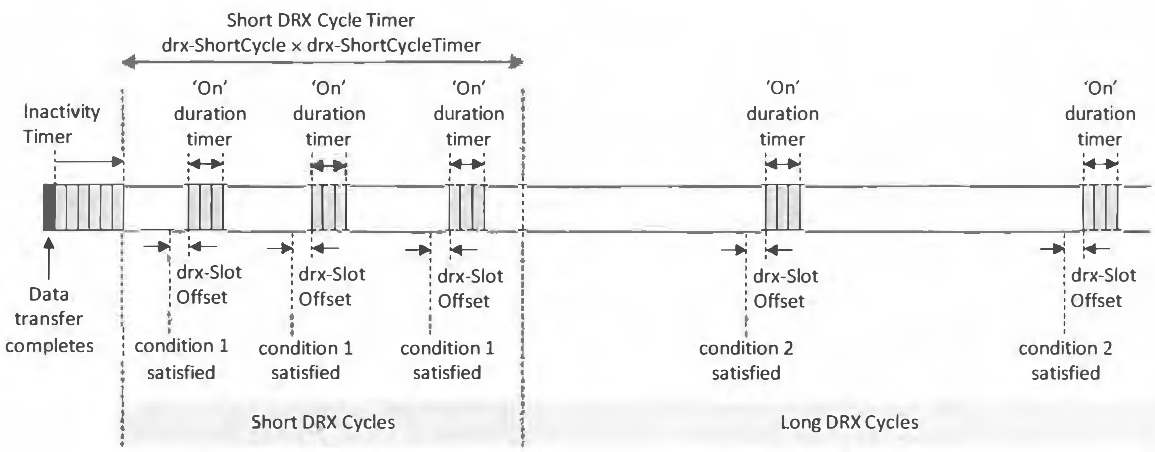


Figure 428 – DRX pattern (both short and long DRX cycles configured)

★ The *DRX-Config* presented in Table 318 provides the UE with the parameters required for the operation of Connected Mode DRX. The inactivity timer defined by *drx-InactivityTimer* is started/re-started after each PDCCH reception. Assuming that the inactivity timer expires, there is an optional period of short DRX cycles. Short DRX cycles can be used initially because the probability of further activity tends to be greater during the time window immediately after any previous activity. The probability of further activity tends to decrease as the period of inactivity increases. The Base Station instructs the UE to use a period of short DRX cycles by including the *shortDRX* parameter set within the *DRX-Config*. The UE uses only long DRX cycles if this parameter set is excluded

★ The period of short DRX cycles is defined by *drx-ShortCycle* × *drx-ShortCycleTimer*, i.e. it is an integer multiple of the short DRX cycle duration. During the period of short DRX cycles, the UE triggers 'DRX Active' periods using the following condition:

Condition 1:	[(SFN × 10) + subframe number] modulo (*drx-ShortCycle*) = (*drx-StartOffset*) modulo (*drx-ShortCycle*)

★ This triggering condition is satisfied at the start of a specific subframe, while the actual 'DRX Active' period can start a short time later. The *drx-SlotOffset* defines the start of the 'DRX Active' period relative to the start of the subframe which satisfies the triggering condition. *drx-SlotOffset* has units of 1/32 ms so the corresponding number of slots depends upon the subcarrier spacing. For example, if using the 15 kHz subcarrier spacing, a value of 31 means that the UE becomes 'DRX Active' after 1 slot. If using the 30 kHz subcarrier spacing, a value of 15 means that the UE becomes 'DRX Active' after 1 slot

★ The UE remains 'DRX Active' for a period defined by *drx-onDurationTimer*. This timer can be configured using units of 1/32 ms or using units of ms. The former is applicable when the *DRX-Config* includes the *subMilliSeconds* option. The DRX Inactivity Timer is re-started if data transfer is initiated during the period of 'DRX Active'. This re-starts the overall DRX cycle pattern when the DRX Inactivity Timer expires

★ The period of long DRX cycles starts after the Short DRX Cycle Timer expires. During the period of long DRX cycles, the UE triggers 'DRX Active' periods using the following condition:

Condition 2:	[(SFN × 10) + subframe number] modulo (*drx-LongCycle*) = *drx-StartOffset*

★ Similar to the condition for short DRX cycles, this triggering condition is satisfied at the start of a specific subframe, while the actual 'DRX Active' period can start a short time later, i.e. based upon the *drx-SlotOffset*

DRX-Config								
drx-onDurationTimer	CHOICE							
	subMilliSeconds	milliSeconds						
	1 to 31	1, 2, 3, 4, 5, 6, 8, 10, 20, 30, 40, 50, 60, 80, 100, 200, 300, 400, 500, 600, 800, 1000, 1200, 1600 ms						
drx-InactivityTime	0, 1, 2, 3, 4, 5, 6, 8, 10, 20, 30, 40, 50, 60, 80, 100, 200, 300, 500, 750, 1280, 1920, 2560 ms							
drx-HARQ-RTT-TimerDL	0 to 56							
drx-HARQ-RTT-TimerUL	0 to 56							
drx-RetransmissionTimerDL	0, 1, 2, 4, 6, 8, 16, 24, 33, 40, 64, 80, 96, 112, 128, 160, 320 slots							
drx-RetransmissionTimerUL	0, 1, 2, 4, 6, 8, 16, 24, 33, 40, 64, 80, 96, 112, 128, 160, 320 slots							
drx-LongCycleStartOffset	CHOICE							
	10 ms	0 to 9	20 ms	0 to 19	32 ms	0 to 31	40 ms	0 to 39
	60 ms	0 to 59	64 ms	0 to 63	70 ms	0 to 69	80 ms	0 to 79
	128 ms	0 to 127	160 ms	0 to 159	256 ms	0 to 255	320 ms	0 to 319
	512 ms	0 to 511	640 ms	0 to 639	1024 ms	0 to 1023	1280 ms	0 to 1279
	2048 ms	0 to 2047	2560 ms	0 to 2559	5120 ms	0 to 5119	12040 ms	0 to 10239
short DRX	drx-ShortCycle	2, 3, 4, 5, 6, 7, 8, 10, 14, 16, 20, 30, 32, 35, 40, 64, 80, 128, 160, 256, 320, 512, 640 ms						
	drx-ShortCycleTimer	1 to 16						
drx-SlotOffset	0 to 31							

Table 318 – Content of DRX configuration information

★ If a UE becomes 'DRX Inactive' after transmitting uplink data on the PUSCH, the UE is required to temporarily return to 'DRX Active' in order to check for a re-transmission request from the Base Station. The Base Station may request a re-transmission by sending a New Data Indicator (NDI) flag with its value unchanged relative to the original transmission. The NDI flag is included within DCI Format 0_0 or 0_1 on the PDCCH

★ *drx-HARQ-RTT-TimerUL* specifies the timing of the return to 'DRX Active' relative to the end of the first repetition of the PUSCH transmission (if PUSCH repetition is not configured then this corresponds to the end of the PUSCH transmission). The UE remains 'DRX Active' for a period defined by *drx-RetransmissionTimerUL*. The UE returns to 'DRX Inactive' if a re-transmission request is not received during this time window. Figure 429 illustrates the combination of *drx-HARQ-RTT-TimerUL* and *drx-RetransmissionTimerUL*

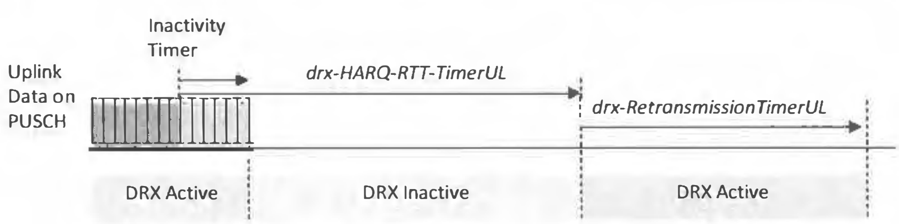


Figure 429 – Period of DRX Active for uplink re-transmissions on the PUSCH

★ Similarly, if a UE becomes 'DRX Inactive' after receiving downlink data on the PDSCH and the UE has sent a negative acknowledgement for that data on the PUCCH, the UE is required to return to 'DRX Active' in order to receive the re-transmission from the Base Station. In this case, *drx-HARQ-RTT-TimerDL* is started after the UE has transmitted the negative acknowledgement on the PUCCH. The UE then remains 'DRX Active' for a period defined by *drx-RetransmissionTimerDL* while waiting to receive the re-transmission. Figure 430 illustrates the combination of *drx-HARQ-RTT-TimerDL* and *drx-RetransmissionTimerDL*

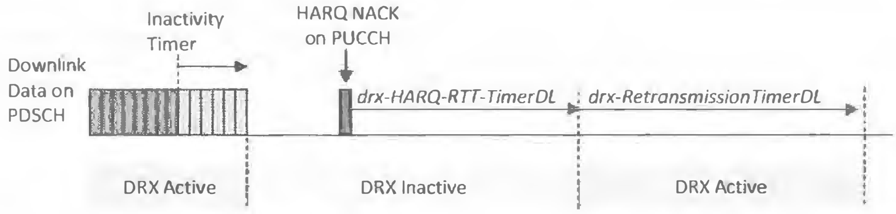


Figure 430 – Period of DRX Active for downlink re-transmissions on the PDSCH

★ 3GPP TS 38.321 specifies MAC Control Elements (MAC CE) which can be used to send the UE to the 'DRX Inactive' state immediately without having to wait for the DRX Inactivity Timer to expire:

  o DRX Command MAC CE: instructs the UE to enter the 'DRX Inactive' state and to start the short DRX cycles if they have been configured. If short DRX cycles have not been configured, the UE starts the long DRX cycles

  o Long DRX Command MAC CE: instructs the UE to enter the 'DRX Inactive' state and to start the long DRX cycles

★ These MAC CE do not include any payload information. They simply use the Logical Channel Identity (LCID) within the MAC sub-header to identify the MAC CE. An LCID of 60 identifies a DRX Command, whereas an LCID of 59 identifies a Long DRX Command

★ DRX patterns should account for the end-user application. Delay tolerant applications can be configured with longer DRX cycle durations. Delay sensitive applications should be configured with shorter DRX cycle durations

★ Voice over NR (VoNR) connections can be configured with a 20 ms DRX cycle duration to align with the rate at which the codec generates speech packets. Alternatively, VoNR connections can be configured with a 40 ms DRX cycle duration (and a 40 ms Scheduling Request period) to force the use of Packet Aggregation. This means that speech packets are sent in pairs rather than individually. Packet Aggregation can increase air-interface capacity because the PDCCH load is decreased when using dynamic grants. The PDSCH and PUSCH may also become more efficient when transferring pairs of small packets rather than individual small packets. The drawback associated with Packet Aggregation is the increased delay caused by buffering the speech packets

★ 3GPP References: TS 38.321, TS 38.331

14 VOICE SERVICES

★ Legacy 2G and 3G networks support voice services using Circuit Switched (CS) connections which benefit from dedicated resources throughout the lifetime of each call. 4G networks do not support the CS domain so are unable to provide CS services. However, CS Fallback procedures can be used to move connections from a 4G network to a 2G or 3G network whenever there is a requirement to establish a CS connection. CS Fallback procedures rely upon the SGs interface between the MME and MSC when moving a connection towards GERAN or UTRAN. CS Fallback procedures can be based upon a blind release with redirection, a measurement based release with redirection or an inter-system handover

★ 4G networks can be configured to support voice services using Packet Switched (PS) connections which rely upon the Evolved Packet Core (EPC) to provide connectivity to an IP Multimedia Subsystem (IMS). The IMS provides the control plane functions which manage the setup, maintenance and release of PS voice services. These control plane functions use Session Initiation Protocol (SIP) signalling to communicate with the UE. PS voice services over LTE are known as Voice over LTE (VoLTE). PS voice services provide increased capacity and efficiency but require stringent packet prioritisation to ensure that Quality of Service (QoS) requirements are satisfied. VoLTE relies upon Single Radio Voice Call Continuity (SRVCC) to provide inter-system mobility at locations where VoLTE coverage is not contiguous. The SRVCC procedure toward either GERAN or UTRAN changes the core network domain from PS to CS

★ 4G networks can also support PS voice services using Over The Top (OTT) applications such as 'Skype' and 'WhatsApp'. These applications typically rely upon general data connections to support Voice over IP (VoIP) services. This means that speech packets will be handled with lower priority and the user experience may be compromised during periods of congestion. OTT applications typically use the same non-Guaranteed Bit Rate (non-GBR) EPS Bearer as used for normal data transfer. In contrast, VoLTE connections benefit from GBR EPS Bearers which are handled with high priority

★ In the case of 5G, the availability of specific solutions for the voice service depends upon the Base Station architecture. The solutions associated with each architecture are summarised in Figure 431. All architectures support OTT applications because these only require a data connection which can be either an EPS Bearer towards the 4G core network, or a PDU Session towards the 5G core network

★ Base Station architecture 3/3a/3x is based upon a 4G Master Node connected to the 4G core network. This allows the use of all legacy 4G voice service solutions, i.e. both CS Fallback and VoLTE can be used. This is attractive when evolving towards a standalone 5G solution because it allows the data capability to be upgraded with minimal impact upon existing voice services. The call setup delay associated with the CS Fallback procedure may increase marginally when using option 3/3a/3x because the procedure will include additional X2AP signalling to release the 5G Secondary Node (assuming it has already been added at the time of the CS Fallback)

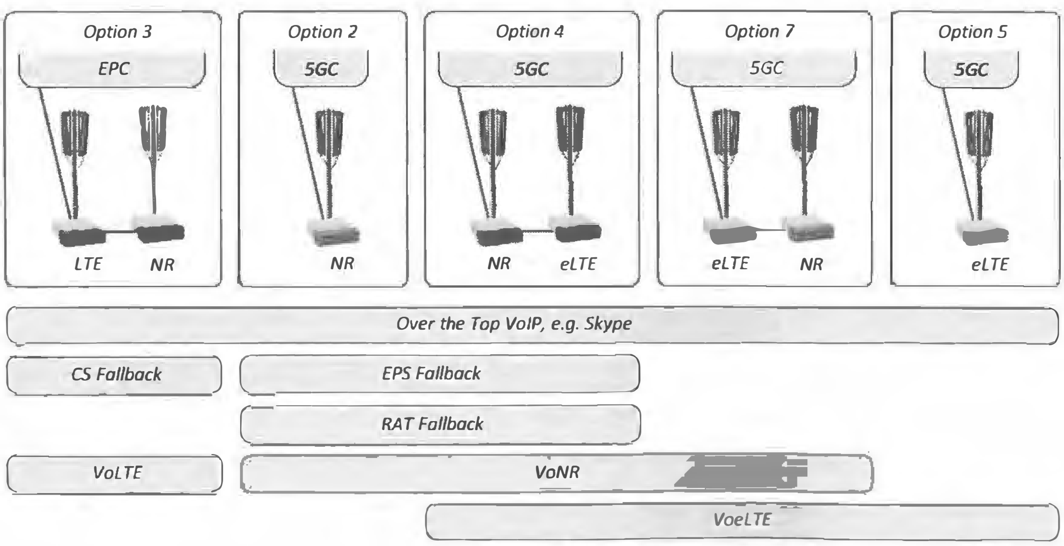


Figure 431 – Solutions for the 5G Voice Service

★ Base Station architectures 2 and 4/4a are based upon a 5G Master Node connected to the 5G core network. These require the use of new 5G voice service solutions, i.e. Voice over New Radio (VoNR), EPS Fallback and RAT Fallback. CS Fallback is not supported when using the 5G core network. EPS Fallback and RAT Fallback provide alternatives which redirect the UE towards an LTE Base Station connected to the 4G core network and 5G core network respectively

★ Base Station architectures 5 and 7/7a/7x are based upon a 4G Master Node connected to the 5G core network. These architectures support Voice over enhanced LTE (VoeLTE) which relies upon the 4G air-interface to transfer speech packets belonging to a GBR QoS Flow. Base Station architecture 4/4a can also support VoeLTE when the speech packets are transferred using the 4G Secondary Node. Similarly, architecture 7/7a/7x can support VoNR when the speech packets are transferred using the 5G Secondary Node

★ The release 15 version of the 3GPP specifications does not support SRVCC for 5G. Speech service continuity at locations with non-contiguous 5G coverage relies upon Packet Switched inter-system handover towards 4G. SRVCC can then be completed from 4G if necessary. SRVCC from 5G to 3G (UTRAN) is planned for the release 16 version of the 3GPP specifications

14.1 VOICE OVER NEW RADIO

★ Both VoNR and VoLTE rely upon connectivity to an IP Multimedia Subsystem (IMS) to manage the setup, maintenance and release of voice call connections. Session Initiation Protocol (SIP) is used for signalling procedures between the UE and IMS. VoNR uses a QoS Flow with 5QI = 5 to transfer SIP signalling messages. In contrast, VoLTE uses an EPS Bearer with QCI = 5. The general network architecture for SIP signalling with IMS is illustrated in Figure 432

★ The PDU Session provides connectivity between the UE and the User Plane Function (UPF). The N6 interface provides connectivity between the UPF and the IMS

- the 'Proxy' Call Session Control Function (P-CSCF) acts a first point of contact for the IMS, i.e. all SIP signalling is forwarded through the P-CSCF. If a UE is roaming then the P-CSCF will belong to the visited network. Otherwise, the P-CSCF will belong to the home network. When a UE completes the registration procedure with the IMS, the P-CSCF is responsible for routing the SIP: *REGISTER* message towards the 'Interrogating-CSCF' (I-CSCF) within the home network. Once a UE has completed registration and a Serving-CSCF (S-CSCF) has been identified, the P-CSCF can forward messages directly to the S-CSCF. The P-CSCF communicates with the Policy Control Function (PCF) during the setup of a VoNR call. This communication triggers the PCF to initiate the setup of the QoS Flow with 5QI = 1 for the subsequent transfer of speech packets
- the 'Interrogating-CSCF' (I-CSCF) communicates with the User Data Management (UDM) function during the IMS registration procedure. The UDM determines whether or not the UE is already registered and provides the identity of the S-CSCF if one has already been allocated. Otherwise, the I-CSCF is responsible for selecting an S-CSCF. For incoming VoNR calls, the I-CSCF is used as an entry point into the IMS belonging to the UE which is being called. For example, the S-CSCF belonging to the UE which originates the call, forwards the SIP: *INVITE* to the I-CSCF belonging to the UE which is responsible for answering the call. The I-CSCF can then interrogate its UDM to identify the appropriate S-CSCF to which the *SIP: INVITE* should be forwarded
- the 'Serving-CSCF' (S-CSCF) is responsible for processing and responding to SIP signalling messages from the UE. The S-CSCF communicates with the UDM during the IMS registration procedure. During the first stage of registration, the S-CSCF obtains an authentication vector from the UDM. During the second stage of registration, the S-CSCF informs the UDM that the UE has registered and provides its S-CSCF identity. This allows the UDM to be interrogated in the future, when there is a requirement to identify the allocated S-CSCF. During a VoNR call setup procedure, the S-CSCF interacts with a Telephony Application Server (TAS) which is responsible for providing the end-user application in combination with supplementary services, e.g. call waiting, call forwarding and call conferencing

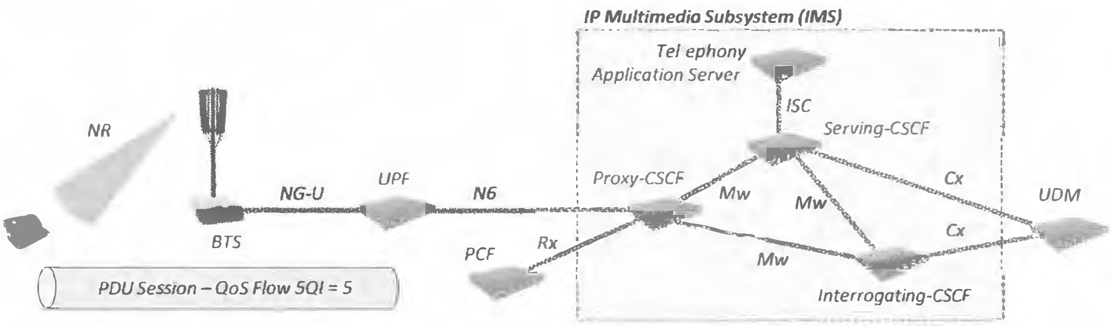


Figure 432 – Network architecture for SIP signalling with IMS

★ QoS Flows with 5QI = 5 are non-GBR but they are treated with high priority to ensure that SIP signalling procedures are completed with minimal latency and high reliability. The characteristics belonging to a QoS Flow with 5QI = 5 are presented in Table 319. This table also includes the characteristics belonging to the GBR QoS Flow with 5QI = 1. This QoS Flow is used to transfer the speech packets after connection establishment

★ The SMF has an opportunity to reconfigure the Priority and Averaging Window during the QoS Flow setup procedure. A lower numerical value corresponds to a higher priority so the default values provide the QoS Flow for SIP signalling with a higher priority than the QoS Flow for speech packet transfer. The Averaging Window ensures that the Guaranteed Flow Bit Rate (GFBR) is maintained at a relatively consistent level as a function of time (rather than achieving the GFBR by allocating a very high throughput for a short duration, and then allocating a very low throughput for a long duration)

★ The Packet Delay Budget represents the maximum permitted delay between the UE and UPF. If both the originating and terminating voice call users have VoNR connections, then the total end-to-end Packet Delay Budget will include 2 × 100 ms. The ITU-T recommends a maximum packet delay of 200 ms to ensure that users are very satisfied with their call quality (ITU-T Rec G.114)

5QI	Resource Type	Default Priority	Packet Delay Budget	Packet Error Loss Rate	Default Averaging Window	Services
1	GBR	20	100 ms	10^{-2}	2000 ms	Conversational Voice
5	Non-GBR	10	100 ms	10^{-6}	Not Applicable	IMS Signalling

Table 319 – 5G QoS Identifiers (5QI) applicable to VoNR

★ The general network architecture for transferring the user plane speech packets is illustrated in Figure 433. This figure illustrates paths towards another IP Multimedia network and towards a Circuit Switched (CS) network. The PDU Session provides connectivity between the UE and the UPF, whereas the N6 interface provides connectivity between the UPF and the IMS:

- o the Breakout Gateway Control Function (BGCF) is responsible for selecting an MGCF for connections which terminate at a PSTN, and for selecting an IBCF for connections which terminate at another IP multimedia network. The BGCF has been excluded from Figure 432 to keep the diagram relatively simple, but the BGCF is also involved in SIP signalling procedures. It can be used to identify the next hop when routing SIP messages. If the next hop is within another IMS then the BGCF can forward the SIP messages to a peer BGCF within the other IMS
- o the Interconnection Border Control Function (IBCF) is responsible for controlling the transport plane functions provided by the Transition Gateway (TrGW). The TrGW is responsible for providing the path for speech packets when the destination is another IP multimedia network. The TrGW is responsible for transcoding if the end-users are generating their speech packets with different codecs. The TrGW can also provide functions such as echo cancellation and the detection of inactivity
- o the Media Gateway Control Function (MGCF) provides control plane inter-working towards circuit switched networks. It is responsible for the translation between the SIP messages used by the IMS and the corresponding messages used by the CS domain network, e.g. BICC messages. Within the context of the user plane, the MGCF is responsible for managing the IP Multimedia Media Gateway (IM MGW). The IM MGW and TrGW have similar responsibilities but the IM MGW provides connectivity towards a CS domain network rather than an IP Multimedia network

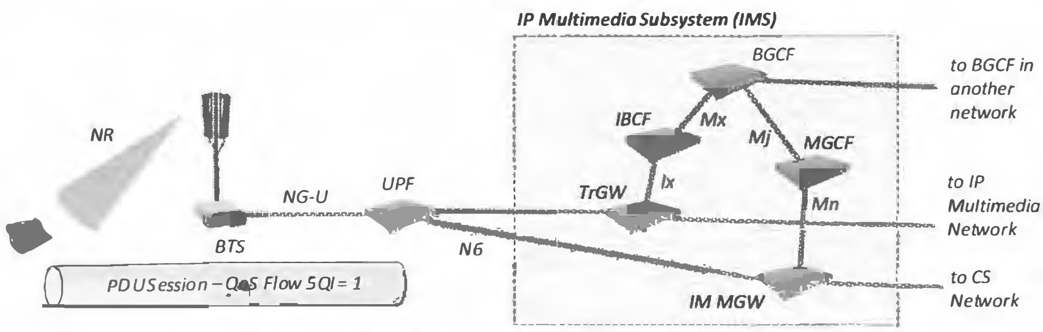


Figure 433 – Network architecture for the transfer of speech packets

★ Figure 434 illustrates the Radio Access Network protocol stacks for both SIP signalling and the end user speech packets. SIP signalling messages can be transferred using either TCP for reliability or UDP for lower latency. The upper IP layer is used for routing the packets to the P-CSCF. The SDAP layer provides the mapping between the QoS Flow associated with the higher layer packets and Data Radio Bearer (DRB) used to transfer the packets across the Radio Access Network. The PDCP layer provides ciphering and integrity protection. It also adds a sequence number for re-ordering and duplicate packet detection. The RLC layer operates using Acknowledged Mode (AM) to allow ARQ re-transmissions. The MAC layer provides support for HARQ re-transmissions to help avoid the requirement for the slower RLC re-transmissions. Layer 1 supports the New Radio (NR) air-interface

★ The Base Station adds header information belonging to the PDU Session User Plane protocol before forwarding uplink packets across the NG-U interface. This header information identifies the QoS Flow to which the packet belongs. A GTP-U tunnel is then used to transfer the higher layer IP packets towards the UPF. The GTP-U tunnel operates over UDP and IP layers. This means that packets transferred across the NG-U interface have two IP headers – an upper layer IP header which addresses the P-CSCF, and a lower layer IP header which address the UPF (assuming uplink packet transfer)

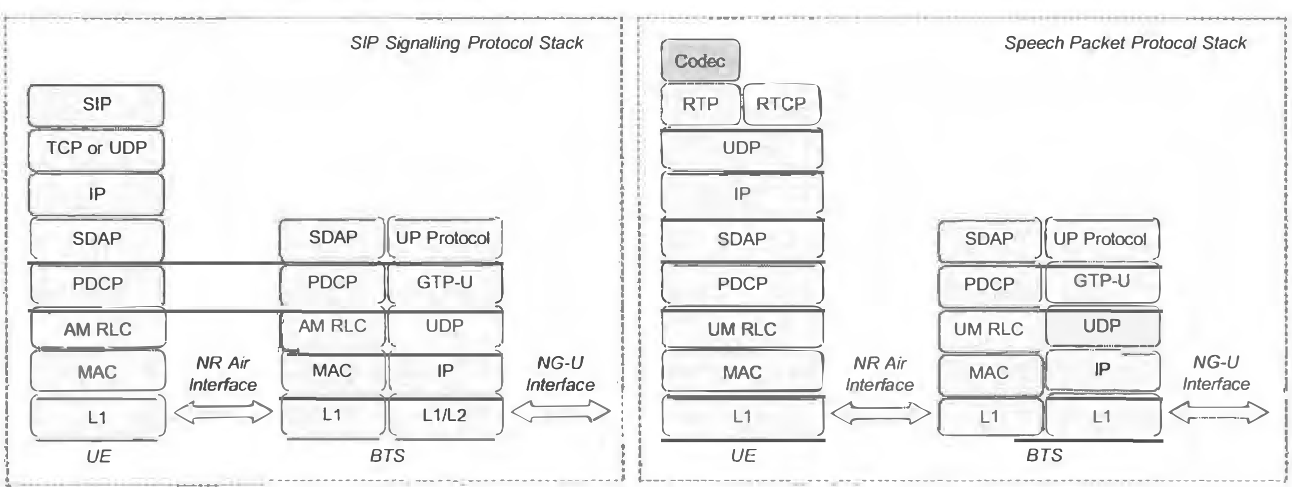


Figure 434 – Radio Access Network protocol stacks for Voice over New Radio (VoNR)

★ The codec is responsible for generating speech packets by sampling the audio and subsequently encoding to generate packets of a specific size. The encoded packet size determines the bit rate of the codec. Speech packets are generated once every 20 ms during periods of speech activity so the bit rate is given by: packet size / 0.02. The bit rate can vary as a function of time as the codec adapts to the channel conditions, i.e. the codec can generate low bit rates for poor channel conditions and high bit rates for good channel conditions

★ The 'Enhanced Voice Services' (EVS) codec is the current recommendation for 5G. This codec was introduced within the release 12 version of the 3GPP specifications and is already used by 4G networks

★ The EVS codec supports a range of sampling frequencies to capture a range of audio bandwidths. These sampling frequencies are categorised as Narrowband, Wideband, Super Wideband and Fullband. Table 320 presents the set of codec bit rates which can be generated by each sampling frequency

★ Human hearing is normally assumed to span the bandwidth between 20 Hz and 20 kHz. The Nyquist sampling theorem states that at least 2 samples per cycle are required to regenerate the original waveform. Thus, a sampling frequency greater than 40 kHz is required for high quality audio. As a reference, CD audio is generated using a sampling frequency of 44.1 kHz. The sampling frequency of 8 kHz for the Narrowband category captures up to 4 kHz of audio bandwidth

Category	Sampling Frequency	Bit Rate generated by Codec (kbps)											
		5.9	7.2	8.0	9.6	13.2	16.4	24.4	32	48	64	96	128
Narrowband	8 kHz	✓	✓	✓	✓	✓	✓	✓	-	-	-	-	-
Wideband	16 kHz	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
Super Wideband	32 kHz	-	-	-	✓	✓	✓	✓	✓	✓	✓	✓	✓
Fullband	48 kHz	-	-	-	-	-	✓	✓	✓	✓	✓	✓	✓

Table 320 – Bit rates generated by the EVS codec

★ Each sample of the audio waveform generates a 16 bit Pulse Code Modulation (PCM) word. As an example, the 16 kHz Wideband sampling frequency generates a bit rate of 16 × 16 000 = 256 kbps. The encoding process reduces this throughput to a level between 5.9 and 128 kbps. The codec can change the bit rate every 20 ms to adapt to the current channel conditions

★ The EVS codec is capable of transferring either mono or stereo content. Stereo content is generated by encoding two mono channels. This means that the throughputs presented in Table 320 are doubled when transferring stereo content

★ The EVS codec can be used in an AMR-WB 'Inter-Operable' (IO) mode. This mode provides compatibility with the legacy AMR-WB codec, which means that speech packets generated by the EVS codec can be decoded by the AMR-WB codec, and vice versa. This avoids the requirement for transcoding when using a combination of EVS and AMR-WB codecs

★ The EVS codec can add header information to the speech packets before passing them to the Real-time Transport Protocol (RTP) layer. This means that the throughputs generated by the codec can be higher than the figures presented in Table 320. The inclusion of header information can change between individual speech packets. The requirement for header information depends upon the use of specific codec functionality. For example, requesting changes to the received speech codec bit rate requires header information. Similarly, the transmission of stereo content also requires header information. 3GPP TS 26.445 specifies two categories of header information:

- o Compact Format:
  - ▪ EVS Primary mode: speech packets are transferred without header information. The receiver deduces the codec bit rate from the size of the received packet. This category can be used for the transmission of single mono speech packets when there is not a requirement to include Codec Mode Request (CMR) information
  - ▪ EVS AMR-WB IO mode: speech packets are transferred with the addition of a 3 bit Codec Mode Request (CMR) field. The CMR field can be used to request a specific codec bit rate from the peer codec at the remote device. The set of 3 bits are used to specify one of seven AMR-WB bit rates ranging from 6.6 kbps to 23.85 kbps
- o Header-Full Format: allows the inclusion of 'Table of Content' (ToC) and 'Codec Mode Request' (CMR) headers (illustrated in Figure 435). Each of these headers occupies 1 byte. The codec may also include zero-padding bytes to ensure that the resultant packet size does not equal one of the 'protected' sizes used by the Compact Format. If a codec receives a speech packet size equal to one of the 'protected' sizes then the codec deduces that it has received a Compact Format speech packet and the bit rate is then deduced from the size of the packet. Thus, it is necessary to avoid generating packets with a 'protected' size when using the Header-Full Format otherwise the receiving codec would assume that it is a Compact Format packet

Table of Content (ToC) Header Byte

H	F	Frame Type (FT)

Codec Mode Request (CMR) Header Byte

H	Type of Request (T)	Requested Bit Rate (D)

Figure 435 – Header-Full Format information which can be added by EVS codec

★ The ToC header byte is used to identify the type of speech packet included within the payload. It includes a Header Type identification bit (H) which is always set to '0'. The 'F' field indicates whether or not another ToC header byte follows the current header byte. Multiple ToC header bytes are included when transferring multiple speech packets, e.g. when transferring stereo content. The first bit of the Frame Type (FT) field indicates the codec operating mode (EVS Primary Mode or EVS AMR-WB IO mode). The last four bits of the FT field indicate the codec bit rate, i.e. the speech packet payload size. These last four bits can also indicate the transfer of a Silence Insertion Descriptor (SID) packet

★ The EVS codec generates SID packets during periods of speech inactivity. These packets are used to generate 'comfort noise' at the receiving codec to avoid the remote user hearing complete silence and thinking that the connection may have dropped. SID packets generated by the EVS codec have a size of 48 bits which corresponds to a codec bit rate of 2.4 kbps. SID packets are typically transferred once every 160 ms rather than once every 20 ms. However, SID packets can be transferred more frequently and can be configured to use an adaptive mode which changes the transmission rate according to the Signal to Noise Ratio (SNR) (within this context SNR refers to audio Signal to Noise Ratio rather than RF power Signal to Noise Ratio)

★ The CMR header byte illustrated in Figure 435 is used to request a specific operating mode and bit rate from the peer codec at the remote device. It includes a Header Type identification bit (H) which is always set to '1'. The Type of Request (T) field is used to specify the requested operating mode in terms of Narrowband, Wideband, Super Wideband, Fullband and AMR-WB IO. The Requested Bit Rate (D) field is used to specify the requested bit rate belonging to the requested operating mode

★ The Real-time Transport Protocol (RTP) is specified by the IETF within RFC 3550. It has been designed to transfer real time audio and video content across IP networks. The RTP layer provides services which include payload type identification, sequence numbering and time stamping. The RTP layer does not provide support for retransmissions

★ The RTP header has a minimum size of 12 bytes. These 12 bytes are illustrated in Figure 436

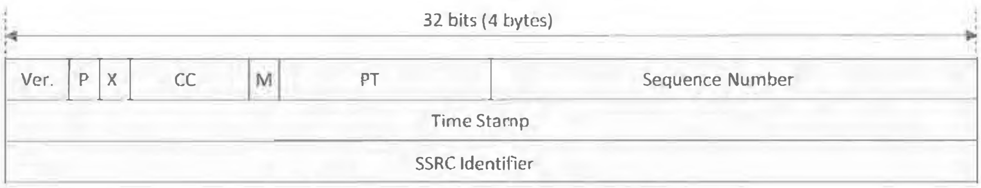


Figure 436 – Content of RTP header (12 bytes)

★ The RTP header fields include:

- Version: signals the version of the RTP protocol (2 bits)
- Padding (P): indicates whether or not there is any additional padding at the end of the RTP packet (1 bit)
- Extension (X): indicates whether or not an extension header is present between the fixed header and the payload (only fixed header is shown in Figure 436) (1 bit)
- CSRC Count (CC): defines the number of Contributing Source (CSRC) identifiers which follow the fixed header. These are applicable when the data stream originates from multiple sources (4 bits)
- Marker (M): defines a flag which can be used by the application layer. It is intended to allow events such as frame boundaries to be marked in the packet stream (1 bit)
- Payload Type (PT): signals the content of the payload so the receiving application layer can interpret it appropriately. The payload type defines the codec and indicates if the content is audio or video (7 bits)
- Sequence Number: is incremented by 1 for every RTP packet which is sent. The sequence number is used for re-ordering and packet loss detection at the receiver (16 bits)
- Time Stamp: is used by the receiver to playback the received data frames at appropriate time intervals (32 bits). The EVS codec uses a timestamp clock frequency of 16 kHz so each unit corresponds to 1 / 16000 = 0.0625 ms. This means that consecutive speech packets should have time stamps which increase by 20 / 0.0625 = 320
- Synchronisation Source (SSRC) Identifier: is used to identify the source of a data stream (32 bits)

★ The Real-time Transport Control Protocol (RTCP) is specified by the IETF within RFC 3550. It operates in combination with the RTP layer. The RTCP layer within the receiving device collects statistics regarding the quality of the received speech signal. These statistics are sent back to the transmitting device where they can be used to adapt the transmitted signal, e.g. step down to a lower codec rate when the received signal quality is poor

★ The User Datagram Protocol (UDP) layer is specified by the IETF within RFC 768. It provides a simple solution for transferring data without providing services for retransmissions nor sequence numbering. UDP is often used rather than TCP for time sensitive applications because packet loss can be preferable to packet delay. The UDP layer differentiates between RTP and RTCP payloads using the Port Numbers within its header information. Packets belonging to the RTP layer are allocated an even Port Number, whereas packets belonging to the RTCP layer are allocated the next higher odd Port Number. The same Port Numbers should be used for both sending and receiving packets

★ Figure 437 illustrates a UDP header. It has a fixed size of 8 bytes

32 bits (4 bytes)

Source Port	Destination Port
Length	Checksum

Figure 437 – Content of UDP header (8 bytes)

★ The UDP header fields include:

- o Source Port: identifies the port number used for transmission at the sending device (16 bits)
- o Destination Port: identifies the port number used for reception at the receiving device (16 bits)
- o Length: indicates the total number of bytes within both the UDP header and the payload (16 bits)
- o Checksum: can be used by the receiver for error checking across both the UDP header and the payload (16 bits)

★ Internet Protocol version 4 (IPv4) is specified by the IETF within RFC 791, whereas Internet Protocol version 6 (IPv6) is specified by the IETF within RFC 2460. This section focuses upon IPv6. The IP layer provides support for packet delivery from a source IP address to a destination IP address. The RTP/UDP and RTCP/UDP packets are sent in separate IP packets

★ An IPv6 header has a minimum size of 40 bytes (an IPv4 header has a minimum size of 20 bytes). The minimum 40 bytes of an IPv6 header are illustrated in Figure 438

32 bits (4 bytes)

<table>
<tr><td>Version</td><td>Traffic Class</td><td colspan="2">Flow Label</td></tr>
<tr><td colspan="2">Payload Length</td><td>Next Header</td><td>Hop Limit</td></tr>
<tr><td colspan="4">Source IP Address (16 bytes)</td></tr>
<tr><td colspan="4">Destination IP Address (16 bytes)</td></tr>
</table>

Figure 438 – Content of IPv6 header (40 bytes)

★ The IPv6 header fields include:

- o Version: identifies the version of the IP protocol, i.e. version 6 (4 bits)
- o Traffic Class: specifies the priority using a Differentiated Services Code Point (DSCP) value. The DSCP determines the Per Hop Behaviour (PHB) to be applied by each node within the IP network, i.e. the DSCP determines the prioritisation of the packet. The DSCP value occupies 6 bits. The remaining 2 bits can be used for Explicit Congestion Notification (ECN) to indicate network congestion (8 bits)
- o Flow Label: can be used to identify a specific flow of packets between the source and destination IP addresses. This allows routers to apply different packet handling rules to different packet flows (20 bits)
- o Payload Length: specifies the length of the payload which follows the 40 bytes of header information. The Payload Length is specified in units of bytes. Extension headers are included within the Payload Length (16 bits)
- o Next Header: specifies the content of the payload. When transferring speech packets using RTP and UDP, the Next Header field indicates that the payload includes a UDP packet (8 bits)
- o Hop Limit: is used to limit the number of hops when delivering a packet to the destination IP address. Each node which forwards the packet reduces the Hop Limit by '1'. The packet is discarded if the Hop Limit reaches 0 (8 bits)

★ The Service Data Adaptation Protocol (SDAP) is specified by 3GPP within TS 37.324. The SDAP layer is responsible for mapping packets belonging to a specific QoS flow onto an appropriate Data Radio Bearer (DRB), and vice versa at the receiver. The SDAP layer can be configured by the RRC layer to operate either with or without header information. When header information is included, it generates an overhead of 1 byte. Header information is required when using reflective QoS or when it is necessary to explicitly specify the QoS Flow to which a packet belongs. This section assumes that an SDAP header is not necessary for VoNR

★ The Packet Data Convergence Protocol (PDCP) is specified by 3GPP within TS 38.323. The PDCP layer provides header compression for both the RTP and RTCP packets. Header compression is a requirement for VoNR due to the significant overhead added by the RTP, UDP and IP protocol stack layers. Speech packets have overheads added by all three of these layers whereas RTCP packets have overheads added by the UDP and IP layers. Header compression is based upon the Robust Header Compression (RoHC) framework specified within IETF RFC 3095 and RFC 4815

★ The protocol stack layers targeted by header compression are illustrated in Figure 439. Header compression operates between the UE and the Base Station so it benefits the Radio Access Network but does not benefit the connection from the Base Station towards the IMS. Header compression generates a significant increase in air-interface capacity in terms of the maximum number of supported speech connections

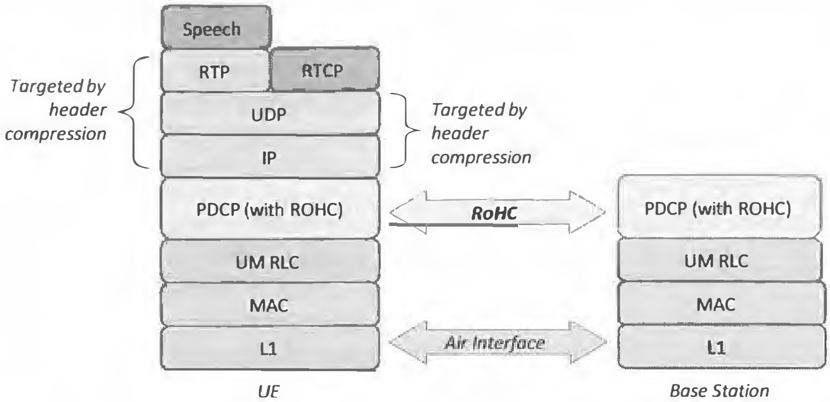


Figure 439 – VoNR protocol stack layers targeted by header compression

★ Figure 440 compares the throughput requirement for Circuit Switched voice over 3G when using a Dedicated Channel (DCH), with the throughput requirement for VoNR, both with and without header compression. The comparison assumes an AMR 12.2 kbps codec for 3G and an EVS 13.2 kbps codec for VoNR. The comparison also assumes: 1 byte of header information added by the EVS codec; IPv6 rather than IPv4; no header added by the SDAP layer (and so excluded from the figure); a 12 bit Sequence Number for the PDCP layer which leads to a header size of 2 bytes; no segmentation at the RLC layer allowing the use of a single byte header without Sequence Number; a MAC header which includes an 8 bit Length field which leads to a header size of 2 bytes

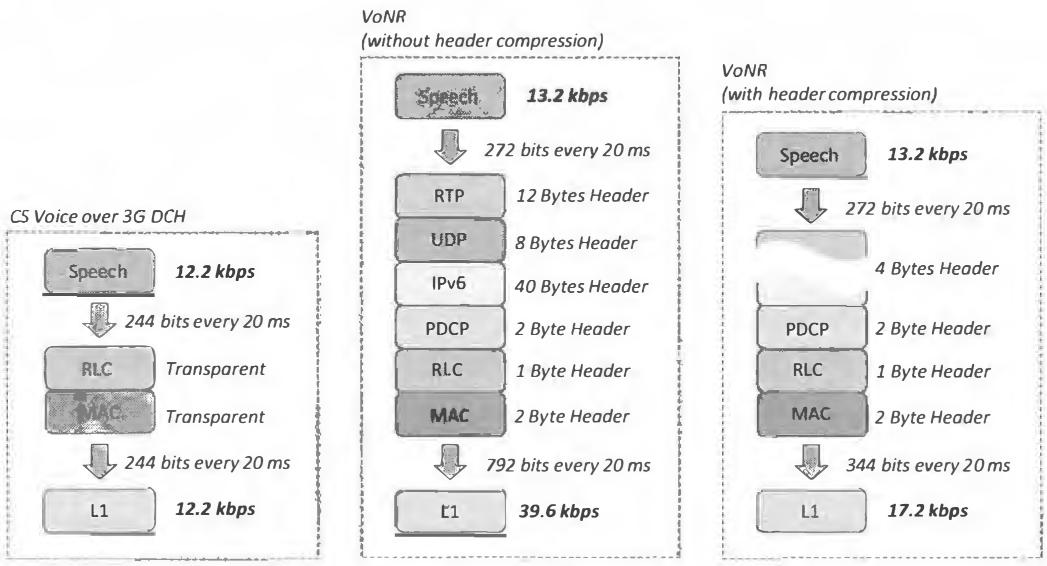


Figure 440 – Comparison of CS Voice over 3G with Voice over NR (VoNR), with and without header compression

★ Circuit Switched voice over a 3G Dedicated Channel uses transparent RLC and MAC layers so the resultant throughput requirement is equal to the bit rate generated by the AMR codec

★ In the case of VoNR without header compression, the RTP/UDP/IP protocol stack layers generate a significant overhead. The resultant throughput requirement at the top of the Physical layer is 39.6 kbps, i.e. 3 × the bit rate generated by the EVS codec. It is assumed that header compression reduces the overheads generated by the RTP/UDP/IP layers to 4 bytes. This results in a throughput requirement of 17.2 kbps at the top of the Physical layer

★ The IETF defines multiple RoHC profiles to support different protocol stack combinations. Table 321 presents the set of profiles specified for use by NR within 3GPP TS 38.323. Profiles 1 and 101 are applicable to the speech protocol stack, whereas profiles 2 and 102 are applicable to the RTCP protocol stack. Profiles 101 and 102 are updated versions of profiles 1 and 2

★ It is not mandatory for UE to support all of these profiles. UE report their PDCP capability within the RRC: *UE Capability Information* message. UE specify which RoHC profiles are supported and also the maximum number of concurrently active RoHC contexts

Profile Identity	Application	Reference
0000	No compression	RFC 4995
0001	RTP/UDP/IP	RFC 3095, RFC 4815
0002	UDP/IP	RFC 3095, RFC 4815
0003	ESP/IP	RFC 3095, RFC 4815
0004	IP	RFC 3843, RFC 4815

Profile Identity	Application	Reference
0006	TSCP/IP	RFC 4996
0101	RTP/UDP/IP	RFC 5225
0102	UDP/IP	RFC 5225
0103	ESP/IP	RFC 5225
0104	IP	RFC 5225

Table 321 – Header compression profiles supported by the PDCP layer

★ The main principles of header compression are:

  - o avoid sending fields which do not change between consecutive packets
  - o allow the receiver to deduce some changing fields without sending them
  - o apply efficient coding to other changing fields

★ For example, within an IPv6 header, the Source Address (16 bytes) and Destination Address (16 bytes) do not change for a specific connection. In addition, this information is not used to transfer the packets between the Base Station and UE. Thus, the sending device can remove both of these fields while the receiving device can re-insert them. This is possible after the receiving device has learnt the Source and Destination Addresses by receiving at least one non-compressed header

★ The PDCP layer can also provide integrity protection and ciphering to maintain the security of the connection. If integrity protection is enabled, the PDCP layer adds a MAC-I field to the end of the speech packet. The MAC-I has a length of 4 bytes and is used by the receiver to verify that the packet is authentic

★ The PDCP header includes a Sequence Number which is configured by the RRC layer to have a length of either 12 or 18 bits. A 12 bit Sequence Number is accommodated within a header size of 2 bytes, whereas an 18 bit Sequence Number is accommodated within a header size of 3 bytes. A 12 bit Sequence Number is expected to be sufficient for the voice service so a header size of 2 bytes can be assumed. The Sequence Number is used to provide in-sequence delivery of the packets to the higher layers

★ The Radio Link Control (RLC) layer is specified by 3GPP within TS 38.322. Both the RTP and RTCP protocol stacks belonging to VoNR use Unacknowledged Mode (UM) RLC to transfer packets without ARQ re-transmissions. The ARQ re-transmissions supported by Acknowledged Mode RLC are relatively slow and would impact the VoNR delay budget. UM RLC supports segmentation so a packet can be segmented and transferred using multiple resource allocations if the link budget does not permit the throughput required to transfer the whole packet in a single transmission. The UM RLC header size is 1 byte when segmentation is not required. If segmentation is required then the header size can increase to 3 bytes when using a 6 bit Sequence Number, or to 4 bytes when using a 12 bit Sequence Number

★ The Medium Access Control (MAC) layer is specified by 3GPP within TS 38.321. The MAC layer provides support for HARQ re-transmissions which are relatively fast and can be completed without having a significant impact upon the VoNR delay budget. The MAC layer also supports multiplexing of data belonging to different logical channels. For example, a speech packet can be multiplexed with a SIP signalling packet, an SRB packet or a data packet

★ The MAC header includes a Logical Channel Identity (LCID) and a Length indicator. An 8 bit Length indicator is accommodated within a header size of 2 bytes, whereas a 16 bit Length indicator is accommodated within a header size of 3 bytes. An 8 bit Length indicator is sufficient for the voice service so a header size of 2 bytes can be assumed

★ In terms of Radio Resource Management (RRM) the voice service can benefit from:

  - o Discontinuous Reception (DRX): which allows the UE to 'sleep' between consecutive packet transfers. A UE can be configured with a DRX cycle period of 20 ms to match the rate at which the codec generates speech packets. The UE power consumption is reduced if the UE is permitted to sleep for the majority of the 20 ms DRX cycle. For example, a UE could be DRX Active for 4 ms and DRX Inactive for 16 ms. The timing of the periodic Scheduling Request cycle can be aligned with the DRX pattern to ensure that the UE only transmits a Scheduling Request when the UE is already DRX Active. This avoids the UE disrupting its sleep cycle to transmit a Scheduling Request. A UE is typically required to disrupt its sleep cycle after transmitting an uplink packet. This is necessary for the UE to check whether or not the Base Station has requested a HARQ re-transmission. DRX is described in section 13.10

  - o Packet Aggregation: which is used to increase the period between packet transfers. For example, speech packets could be transferred every 40 ms rather than every 20 ms. This requires the sender to buffer packets so there is a negative impact upon the delay budget. Packet Aggregation improves the efficiency of the air-interface by transferring a relatively small number of larger transport blocks, rather than a relatively large number of smaller transport blocks. It reduces the PDCCH load when using dynamic resource allocations because PDCCH transmissions are required once every 40 ms rather than once every 20 ms (assuming a 40 ms aggregation period). Packet Aggregation also helps to improve the sleep ratio provided by DRX because the UE becomes DRX Active less frequently. An aggregation period of 40 ms can be implemented by configuring a 40 ms Scheduling Request period and a 40 ms DRX cycle duration

- o Semi-Persistent Scheduling in the downlink and Configured Grants in the uplink: which can be used to reduce the PDCCH load generated by the speech service. The speech service requires a continuous stream of periodic PDCCH transmissions when using dynamic resource allocations. Semi-Persistent Scheduling and Configured Grants reduce the requirement for dynamic resource allocations on the PDCCH (resources for re-transmissions are still allocated using the PDCCH). Semi-Persistent Scheduling and Configured Grants rely upon RRC signalling to pre-configure information regarding the resources to be allocated. The PDCCH (or a MAC Control Element) can then be used to activate/deactivate the resources. This approach reduces the flexibility of the Packet Scheduler and Link Adaptation because the resource allocations become relatively fixed. However, these solutions remove the risk of resource allocations being missed due to the UE failing to receive a PDCCH transmission, or the Base Station failing to receive a Scheduling Request. Semi-Persistent Scheduling is described in section 3.6.4.3, whereas Configured Grants are described in section 7.4.4.3
- o PUSCH Repetition: which is the equivalent of TTI Bundling in LTE. The Base Station can use the *pusch-AggregationFactor* shown in Table 196 (section 7.4) to configure a repetition level of 2, 4 or 8 (TTI Bundling in LTE uses a repetition level of 4). The UE repeats each transmission in consecutive uplink slots. There is one repetition within each slot and each repetition uses the same allocation of symbols. The PUSCH is limited to a single transmission layer when repetition is used, i.e. it is intended to improve coverage and should not be required at locations where the PUSCH is able to benefit from multiple transmission layers

★ The UE provides VoNR capability information during the Non Access Stratum (NAS) Registration procedure presented in Figure 441.

★ The NAS: *Registration Request* message can include the '*UE's Usage Setting*' field presented in Table 322. Inclusion of this field within the NAS: *Registration Request* indicates that the higher layers of the UE support the IMS Voice service. The actual value of the field indicates a preference for voice services or data services but does not indicate any further UE capability information, i.e. a UE which specifies a value of 'Data Centric' also supports the voice service

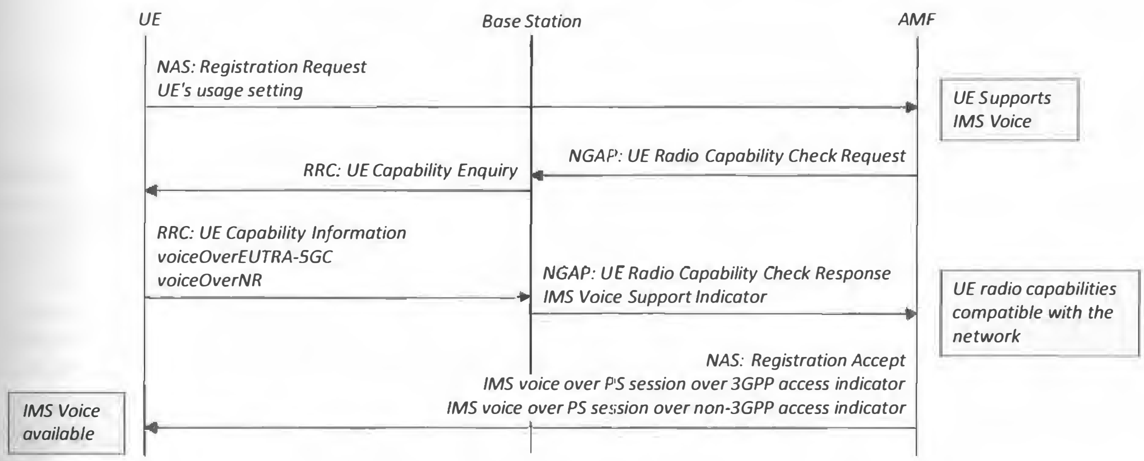


Figure 441 – Exchange of capability information during the NAS Registration procedure

extract from NAS: Registration Request	
UE's Usage Setting	Voice Centric, Data Centric

Table 322 – UE's Usage Setting from NAS: *Registration Request* message

★ The AMF can use the NGAP: *UE Radio Capability Check Request* to obtain information regarding the UE's support for IMS Voice within the Radio Access Network. This message triggers the Base Station to forward an RRC: *UE Capability Enquiry* to the UE. Within the context of the NR voice service, the UE responds with the information shown in Table 323. The UE indicates its support for IMS voice when the air-interface is EUTRA (LTE) rather than New Radio (NR). In the case of Voice over NR, the UE implementation for handling voice packets can be differ between Frequency Range 1 and Frequency Range 2. This means that the UE is required to signal its support for each Frequency Range separately

extract from UE-NR-Capability-v1540			
ims-Parameters	ims-ParametersCommon	voiceOverEUTRA-5GC	supported
	ims-ParametersFRX-Diff	voiceOverNR	supported
fr1-Add-UE-NR-Capabilities-v1540	ims-ParametersFRX-Diff	voiceOverNR	supported
fr2-Add-UE-NR-Capabilities-v1540	ims-ParametersFRX-Diff	voiceOverNR	supported

Table 323 – UE capability information for the IMS Voice service

★ The Base Station responds to the AMF using the NGAP: *UE Radio Capability Check Response*. This message includes the 'IMS Voice Support Indicator', which specifies whether or not the UE supports the IMS Voice service when using the air-interface provided by the Base Station

★ The UE is informed whether or not it is able to use the IMS Voice service within the NAS: *Registration Accept* message. This message provides information regarding the availability of the IMS Voice service for both 3GPP and non-3GPP access networks. The latter can be applied to Voice over WiFi if a WiFi access network is connected to the 5G Core Network

★ 3GPP References: TS 23.501, TS 23.228, TS 26.441, TS 26.445, TS 38.413, TS 38.331, TS 38.306

14.2 EPS FALLBACK

★ EPS Fallback can be triggered when a UE initiates an IMS voice call while connected to the 5G Core Network using New Radio (NR). It requires the 5G Core Network to have connectivity to an IP Multimedia Subsystem (IMS) so the SIP signalling procedures can be initiated while the UE is connected to the NR Radio Access Network. The fallback procedure moves the UE onto a 4G Core Network using EUTRA. The 4G Core Network also has connectivity to the IMS so the voice call setup can then be completed. The general network architecture for EPS Fallback is illustrated in Figure 442

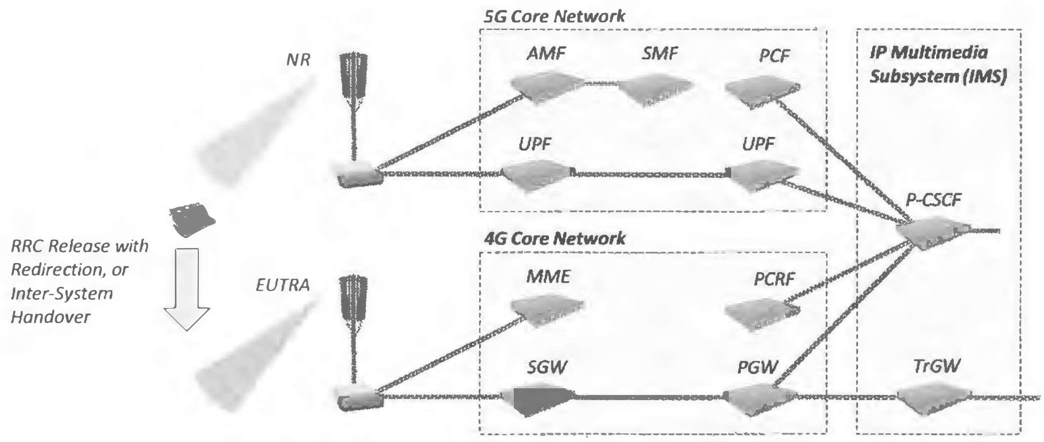


Figure 442 – Network architecture for EPS Fallback

★ EPS Fallback avoids the 5G system having to support a QoS Flow with 5QI = 1, i.e. the 5G system can focus upon providing non-real time data services. In addition, the EUTRA Radio Access Network is likely to have wider coverage than the NR Radio Access Network (at least during early deployment) so the setup of IMS voice calls on 4G avoids the requirement for a 5G to 4G inter-system handover during an ongoing call

★ Figure 443 illustrates the general signalling flow associated with the EPS Fallback procedure. It is assumed that the UE is already registered with the IMS before the procedure begins. The IMS voice call setup is initiated using the SIP Invite message. Figure 443 illustrates a mobile originated message but the SIP Invite could also be mobile terminated. The first stages of voice call setup proceed in the normal manner, i.e. the IMS triggers the PCF to setup a QoS Flow with 5QI = 1 and the Base Station receives an NGAP: *PDU Session Resource Setup Request*

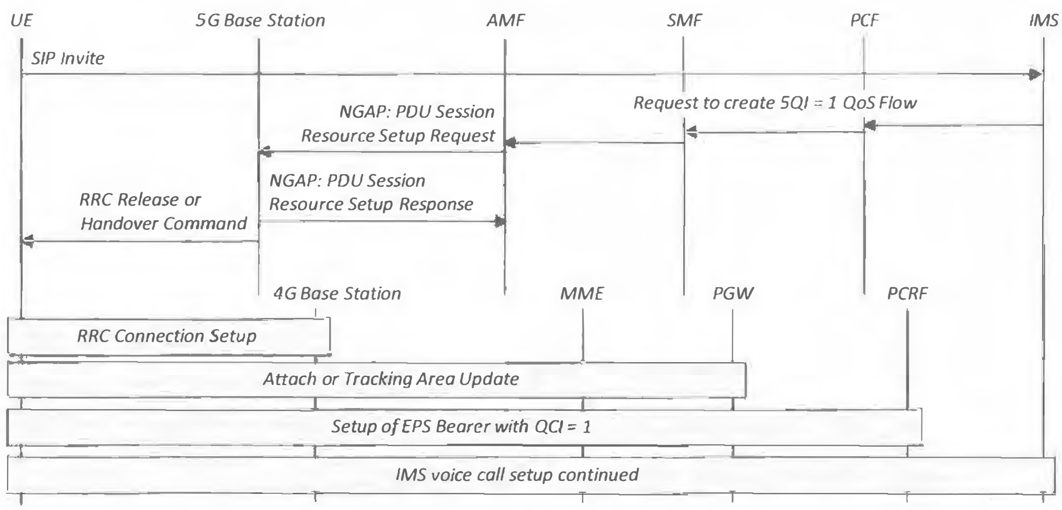


Figure 443 – General signalling flow for EPS Fallback

★ The Base Station is then responsible for taking the decision to apply the EPS Fallback procedure. After taking the decision, the Base Station rejects the request to setup the QoS Flow with 5QI = 1, using the NGAP: *PDU Session Resource Setup Response*. This message specifies the failure cause as 'IMS voice EPS Fallback or RAT Fallback triggered'. The Base Station is then responsible for moving the UE across to EUTRA from where it can connect to the 4G Core Network. This can be done using an RRC Release with Redirection or a handover. An RRC Release with Redirection uses the *RRC Release* message to specify a target carrier. This procedure does not specify a target cell. The UE may be requested to complete measurements before the redirection to verify that the target carrier has coverage. A handover uses the *RRC Reconfiguration* message to specify a target cell. Handover procedures usually take advantage of measurements to identify the target cell but it is also possible to use a blind handover procedure without measurements

★ If the UE is moved to the 4G network using a handover then the UE completes a Tracking Area Update upon arrival. Similarly, the UE completes a Tracking Area Update if the UE is moved using an RRC Release with Redirection and there is an N26 interface between the AMF and MME. If the UE is moved to the 4G network using an RRC Release with Redirection and there is no N26 interface, then the UE completes an Attach procedure

★ The IMS voice call setup procedure then continues on 4G. Once the EPS Bearer with QCI = 1 has been setup, it is possible to trigger an SRVCC towards 2G or 3G. This would change the Core Network domain from packet switched to circuit switched. It is also possible for the 4G network to trigger a CS Fallback procedure towards 2G or 3G during the initial setup

★ A UE does not explicitly indicate its support for the EPS Fallback procedure. It is assumed that the UE supports the procedure if the UE has indicated that it supports VoLTE. The AMF uses the 'Redirection for Voice EPS Fallback' flag within the NGAP: *Initial Context Setup Request* to inform the Base Station whether or not EPS Fallback is supported for a specific UE. This flag can also be provided within the NGAP: *Handover Request* and NGAP: *Path Switch Request Acknowledge* messages

★ 3GPP References: TS 23.501, TS 23.502, TS 38.413, TS 38.331

14.3 RAT FALLBACK

★ RAT Fallback can be triggered when a UE initiates an IMS voice call while connected to the 5G Core Network using New Radio (NR). It requires the 5G Core Network to have connectivity to an IP Multimedia Subsystem (IMS) so the SIP signalling procedures can be initiated while the UE is connected to the NR Radio Access Network. The fallback changes the Radio Access Network from NR to EUTRA while maintaining connectivity to the 5G Core Network. The general network architecture for the RAT Fallback is illustrated in Figure 444

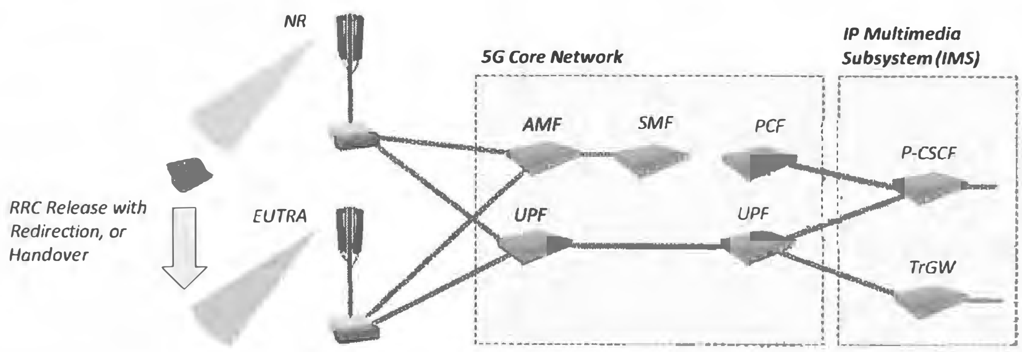


Figure 444 – Network architecture for RAT Fallback

★ RAT Fallback avoids the NR Base Station having to support QoS Flows with 5QI = 1. In addition, EUTRA Base Stations may provide better coverage than NR Base Stations – typically due to lower operating bands and larger site numbers during early NR deployment

★ The signalling flow associated with RAT Fallback is similar to the signalling flow associated with EPS Fallback (illustrated in Figure 443). The SIP signalling used to initiate the IMS voice call setup is initiated while the UE is using the NR air-interface. The IMS triggers the PCF to setup a QoS Flow with 5QI = 1 and the Base Station receives an NGAP: *PDU Session Resource Setup Request*

★ The Base Station is then responsible for taking the decision to apply the RAT Fallback procedure. After taking the decision, the Base Station rejects the request to setup the QoS Flow with 5QI = 1, using the NGAP: *PDU Session Resource Setup Response*. This message specifies the failure cause as 'IMS voice EPS Fallback or RAT Fallback triggered'. The Base Station is then responsible for moving the UE across to EUTRA. This can be done using an RRC Release with Redirection or a handover

★ The IMS voice call setup procedure then continues on EUTRA in combination with the 5G Core Network. In this case, it is not possible to trigger an SRVCC towards 2G nor 3G when the system is based upon the release 15 version of the specifications. An SRVCC towards 3G is planned for the release 16 version of the specifications

★ 3GPP References: TS 23.501, TS 23.502, TS 38.413, TS 38.331

15 SIGNALLING PROCEDURES

15.1 LTE RRC IDLE MODE

★ System Information Blocks (SIB) belonging to LTE can be used to broadcast:

- a 5G Status Indicator within SIB2 which allows the UE to display a 5G icon. This icon informs the end-user that 5G services are available at that location. The 5G Status Indicator is important for network configurations which provide 5G services while relying upon LTE to support RRC Idle mode. For example, LTE cells which belong to an EN-DC Non-Standalone Base Station can broadcast the 5G Status Indicator
- cell reselection information within SIB24 which allows the UE to move from LTE to NR while in RRC Idle mode. This content is applicable to networks which support RRC Idle mode for both LTE and NR. SIB5 belonging to the NR radio access network broadcasts cell reselection information which allows the UE to move from NR to LTE while in RRC Idle mode

★ The 5G Status Indicator broadcast by SIB2 is presented in Table 324. The RRC signalling protocol uses the 'upperLayerIndication' to serve as the 5G Status Indicator. A separate instance can be broadcast for each PLMN identity associated with the LTE cell

extract from *SystemInformationBlockType2* belonging to the LTE system			
PLMN-InfoList-r15	SEQUENCE {1 to 6 instances}		
	PLMN-Info-r15	upperLayerIndication-r15	true

Table 324 – 5G Status Indicator within LTE SIB2

★ Use of the 5G Status Indicator is dependent upon the UE implementation. UE are expected to evaluate the 5G Status Indicator in combination with other information prior to displaying the 5G icon to the end-user. A 5G capable device is not expected to display the 5G icon if the end-user has not subscribed to 5G services. The 4G NAS: *Attach Accept* message can include the 'EPS Network Feature Support' parameter set presented in Figure 445. This parameter set includes the 'RestrictDCNR' flag which indicates whether or not the end-user is authorised to use Dual Connectivity with NR. The UE can use this flag in combination with the 5G Status Indicator to determine whether or not the 5G icon should be displayed

8 bits

CP CIoT	ERw/o PDN	ESR PS	CS-LCS		EPC-LCS	EMC BS	IMS VoPS
15 bearers	IWKN26	Restrict DCNR	Restrict EC	ePCO	HC-CP CIoT	S1-U data	UP CIoT

Figure 445 – EPS Network Feature Support information element from NAS: Attach Accept

★ Use of the 5G Status Indicator is complicated by potential differences in the LTE and NR coverage areas. Figure 446 illustrates a scenario which is based upon LTE coverage provided by a low operating band and NR coverage provided by a high operating band. In this case, LTE coverage extends further than NR coverage due to the difference in propagation loss. This allows a UE to receive the 5G Status Indicator from LTE at locations where 5G services are not available. In this case, it can be misleading to display the 5G icon to the end-user

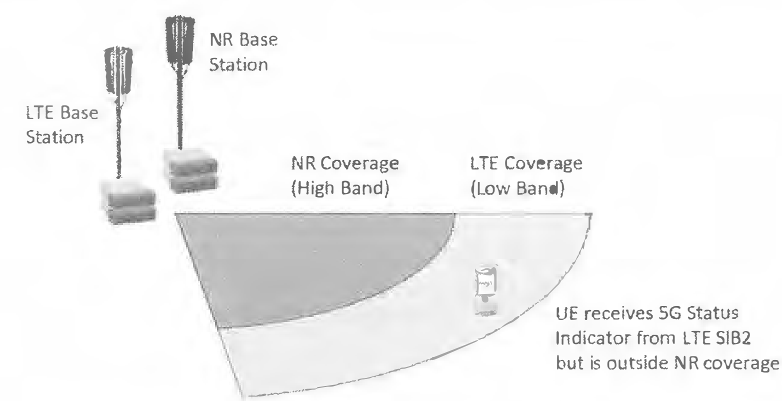


Figure 446 – Reception of 5G Status Indicator while outside NR coverage

★ Ideally, the UE should complete inter-system measurements to verify that NR coverage exists prior to displaying the 5G icon. However, these inter-system measurements are not simplistic because the UE may not have knowledge of the NR carrier to be measured. When using the EN-DC Non-Standalone Base Station architecture, the LTE system does not specify NR carrier information within SIB24 because cell reselection towards NR is not supported. The UE could complete a band scan to identify candidate NR carriers but the NR Base Station is not required to broadcast SIB1 so the UE may not be able to determine which NR carriers belong to the registered network. In addition, if measurements are completed to verify 5G coverage then the UE is likely to require an SS-RSRP threshold to determine whether or not the NR signal strength is adequate. If the LTE Base Station uses measurement based Secondary Cell addition, then the SS-RSRP threshold used by the Base Station should ideally be aligned with the threshold used by the UE

★ The GSM Association (GSMA) has agreed upon a set of 4 candidate UE configurations which determine when a UE should display the 5G icon. These 4 configurations are presented in Table 325. None of the configurations allow the UE to display the 5G icon when using an LTE cell which does not belong to a Non-Standalone (NSA) Base Station. All of the configurations allow the UE to display the 5G icon when using an NG-RAN connected to the 5G Core Network (5GC)

★ Otherwise, configuration 'A' is the most conservative because it limits the UE to displaying the 5G icon when the UE is already connected to both LTE and NR cells. In contrast, Configuration 'D' is the most aggressive because it allows the UE to display the 5G icon when using only an LTE cell belonging to an NSA Base Station, without having to verify NR coverage. Configurations 'B' and 'C' rely upon the UE verifying that NR coverage exists

★ The national regulator may specify the configuration to be used. Otherwise, an operator may specify the preferred configuration to each UE vendor

		Config A	Config B	Config C	Config D
1	UE is Idle under LTE cell not supporting NSA, or UE is Connected to LTE cell not supporting NSA	4G	4G	4G	4G
2	UE is Idle under LTE cell supporting NSA, without detection of NR coverage, or UE is Connected to LTE cell supporting NSA, without detection of NR coverage	4G	4G	4G	5G
3	UE is Connected to LTE only, while connected to an LTE cell supporting NSA, with detection of NR coverage	4G	4G	5G	5G
4	UE is Idle under LTE cell supporting NSA, with detection of NR coverage	4G	5G	5G	5G
5	UE is connected to both LTE and NR under an LTE cell supporting NSA	5G	5G	5G	5G
6	UE is Idle under NG-RAN while attached to 5GC, or UE is Connected to NG-RAN while attached to 5GC	5G	5G	5G	5G

Table 325 – UE configurations for displaying the 5G icon

★ The content of the LTE SIB24 is presented in Table 326. This SIB is broadcast when cell reselection from LTE to NR is supported. It is not applicable to the EN-DC Non Standalone Base Station because in this case, NR does not support an RRC Idle mode

★ LTE SIB24 allows up to 8 NR carriers to be specified using their ARFCN. These ARFCN correspond to the center frequency of the SS/PBCH Blocks rather than the center frequency of the channel bandwidth. Multiple operating bands can be linked to each of the specified ARFCN, i.e. in the case that operating bands overlap

★ *measTimingConfig* provides the periodicity and time offset to be used when measuring the SS/PBCH Blocks belonging to the target NR carrier. It also provides a measurement duration which should be sufficiently long to capture all of the SS/PBCH Blocks available to measure

★ *subcarrierSpacingSSB* specifies the subcarrier spacing of the SS/PBCH Blocks belonging to the target NR carrier so can be configured with values of 15 or 30 kHz for Frequency Range 1, and 120 or 240 kHz for Frequency Range 2

★ *ss-RSSI-Measurement* specifies the slots and symbols which can be used for RSSI measurements when evaluating RSRQ.

★ *measurementSlots* defines a bit string where each bit corresponds to a slot within the measurement duration. For example, if *ssb-Duration* is set to 5 subframes and the subcarrier spacing is 15 kHz then the bit string will have a length of 5 bits because there are 5 slots in 5 subframes. In contrast, if *ssb-Duration* is set to 5 subframes and the subcarrier spacing is 240 kHz then the bit string will have a length of 80 bits because there are 80 slots in 5 subframes. The UE measures the RSSI during slots which correspond to a '1' within the bit string

★ *endSymbol* defines the symbols within the *measurementSlots* which can be used to measure the RSSI. The value of *endSymbol* is a pointer to a row within a 3GPP standardised look-up table (Table 241 in section 10.2). For example, *endSymbol* = '0' means that the UE can complete RSSI measurements during symbols 0 and 1, while *endSymbol* = '2' means that the UE can complete RSSI measurements during symbols 0, 1, 2, 3, 4 and 5

★ *cellReselectionPriority* and *cellReselectionSubPriority* define the Absolute Priority of the target NR carrier. These values allow the UE to categorise each NR carrier as either higher priority or lower priority than the current LTE carrier. The appropriate cell reselection procedure and parameter set can then be applied towards each NR carrier

★ *threshX-High* and *threshX-HighQ* are applicable when completing cell reselection towards a higher priority NR carrier. These parameters define minimum SS-RSRP and SS-RSRQ thresholds respectively. *threshX-High* defines a threshold relative to *q-RxLevMin*, whereas *threshX-HighQ* defines a threshold relative to *q-QualMin*. For example, if *q-RxLevMin* is set to -60 (which maps to a value of -120 dBm) and *threshX-High* is set to 5 (which maps to a value of 10 dB), then the target NR cell must have an SS-RSRP > -110 dBm to allow cell reselection

★ *threshX-Low* and *threshX-LowQ* are applicable when completing cell reselection towards a lower priority NR carrier. These parameters define minimum SS-RSRP and SS-RSRQ thresholds respectively. *threshX-Low* defines a threshold relative to *q-RxLevMin*, whereas *threshX-LowQ* defines a threshold relative to *q-QualMin*

LTE *SIB24*						
carrierFreqListNR-r15	SEQUENCE {1 to 8 instances}					
	carrierFreq-r15	0 to 3279165				
	multiBandInfoList-r15	SEQUENCE {1 to 32 instances}				
		FreqBandIndicatorNR-r15	1 to 1024			
	multiBandInfoListSUL-r15	SEQUENCE {1 to 32 instances}				
		FreqBandIndicatorNR-r15	1 to 1024			
	measTimingConfig-r15	periodicityAndOffset-r15	CHOICE			
			sf5-r15	0 to 4	sf40-r15	0 to 39
			sf10-r15	0 to 9	sf80-r15	0 to 79
			sf20-r15	0 to 19	sf160-r15	0 to 159
		ssb-Duration-r15	1, 2, 3, 4, 5 subframes			
	subcarrierSpacingSSB-r15	15, 30, 120, 240 kHz				
	ss-RSSI-Measurement-r15	measurementSlots-r15	BIT STRING {1 to 80 bits}			
		endSymbol-r15	0 to 3			
	cellReselectionPriority	0 to 7				
	cellReselectionSubPriority	0.2, 0.4, 0.6, 0.8				
	threshX-High-r15	0 to 31 (actual value = signalled value × 2)				
	threshX-Low-r15	0 to 31 (actual value = signalled value × 2)				
	threshX-Q-r15	threshX-HighQ-r15	0 to 31			
		threshX-LowQ-r15	0 to 31			
	q-RxLevMin-r15	-70 to -22 (actual value (dBm) = signalled value × 2)				
	q-RxLevMinSUL-r15	-70 to -22 (actual value (dBm) = signalled value × 2)				
	p-MaxNR-r15	-30 to 33 dBm				
	ns-PmaxListNR-r15	SEQUENCE {1 to 8 instances}				
		additionalPmaxNR-r15	-30 to 33 dBm			
		additionalSpectrumEmissionNR-r15	0 to 7			
	q-QualMin-r15	-43 to -12 dB				
	deriveSSB-IndexFromCell-r15	BOOLEAN				
	maxRS-IndexCellQual-r15	1 to 16				
	threshRS-Index-r15	nr-RSRP-r15	0 to 127			
		nr-RSRQ-r15	0 to 127			
		nr-SINR-r15	0 to 127			
	multiBandNsPmaxListNR-v1550	SEQUENCE {1 to 31 instances} of *NS-PmaxListNR-r15*				
	multiBandNsPmaxListNR-SUL-v1550	SEQUENCE {1 to 32 instances} of *NS-PmaxListNR-r15*				
	ssb-ToMeasure-r15	CHOICE				
		shortBitmap-r15	BIT STRING {4 bits}			
		mediumBitmap-r15	BIT STRING {8 bits}			
		longBitmap-r15	BIT STRING {64 bits}			
t-ReselectionNR-r15	0 to 7 seconds					
t-ReselectionNR-SF-r15	sf-Medium	0.25, 0.5, 0.75, 1.0				
	sf-High	0.25, 0.5, 0.75, 1.0				

Table 326 – Content of the LTE System Information Block 24 (SIB24)

★ *q-RxLevMin* and *q-QualMin* define the minimum SS-RSRP and SS-RSRQ requirements for the target NR carrier. The RSRQ requirement is optional so may be excluded from SIB24

★ *q-RxLevMinSUL* defines a minimum SS-RSRP requirement which is applicable if SIB24 specifies a Supplemental Uplink band and if the UE supports the corresponding Supplemental Uplink band combination. The link budget belonging to a Supplemental Uplink may differ from the link budget for the Normal Uplink. If coverage is uplink limited then *q-RxLevMinSUL* can be adjusted relative to *q-RxLevMin* to reflect the difference in link budgets

★ *p-MaxNR* defines the maximum UE transmit power permitted when using a cell belonging to the target NR carrier

★ *ns-PmaxListNR* provides a list of up to 8 pairs of {*additionalPmaxNR*, *additionalSpectrumEmissionNR*}. These pairs specify additional spectrum emission requirements which should be satisfied if the UE uses the corresponding maximum transmit power. The values are applicable to the first operating band listed within *multiBandInfoList*

★ *deriveSSB-IndexFromCell* indicates whether or not the UE can assume radio frame alignment for all cells belonging to the target NR carrier. Radio frame alignment allows the UE to use the timing belonging to one NR cell to derive the SSB Indices belonging to other NR cells. This helps to reduce measurement delays because it avoids the requirement to decode the PBCH belonging to each individual NR cell

★ *maxRS-IndexCellQual* and *threshRS-Index* are used when deriving a 'cell level' result from a set of 'beam level' measurements. If the target NR cell is configured with multiple SS/PBCH beams then it is necessary to derive a 'cell level' result from one or more 'beam level' measurements. If *maxRS-IndexCellQual* is excluded, the UE sets the 'cell level' result equal to the highest 'beam level' measurement. Otherwise, the UE derives the 'cell level' result by calculating a linear average of the highest 'beam level' measurements which exceed *threshRS-Index*. The maximum number of 'beam level' measurements included in the average is defined by *maxRS-IndexCellQual*. If none of the beam level measurements exceed *threshRS-Index*, the 'cell level' result is set equal to the highest 'beam level' measurement

★ *multiBandNsPmaxListNR* provides a list of up to 8 pairs of {*additionalPmaxNR*, *additionalSpectrumEmissionNR*} for each operating band listed within *multiBandInfoList* (with the exception of the first band which is already catered for using *ns-PmaxListNR*). Each list specifies additional spectrum emission requirements which should be satisfied if the UE uses the corresponding maximum transmit power after selecting the corresponding operating band. Similarly, *multiBandNsPmaxListNR-SUL* provides a list of up to 8 pairs of {*additionalPmaxNR*, *additionalSpectrumEmissionNR*} for each operating band listed within *multiBandInfoListSUL*

★ *ssb-ToMeasure* specifies the set of SS/PBCH Blocks to be measured within the measurement duration. A short, medium or long bitmap is broadcast according to the frequency range. A short bitmap is broadcast for carriers below 3 GHz (up to 4 SS/PBCH), a medium bitmap is broadcast for carriers between 3 GHz and 6 GHz (up to 8 SS/PBCH), and a long bitmap is broadcast for carriers greater than 6 GHz (up to 64 SS/PBCH). The UE measures SS/PBCH Blocks which correspond to a '1' within the bit string. The UE measures all SS/PBCH Blocks if *ssb-ToMeasure* is excluded from the SIB

★ *t-ReselectionNR* defines the time-to-trigger for cell reselection towards NR. *sf-Medium* and *sf-High* define scaling factors for medium and high mobility conditions. *t-ReselectionNR* is multiplied by the appropriate scaling factor when medium or high mobility is detected

★ In the case of the EN-DC Non-Standalone Base Station, NR Secondary Cell Addition may be supported from only a subset of LTE carriers. This may result from band combinations which have not been standardised within the 3GPP specifications. It then becomes necessary to move 5G subscribers onto an LTE carrier which supports NR Secondary Cell Addition. This scenario is illustrated in Figure 447

★ 5G subscribers can be moved onto the appropriate LTE carrier using RRC Idle mode procedures but it is necessary to ensure that the solution is transparent to non-5G subscribers. The LTE Base Station can receive subscription information within the S1AP: *Initial Context Setup Request*. This message can include an 'NR Restriction in EPS as Secondary RAT' flag and also a Subscriber Profile Identity (SPID). The EPC can allocate specific SPID values to 5G subscribers allowing the Base Station to differentiate those subscribers. In addition, the S1AP: *Initial Context Setup Request* includes UE capability information so the Base Station can verify that the subscriber is using a 5G capable device

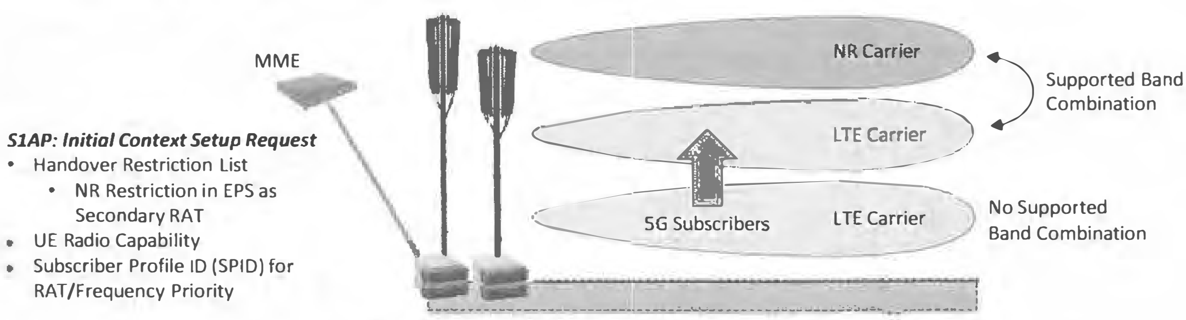


Figure 447 – NR Secondary Cell Addition supported from a subset of LTE carriers

★ The LTE Base Station can allocate UE specific Absolute Priorities to the 5G subscribers within the *RRC Release* message. These Absolute Priorities can be configured to ensure that UE move onto an LTE carrier which supports 5G Secondary Cell Addition

★ 3GPP References: TS 36.331, TS 36.413, TS 24.301

15.2 EN-DC SECONDARY CELL ADDITION

★ The EUTRA-NR Dual Connectivity (EN-DC) Secondary Cell Addition procedure is used to provide a UE with an NR Secondary Cell. The UE must already be connected to the 4G Master Node as a prerequisite to this procedure. Figure 448 illustrates the radio network signalling for the initial 4G connection. It is assumed that the UE has already completed the Non-Access Stratum (NAS) Attach procedure so the UE is already registered with the 4G Core Network

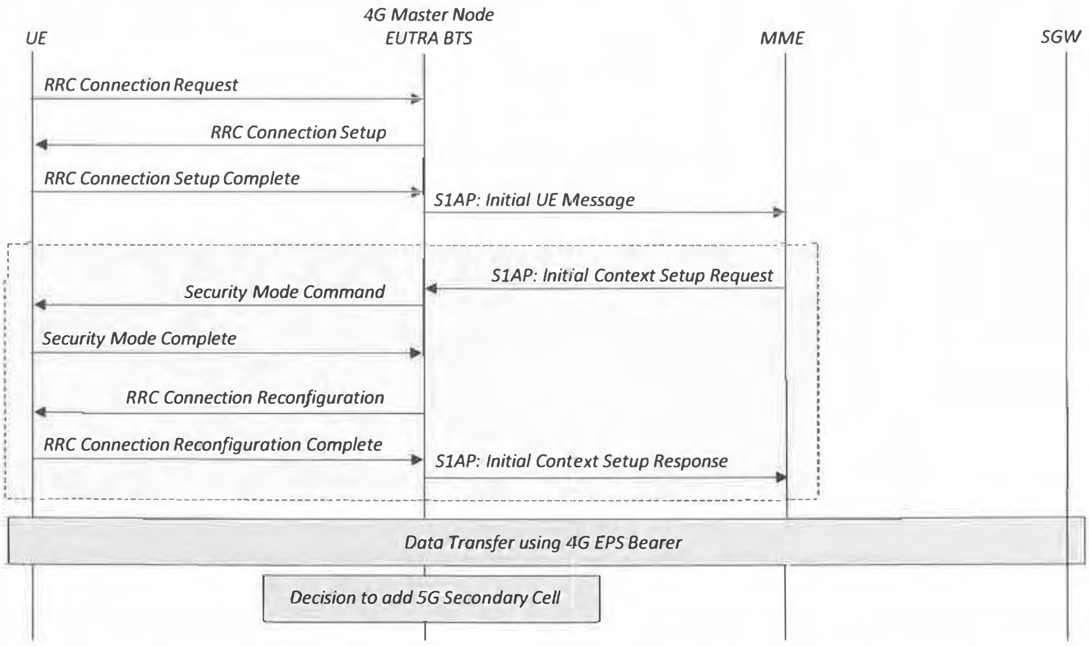


Figure 448 – Setup of 4G EPS Bearer as a prerequisite to EN-DC Secondary Cell Addition

★ From the perspective of the EN-DC Secondary Cell Addition procedure, the most important part of this connection setup is the S1AP: *Initial Context Setup Request* message (specified by 3GPP TS 36.413). This message includes both UE capability information and UE subscription information. The most relevant content from within this message is presented in Table 327

★ The 'UE Aggregate Maximum Bit Rate' (UE-AMBR) is part of the UE subscription information. Limits are specified for both the uplink and downlink directions. These must be high enough to support the throughputs provided by the 5G air-interface. The 4G Master Node is responsible for allocating either some or all of the UE-AMBR to the 5G Secondary Node during the Secondary Cell Addition procedure (using the X2AP: *SGNB Addition Request* presented later in this section)

★ The 'E-RAB to be Setup List' specifies the set of E-RAB belonging to the set of EPS Bearers which are to be established. This may include a non-Guaranteed Bit Rate (non-GBR) EPS Bearer with QCI = 6, 7, 8 or 9, for data transfer. It may also include a non-GBR EPS Bearer with QCI = 5, for signalling to an IMS

Information Elements			Presence
UE Aggregate Maximum Bit Rate			Mandatory
E-RAB to be Setup List	SEQUENCE {1 to 256 instances}		Mandatory
	E-RAB Identity & E-RAB Level QoS Parameters		Mandatory
	Transport Layer Address & GTP-TEID		Mandatory
Handover Restriction List	NR Restriction in EPS as Secondary RAT		Optional
	Core Network Type Restrictions	SEQUENCE {0 to 16 instances}	Optional
		PLMN Identity	Optional
		Core Network Type	Optional
	NR Restriction in 5GS		Optional
	Last NG-RAN PLMN Identity		Optional
UE Radio Capability			Optional
Subscriber Profile ID (SPID) for RAT/Frequency Priority			Optional
NR UE Security Capabilities			Optional

Table 327 – Extract from S1 Application Protocol (S1AP) *Initial Context Setup Request*

★ The '*E-RAB Level QoS Parameters*' within the 'E-RAB to be Setup List' includes the subscribed Allocation and Retention Priority (ARP). This could be used as part of the Admission Control decision for Secondary Cell Addition, e.g. only UE with a specific ARP value are considered for Secondary Cell Addition. The use of ARP in this way depends upon the network implementation

★ The 'Handover Restriction List' can include the '*NR Restriction in EPS as Secondary RAT*' field which can serve as the primary indication of the UE's 5G subscription. Inclusion of this field with a value of '*NRrestrictedinEPSasSecondaryRAT*' indicates that the end-user has not subscribed to 5G services and the EPS Bearers are to be kept on 4G. Exclusion of this field indicates that the end-user has subscribed to 5G services and is not restricted in terms of EN-DC Secondary Cell Addition. The 4G Master Node can use this field when executing its Admission Control decision for Secondary Cell Addition

★ The 'Handover Restriction List' can also include the '*Core Network Type Restrictions*' and '*NR Restriction in 5GS*' fields but these are applicable to deployments which include the 5G Core Network. The '*Core Network Type Restrictions*' field can be used to forbid connection to specific 5G Core Networks, whereas the '*NR Restriction in 5GS*' field can be used to forbid the use of NR when connecting to a 5G System (the UE could use LTE if a Next Generation eNode B is connected to the 5G Core Network)

★ The 'UE Radio Capability' provides the 4G Master Node with information which has previously been reported by the UE. This information is stored as part of the UE context within the MME to avoid having to re-request it for every RRC Connection setup. The 4G Master Node uses this field to gain knowledge of the UE's 5G capability which can then impact the Admission Control decision for the EN-DC Secondary Cell Addition

★ The 'Subscriber Profile ID' (SPID) can be allocated as part of the UE's subscription information. It can be used to identify specific mobility preferences for each UE. Within the context of EN-DC, it is useful when the Secondary Cell Addition procedure is supported from only a subset of the 4G carriers. In this case, the SPID can be used to identify the requirement to move the UE onto an RF carrier which supports the addition procedure. For example, all UE which have subscribed to 5G services could be allocated an SPID = 100, which could then trigger the 4G Master Node to apply a specific set of mobility management rules to move the UE onto an appropriate RF carrier. The mobility management rules could be applied in RRC Idle mode by assigning a specific set of Absolute Priorities, or in RRC Connected mode by triggering inter-frequency handovers

★ The 'NR UE Security Capabilities' provides information regarding the integrity protection and encryption algorithms supported by the UE. This information can be used during the subsequent EN-DC Secondary Cell Addition procedure

★ Data transfer can start, using the 4G Master Node and the LTE air-interface once the Data Radio Bearers (DRB) have been setup at the UE using the RRC Connection Reconfiguration procedure. The 4G Master Node is then responsible for triggering the EN-DC Secondary Cell addition. For example, the triggering mechanism could be based upon data volume, i.e. if the UE transfers a small quantity of data then there is less justification to proceed with the additional signalling associated with Secondary Cell addition. If the UE transfers a larger volume of data then Secondary Cell addition is more likely to benefit both the network and the end-user

★ If 4G Master Node will also check its Admission Control criteria before initiating the Secondary Cell addition. The criteria could include: the UE capability, the NR Restriction flag within the Handover Restriction List, the QCI belonging to each EPS Bearer, the allocated ARP, the current 4G RF Carrier and consequently the resultant LTE/NR band combination. The Secondary Cell Addition procedure can be applied to a subset of the allocated EPS Bearers. For example, if the UE is allocated an EPS Bearer with QCI 8 for data transfer, and an EPS Bearer with QCI 5 for SIP signalling, then the Secondary Cell Addition procedure can be applied to the QCI 8 EPS Bearer, while leaving the QCI 5 EPS Bearer to use only the 4G Master Node

★ Secondary Cell Addition can be blind which means that the 4G Master Node adds a default 5G Secondary Cell without relying upon measurements. This approach is less reliable unless the 4G and 5G coverage footprints are the same and there is a clear one-to-one mapping between each 4G cell and 5G cell. Blind Secondary Cell Addition can benefit from reduced latency because the UE is not required to complete measurements before the procedure starts

★ Alternatively, Secondary Cell Addition can be based upon inter-system measurements reported by the UE. This approach helps to ensure that there is sufficient NR coverage before initiating the addition procedure, i.e. the success rate of the addition procedure can be improved. However, the measurement procedure introduces additional delay and the Measurement Gaps required for the inter-system measurements disrupt the transfer of data prior to the Secondary Cell Addition

★ The UE capability information does not specify the UE Measurement Gap requirement for individual operating band combinations. Thus, the 4G Base Station always configures Measurement Gaps for NR measurements while connected to 4G. These Measurement Gaps need to be synchronised with the SS/PBCH transmissions which are to be measured. Figure 449 illustrates the general timing of the SS/PBCH transmissions within a Measurement Gap

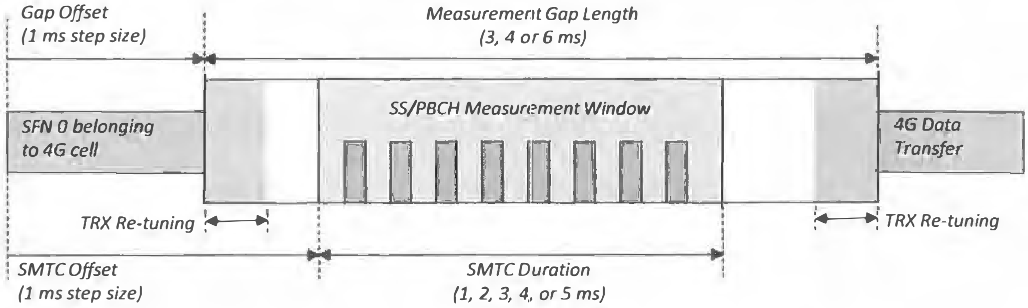


Figure 449 – SS/PBCH Measurement Window within a Measurement Gap

★ A Measurement Gap is configured using the 4G *MeasGapConfig* parameter structure. This parameter structure specifies the 'Gap Pattern Identity' and the 'Gap Offset'. The set of Measurement Gap Patterns is presented in Table 328. Measurement Gap Lengths (MGL) of 3, 4 or 6 ms can be configured. The duration of the Measurement Gap must be longer than the duration of the SS/PBCH transmissions to accommodate the delays generated by transceiver re-tuning, i.e. re-tuning to the NR carrier before starting the measurements and subsequently re-tuning back to the 4G carrier after completing the measurements. Each re-tuning delay is assumed to be 0.5 ms when measuring a carrier within Frequency Range 1, and 0.25 ms when measuring a carrier within Frequency Range 2. This means that a 3 ms Measurement Gap allows 2 ms for measurements when measuring an RF carrier within Frequency Range 1

Gap Pattern Id	*Measurement Gap Length (MGL)*	*Measurement Gap Repetition Period (MGRP)*	*Gap Pattern Id*	*Measurement Gap Length (MGL)*	*Measurement Gap Repetition Period (MGRP)*
0	6 ms	40 ms	6	4 ms	20 ms
1	6 ms	80 ms	7	4 ms	40 ms
2	3 ms	40 ms	8	4 ms	80 ms
3	3 ms	80 ms	9	4 ms	160 ms
4	6 ms	20 ms	10	3 ms	20 ms
5	6 ms	160 ms	11	3 ms	160 ms

Table 328 – Measurement Gap Patterns available to measure NR while connected to 4G

★ The duration of the SS/PBCH transmissions depends upon the subcarrier spacing (which determines the slot duration) and the number of SS/PBCH Blocks within each burst. Table 329 specifies the duration of the SS/PBCH transmissions for each subcarrier spacing when assuming the maximum permitted number of SS/PBCH Blocks within each frequency range

SS/PBCH Subcarrier Spacing	Slot Duration	Symbols per 1 ms	≤ 3 GHz (up to 4 SS/PBCH)	>3 GHz & ≤ 6 GHz (up to 8 SS/PBCH)	>6 GHz (up to 64 SS/PBCH)
15 kHz	1 ms	14	up to 2 ms (symbols 2 to 22)	up to 4 ms (symbols 2 to 50)	-
30 kHz	0.5 ms	28	up to 1 ms (symbols 2 to 22)	up to 2 ms (symbols 2 to 50)	-
120 kHz	0.125 ms	112	-	-	up to 5 ms (symbols 4 to 524)
240 kHz	0.0625 ms	224	-	-	up to 3 ms (symbols 8 to 492)

Table 329 – Duration of SS/PBCH transmissions for each subcarrier spacing (rounded up to nearest millisecond)

★ The Measurement Gap Repetition Period (MGRP) defines the period between consecutive Measurement Gaps. This period should be equal to the SS/PBCH transmission period, or a multiple of the SS/PBCH transmission period. Longer MGRP values reduce the impact upon 4G data transfer while the UE completes its measurements but can increase the overall duration of the measurements

★ 'Gap Offset' has a step size of 1 ms and defines the start of the Measurement Gaps relative to the start of the radio frame with System Frame Number (SFN) equal to 0. The expressions shown below are used to calculate the radio frame and subframe for the start of each Measurement Gap. These expressions are based upon the radio frame and subframe numbering belonging to the 4G system

$$\text{SFN mod } T = \text{FLOOR}\,(gapOffset/10) \qquad T = MGRP/10$$

$$\text{subframe} = gapOffset \text{ mod } 10$$

★ The UE is also provided with information regarding the timing of the SS/PBCH transmissions within the Measurement Gap. This information is provided in terms of an SS/PBCH Block Measurement Timing Configuration (SMTC). The SMTC defines a period, an offset and a duration, i.e. it uses a similar format to the Measurement Gap configuration. The SMTC is configured as part of the NR Measurement Object within an *RRC Connection Reconfiguration* message. The content of an NR Measurement Object is presented in Table 330 (the *measTimingConfig-r15* field corresponds to the SMTC)

★ The SMTC duration can be configured with a value of 1, 2, 3, 4 or 5 subframes (equivalent to 1, 2, 3, 4, or 5 ms). The duration should be large enough to capture all SS/PBCH transmissions. The figures presented in Table 329 can be used when the maximum number of SS/PBCH transmissions are active. Otherwise, the appropriate duration can be determined by identifying the range of symbols occupied by the set SS/PBCH. The candidate starting symbols for the set of SS/PBCH transmissions are presented in Table 56 (section 3.4). For example, if 1 SS/PBCH transmission is active while using the 30 kHz subcarrier spacing then the single transmission is accommodated within a single 0.5 ms slot and the SMTC duration can be set to 1 ms. Alternatively, if the first 32 SS/PBCH transmissions are active while using the 240 kHz subcarrier spacing then the transmissions span 16 slots (symbols 8 to 215). Each slot has a duration of 0.0625 ms so this requires an SMTC duration of 1 ms

★ The 'SMTC Offset' has a step size of 1 ms and defines the start of the SS/PBCH measurement window relative to the start of the radio frame with System Frame Number (SFN) equal to 0. The expressions shown below are used to calculate the radio frame and subframe for the start of each SS/PBCH measurement window. Similar to the Measurement Gap calculations, these expressions are based upon the radio frame and subframe numbering belonging to the 4G system

SFN mod T = FLOOR (*Offset*/10)	T = CEIL(*Periodicity*/10)
subframe = *Offset* mod 10	if Periodicity > 5 subframes
subframe = *Offset* or Offset + 5	if Periodicity <= 5 subframes

★ In many cases, the 4G and 5G radio frames will be aligned and the SS/PBCH transmissions will start at the beginning of a 4G/5G radio frame. In these cases, the 'SMTC Offset' can be set to 0 ms. In some cases, a time offset may be introduced between the 4G and 5G radio frame timing. For example, Figure 463 in section 16.3 illustrates a scenario which involves delaying the 5G radio frames by 3 ms. In this example, the 'SMTC Offset' can be set to 3 ms

★ 3GPP identified an issue with the 1 ms step size for the Measurement Gap and SMTC Offsets. In some cases, it leads to an overlap between the transceiver re-tuning period and the SS/PBCH Measurement Window. Figure 450 illustrates an example of a 6 ms Measurement Gap and a 5 ms SS/PBCH Measurement Window. The Measurement Gap and the SS/PBCH Measurement Window are assumed to have equal offsets so they both start at the same time. This means that the start of the SS/PBCH Measurement Window is lost due to the transceiver re-tuning delay. The Measurement Gap Offset could be reduced by 1 ms but this would cause the end of the SS/PBCH Measurement Window to be lost

★ 3GPP resolved this issue by introducing the use of a Measurement Gap Timing Advance (MGTA) which can be enabled using the *mgta* information element within the 4G *MeasConfig* parameter structure. The timing of the Measurement Gap is advanced by 0.5 ms when MGTA is enabled. This provides support for configurations which require the Measurement Gap to extend 0.5 ms either side of the SS/PBCH Measurement Window

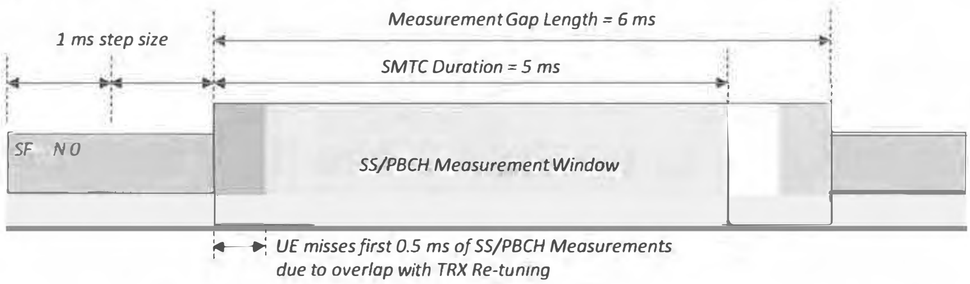


Figure 450 – Overlap of Transceiver Re-Tuning period and SS/PBCH Measurement Window

★ The *MeasObjectNR* starts by specifying the frequency of the NR carrier to be measured. This corresponds to the center frequency of the SS/PBCH rather than the center frequency of the channel bandwidth. The center frequency of the SS/PBCH is expressed in terms of an NR-ARFCN rather than a Global Synchronisation Channel Number (GSCN). This caters for SS/PBCH which may not be positioned on the GSCN frequency raster. SS/PBCH which are used for initial access from RRC Idle must be on the GSCN frequency raster because the UE only checks those frequencies when completing a band scan. However, SS/PBCH which are not used for initial access are not restricted to the GSCN frequency raster. These SS/PBCH can be positioned at any NR-ARFCN (while ensuring that subcarrier alignment is maintained between the SS/PBCH and the channel bandwidth)

★ The SMTC information is followed by a specification of the SS/PBCH subcarrier spacing. Values of 15 and 30 kHz are applicable to Frequency Range 1, whereas values of 120 and 240 kHz are applicable to Frequency Range 2. The 60 kHz subcarrier spacing is not applicable to the SS/PBCH. A bitmap is then used to specify which SS/PBCH Blocks are available for measurement. The bitmap has a length of 4 bits for operating bands ≤ 3 GHz because a maximum of 4 SS/PBCH Blocks can be configured for transmission. Similarly, the bitmap has a length of 8 bits for operating bands > 3 GHz but ≤ 6 GHz, and a length of 64 bits for operating bands > 6 GHz

★ Measurement based Secondary Cell Addition is likely to rely upon Reporting Event B1 which is triggered when an inter-system measurement exceeds a specific threshold. The measurement used to trigger Event B1 is a 'cell level' measurement rather than a 'beam level' measurement. If a cell is configured with multiple SS/PBCH beams then it is necessary to derive the 'cell level' measurement from one or more 'beam level' measurements. The UE derives the 'cell level' measurement using the *threshRS-Index* and *maxRS-IndexCellQual* information elements

★ If *maxRS-IndexCellQual* is not included within the Measurement Object, the UE sets the 'cell level' measurement equal to the highest 'beam level' measurement. Otherwise, the UE derives the 'cell level' measurement by calculating a linear average of the highest 'beam level' measurements which exceed *threshRS-Index*. The maximum number of 'beam level' measurements included in the average is defined by *maxRS-IndexCellQual*. If none of the beam level measurements exceed *threshRS-Index*, the 'cell level' measurement is set equal to the highest 'beam level' measurement

★ *offsetFreq* defines a measurement offset which is applied to the 'cell level' measurement when evaluating the Reporting Event criteria. A negative value makes it more difficult to trigger Event B1 because the measurement result is decreased by the offset

MeasObjectNR				
carrierFreq-r15	0 to 3279165			
rs-ConfigSSB-r15	measTimingConfig-r15 (SMTC)	periodicityAndOffset-r15	CHOICE	
			5 subframes	0 to 4
			10 subframes	0 to 9
			20 subframes	0 to 19
			40 subframes	0 to 39
			80 subframes	0 to 79
			160 subframes	0 to 159
		ssb-Duration-r15	1, 2, 3, 4, 5 subframes	
	subcarrierSpacingSSB-r15	15, 30, 120, 240 kHz		
	ssb-ToMeasure-r15	CHOICE		
		release	setup	
			CHOICE	
			shortBitmap-r15	BIT STRING { 4 bits }
			mediumBitmap-r15	BIT STRING { 8 bits }
			longBitmap-r15	BIT STRING { 64 bits }
threshRS-Index-r15	nr-RSRP-r15	0 to 127		
	nr-RSRQ-r15	0 to 127		
	nr-SINR-r15	0 to 127		
maxRS-IndexCellQual-r15	1 to 16			
offsetFreq-r15	-15 to 15 dB			
blackCellsToRemoveList-r15	SEQUENCE { 1 to 32 instances }			
	CellIndex	1 to 32		
blackCellsToAddModList-r15	SEQUENCE { 1 to 32 instances }			
	cellIndex-r15	1 to 32		
	physCellId-r15	0 to 1007		
quantityConfigSet-r15	1 to 2			
cellsForWhichToReportSFTD-r15	SEQUENCE { 1 to 3 instances }			
	physCellId-r15	0 to 1007		
cellForWhichToReportCGI-r15	physCellId-r15	0 to 1007		
deriveSSB-IndexFromCell-r15	BOOLEAN			
ss-RSSI-Measurement-r15	measurementSlots-r15	BIT STRING { 1 to 80 bits }		
	endSymbol-r15	0 to 3		
bandNR-r15	CHOICE			
	release	setup		
		FreqBandIndicatorNR-r15	1 to 1024	

Table 330 – *MeasObjectNR* parameter structure belonging to the 4G system

★ Up to 32 cells can be blacklisted and thus prevented from triggering the Measurement Reporting Event. These blacklisted cells are identified by their Physical layer Cell Identity (PCI)

★ The *quantityConfigSet* provides a pointer towards a set of layer 3 filter coefficients. These coefficients are used to filter the 'cell level' measurements prior to evaluating the Reporting Event criteria (layer 3 filtering is described in section 11.2)

★ The Base Station can use the Measurement Object to specify a set of cells for which the UE should report the SFN and Frame Timing Difference (SFTD) or the Cell Global Identity (CGI). The former can be used to determine the timing of the 5G air-interface, whereas the latter can be used for Automatic Neighbour Relations (ANR)

★ The *deriveSSB-IndexFromCell* flag indicates whether or not NR cells using the same SS/PBCH center frequency and subcarrier spacing are time aligned, i.e. the timing from one cell can be used to derive the SS/PBCH Block index belonging to another cell

★ *ss-RSSI-Measurement* is used to specify the slots and symbols which can be used for RSSI measurements. *measurementSlots* provides a bit string where each bit corresponds to a slot within the SS/PBCH Measurement Window defined by the SMTC. A '1' indicates that the slot can be used for RSSI measurements. *endSymbol* defines the symbols within the *measurementSlots* which can be used to measure the RSSI. The value of *endSymbol* is a pointer to a row within a 3GPP standardised look-up table (Table 241 in section 10.2)

- *bandNR-r15* specifies the operating band associated with the SS/PBCH measurements. This provides clarification of the operating band when operating bands overlap and share common NR-ARFCN values
- Assuming that the UE has been configured with Measurement Reporting Event B1, the UE will forward an RRC *Measurement Report* to the Base Station if the measurements exceed the Event BI triggering threshold. This *Measurement Report* will include the *measResultneighCellListNR* parameter structure shown in Table 331. The UE uses this parameter structure to report measurements from up to 8 NR cells which have satisfied the Event BI triggering criteria. Each cell is identified by its PCI
- The *measResultCell* field is used to report 'cell level' measurements in terms of RSRP, RSRQ and/or SINR. At this stage, the Base Station has already specified the requirement for each of these reporting quantities within the *RRC Connection Reconfiguration* message that was used to configure the measurements, i.e. using *reportQuantityCellNR* within *ReportConfigInterRAT*
- The *measResultRSIndexList* field is used to report 'beam level' measurements in terms of RSRP, RSRQ and/or SINR. The Base Station can enable/disable the inclusion of 'beam level' measurements using the *reportRS-IndexResultsNR* flag within *ReportConfigInterRAT*. When 'beam level' measurements are to be included, the Base Station specifies the reporting quantities using *reportQuantityRS-IndexNR*. Each beam is identified by its SS/PBCH Block index. 'Beam level' results are useful because they allow the target 5G Secondary Node to allocate dedicated PRACH preambles belonging to the reported beams. The UE can then use one of those dedicated PRACH preambles during the Secondary Cell Addition procedure, i.e. to avoid using the Contention based Random Access procedure
- The *cgi-Info* field is applicable to Automatic Neighbour Relations (ANR) rather than Secondary Cell Addition. This field allows the UE to report a Cell Global Identity (CGI) for a candidate neighbouring cell. The 4G Base Station can use this information to request the transport layer address belonging to the neighbouring 5G Base Station and subsequently initiate an X2 Setup procedure. The UE extracts the CGI from SIB1 so the ANR procedure relies upon the 5G cell broadcasting SIB1. In the case of the Non-Standalone Base Station architecture, the 5G cell may not broadcast any SIB meaning that the normal ANR procedure is not possible. The UE can use the *noSIB1* field to provide additional information when the SS/PBCH being measured does not have an associated SIB1 transmission
- A 5G cell can have multiple SS/PBCH transmissions distributed across the channel bandwidth. Some of these SS/PBCH may have an associated SIB1, whereas other SS/PBCH may not have an associated SIB1. If the UE is requested to report the CGI using an NR-ARFCN which corresponds to an SS/PBCH which does not have an associated SIB1, then the UE can report the *ssb-SubcarrierOffset* and *pdcch-ConfigSIB1* fields from the PBCH. These fields can be used to provide information regarding the frequency domain position of an SS/PBCH which has an associated SIB1 transmission. The 4G Base Station could then request the UE to repeat the CGI decoding attempt using a different NR-ARFCN

measResultNeighCellListNR-r15					
MeasResult CellListNR-r15	SEQUENCE { 1 to 8 instances }				
	pci-r15	0 to 1007			
	measResultCell-r15	rsrpResult-r15	0 to 127		
		rsrqResult-r15	0 to 127		
		rs-sinr-Result-r15	0 to 127		
	measResultRS-IndexList-r15	SEQUENCE { 1 to 32 instances }			
		ssb-Index-r15	0 to 63		
		measResultSSB-Index-r15	rsrpResult-r15	0 to 127	
			rsrqResult-r15	0 to 127	
			rs-sinr-Result-r15	0 to 127	
	cgi-Info-r15	plmn-IdentityInfoList-r15	SEQUENCE { 1 to 12 instances }		
			plmn-IdentityList-r15	SEQUENCE { 1 to 12 instances }	
				mcc	3 digits
				mnc	2 or 3 digits
			trackingAreaCode-r15	BIT STRING { 24 bits }	
			ran-AreaCode-r15	0 to 255	
			cellIdentity-r15	BIT STRING { 36 bits }	
		frequencyBandList-15	SEQUENCE { 1 to 32 instances }		
			FreqBandIndicatorNR-r15	1 to 1024	
		noSIB1-r15	ssb-SubcarrierOffset-r15	0 to 15	
			pdcch-ConfigSIB1-r15	0 to 255	

Table 331 – NR neighbour cell measurement results from an RRC *Measurement Report* message

- The top part of Figure 451 illustrates the RRC Connection Reconfiguration procedure used to configure the Event B1 measurements. The figure also shows the Measurement Report generated by the UE. The 4G Master Node starts the actual EN-DC Secondary Cell Addition procedure once the *Measurement Report* has been received (assuming the report has been triggered by a 5G cell which has an X2 connection with the 4G Master Node). The report will typically be triggered by a co-sited 5G cell

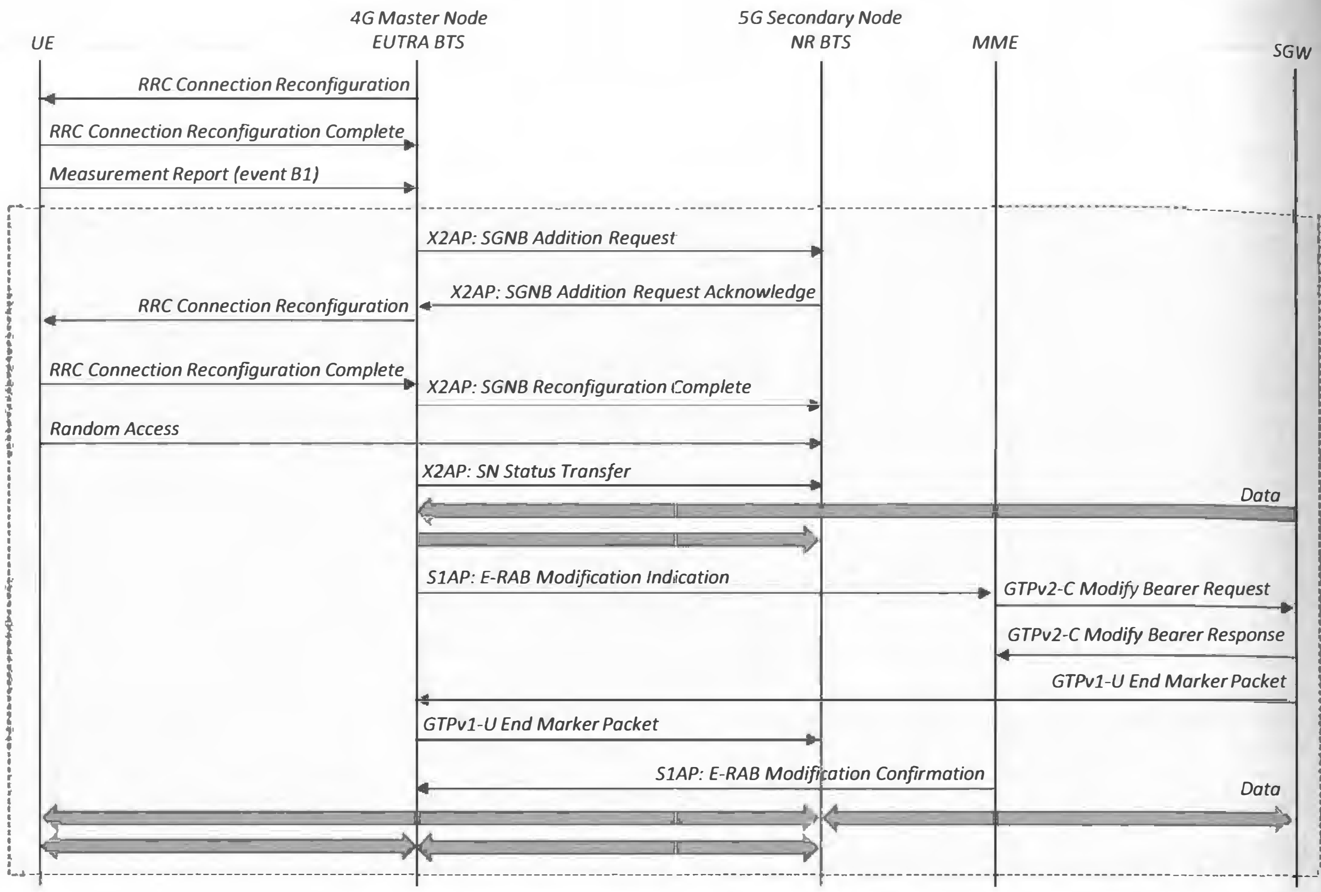


Figure 451 – EN-DC Secondary Cell Addition procedure

★ The content of the X2AP: *SGNB Addition Request* is presented in Table 332. The 4G Master Node allocates the 'MeNB UE X2AP Identity' to allow the Master Node to identify the UE within X2AP signalling procedures. The 'NR UE Security Capabilities' provides the 5G Secondary Node with information regarding the ciphering and integrity protection algorithms supported by the UE. This information is extracted from the S1AP: *Initial Context Setup Request* provided by the MME. The 'SgNB Security Key' is used to derive the keys for the ciphering and integrity protection algorithms at the 5G Secondary Node

★ The 'SgNB UE Aggregate Maximum Bit Rate' is based upon the 'UE Aggregate Maximum Bit Rate' provided by the MME within the S1AP: *Initial Context Setup Request*. The 4G Master Node is responsible for managing the allocated values across the Master and Secondary Nodes. The 'Selected PLMN' can be used to specify the identity of the PLMN to be used at the Secondary Node. The 'Handover Restriction List' is based upon the corresponding field within the S1AP: *Initial Context Setup Request*

★ The 'E-RAB to be Added List' is a relatively large field which provides the information necessary for the 5G Secondary Node to setup each E-RAB and the associated Data Radio Bearers (DRB). This field provides the 5G Secondary Node with the Serving Gateway (SGW) transport layer address and GTP Tunnel Endpoint Identity (TEID) for transferring uplink data across the S1-U interface. It also provides the 5G Secondary Node with the 4G Master Node transport layer address and GTP TEID for transferring downlink data across the X2-U interface

Information Elements	Presence
MeNB UE X2AP Identity	Mandatory
NR UE Security Capabilities	Mandatory
SgNB Security Key	Mandatory
SgNB UE Aggregate Maximum Bit Rate	Mandatory
Selected PLMN	Optional
Handover Restriction List	Optional
E-RAB to be Added List	Mandatory
MeNB to SgNB Container (*CG-ConfigInfo*)	Mandatory
SgNB UE X2AP Identity	Optional
Expected UE Behaviour	Optional

Information Elements	Presence
MeNB UE X2AP ID Extension	Optional
Requested Split SRBs	Optional
MeNB Resource Coordination Information	Optional
SGNB Addition Trigger Indication	Optional
Subscriber Profile Identity (SPID)	Optional
MeNB Cell Identity	Mandatory
Desired Activity Notification Level	Optional
Trace Activation	Optional
Location Information at SgNB Reporting	Optional
Masked IMEISV	Optional

Table 332 – Content of X2 Application Protocol (X2AP) *SGNB Addition Request*

★ The 'MeNB to SgNB Container' is used to encapsulate the *CG-ConfigInfo* message belonging to the 5G RRC signalling protocol. This message provides the 5G Secondary Node with the UE capability. It also specifies one or more candidate 5G cells to be targeted by the EN-DC Secondary Cell addition. Measurements can be included if they have been received from the UE. Permitted EN-DC band combinations can also be specified with feature sets listed for each combination

★ The 'SgNB UE X2AP Identity' is allocated by the 5G Secondary Node but it can be included within the X2AP: *SGNB Addition Request* it if has already been allocated during a previous signalling procedure

★ The 'Expected UE Behaviour' can be used to provide information regarding the expected UE activity and mobility. This information can be used to help determine an optimal RRC Connection duration. The expected activity information can include an expected activity period and an expected idle period. This information can originate from previous measurements, or it can be based upon subscription information. The expected mobility is specified in terms of an expected handover interval

★ The 'MeNB UE X2AP ID Extension' can be used to increase the range of values associated with the 'MeNB UE X2AP Identity'. This may be necessary if there is a requirement to support a large number of UE associated signalling connections across the X2 interface. Each information element supports a range from 0 to 4095. The extension is used in combination with the original identity so the range increases from {0 to 4095} to {0 to 16 777 216}

★ The 'Requested Split SRBs' field is used to specify that SRB 1 and SRB 2 are to be split between the 4G Master Node and 5G Secondary Node, i.e. SRB messages from the 4G Master Node will be forwarded across the X2 interface to the 5G Secondary Node. It is possible to specify that SRB 1 will be split, or SRB 2 will be split, or both SRB 1 and SRB 2 will be split

★ The 'MeNB Resource Coordination Information' can be used to support the coordination of air-interface resources between the 4G Master Node and 5G Secondary Node. This is applicable to Dynamic Spectrum Sharing scenarios. The 4G Master Node uses a bitmap to specify which Resource Blocks within specific subframes it would like to use

★ The 'SGNB Addition Trigger Indication' can be used to indicate the reason for the Secondary Cell Addition procedure. The reason can be specified as 'Secondary Node Change', 'inter-eNode B Handover' or 'intra-eNode B Handover'

★ The 'Subscriber Profile Identity (SPID)' provided by the MME can also be forwarded to the 5G Secondary Node. This may be used to influence mobility procedures at the Secondary Node

★ The 'MeNB Cell Identity' specifies the identity of the primary serving cell within the 4G Master Node

★ The 'Desired Activation Notification Level' can be used to request the 5G Secondary Node to forward X2AP: *SGNB Activity Notification* messages providing either 'UE level' information or 'E-RAB level' information

★ 'Trace Activation' can be used to enable logging at the 5G Secondary Node. The 'Trace Activation' field can specify the interfaces to be logged. These include the X2, Uu, F1-C and E1 interfaces

★ The 'Location Information at SgNB Reporting' field can be used to request the 5G Secondary Node to report the UE location. The UE location can be reported in terms of its cell identity and an update can be provided when the UE changes serving cell

★ The 'Masked IMEISV' can be used to identify a UE model, without identifying the individual UE. The MME can provide this information to the 4G Master Node within the S1AP: *Initial Context Setup Request*. The 5G Secondary Node can use this information if there is a requirement to apply specific rules to some UE models. The 'Masked IMEISV' has the last 4 digits of the Serial Number (SNR) set to 1 to avoid exposing the full UE identity

★ Returning to Figure 451, the 5G Secondary Node responds with an X2AP: *SGNB Addition Request Acknowledge*. The content of this message is presented in Table 333. The 5G Secondary Node provides a list of the E-RAB which have been admitted. This field specifies the transport layer address and GTP Tunnel Endpoint Identity (TEID) for transferring downlink data across the S1-U interface towards the 5G Secondary Node. It also specifies the 5G Secondary Node transport layer address and GTP TEID for transferring uplink data across the X2-U interface, i.e. to allow the 4G Master Node to forward uplink data so it can be sent to the S-GW

★ The 5G Secondary Node can also list any E-RAB which have not been admitted. In this case, the E-RAB identity is specified in combination with a cause value

Information Elements	Presence	Information Elements	Presence
MeNB UE X2AP Identity	Mandatory	MeNB UE X2AP ID Extension	Optional
SgNB UE X2AP Identity	Mandatory	Admitted Split SRBs	Optional
E-RAB Admitted	Mandatory	SgNB Resource Coordination Information	Optional
E-RAB Not Admitted	Optional	RRC Config Indication	Optional
SgNB to MeNB Container (*CG-Config*)	Mandatory	Location Information at SgNB	Optional

Table 333 – Content of X2 Application Protocol (X2AP) *SGNB Addition Request Acknowledge*

★ The 'SgNB to MeNB Container' is used to encapsulate the *CG-Config* message belonging to the 5G RRC signalling protocol. The *CG-Config* message encapsulates:

- o the 5G *RRCReconfiguration* which is to be forwarded to the UE. This message provides all of the information that the UE requires to access the 5G cell. The target Physical layer Cell Identity (PCI) is specified in combination within the ARFCN belonging to the SS/PBCH Blocks. Information is provided to allow the UE to complete either a Contention Based or Contention Free Random

Access procedure. Uplink and downlink Bandwidth Part information is provided to allow use of the PUSCH and PDSCH. Details of the PUCCH and PDCCH are also provided. The UE can also be configured to transmit the SRS and receive the CSI Reference Signal

- the 5G *RadioBearerConfig* parameter structure which is also forwarded to the UE. This parameter structure configures the PDCP layer for the Data Radio Bearer(s) being added at the 5G Secondary Node. This includes security configuration information as well as the PDCP discard timer and Sequence Number sizes

★ The 4G Master Node sends an *RRC Connection Reconfiguration* message to the UE which encapsulates both the 5G *RRCReconfiguration* message and the 5G *RadioBearerConfig* parameter structure. Figure 452 illustrates the encapsulation of this 5G content within the X2AP and 4G RRC messages

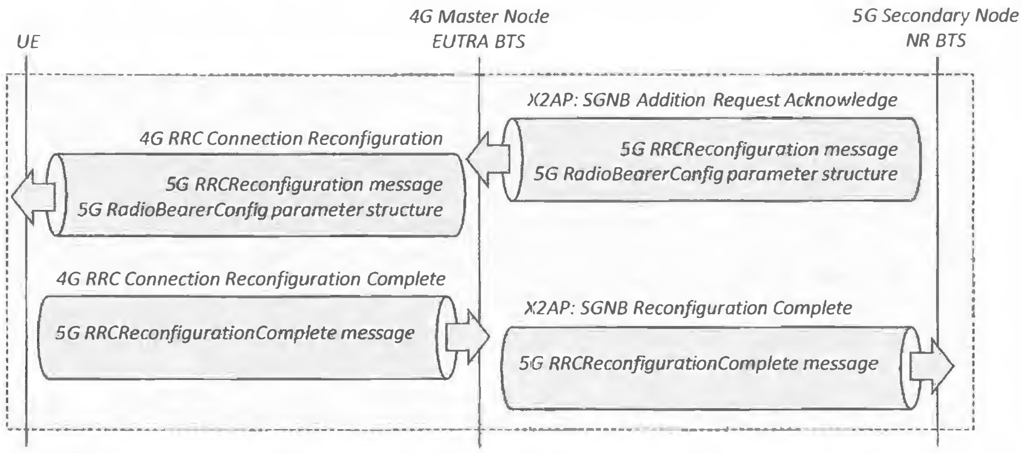


Figure 452 – 5G RRC content encapsulated within X2AP and 4G RRC messages

★ The UE responds to the 4G Master Node with a 4G *RRC Connection Reconfiguration Complete* message, which encapsulates a 5G *RRCReconfigurationComplete* message. This pair of messages allows the reconfiguration procedure to be acknowledged at both the 4G Master Node and the 5G Secondary Node. The 5G message is forwarded towards the 5G Master Node using the X2AP: *SGNG Reconfiguration Complete*

★ The UE can then proceed to complete the Random Access procedure with the target 5G cell. The Random Access procedure is described in section 13.1

★ In parallel, the 4G Master Node forwards the X2AP: *SN Status Transfer* message to the 5G Secondary Node. The content of this message is presented in Table 334. It is used to provide the 5G Secondary Node with information regarding the Sequence Number status at the PDCP layer. The 'UL COUNT' value specifies the Sequence Number of the first missing uplink SDU, whereas the 'DL COUNT' value specifies the next Sequence Number to be allocated to a downlink SDU. The 'Receive Status of UL PDCP SDU' can be used to provide a bitmap where each '0' corresponds to a missing PDCP SDU and the bit position corresponds to a Sequence Number which follows the first missing uplink SDU

Information Elements			Presence
Old eNB UE X2AP Identity			Mandatory
New eNB UE X2AP Identity			Mandatory
E-RAB Subject to Status Transfer List	E-RAB Identity		Mandatory
	Receive Status of UL PDCP SDU		Optional
	UL COUNT Value	PDCP-SN	Mandatory
		HFN	Mandatory
	DL COUNT Value	PDCP-SN	Mandatory
		HFN	Mandatory
Old eNB UE X2AP ID Extension			Optional
New eNB UE X2AP ID Extension			Optional
SgNB UE X2AP ID			Optional

Table 334 – Content of X2 Application Protocol (X2AP) *SN Status Transfer*

★ At this point, the 4G Master Node is still receiving downlink data from the Serving Gateway but this data is now forwarded across the X2 interface towards the 5G Master Node. The 5G Master Node is then able to use the NR air-interface to transfer the downlink data towards the UE

★ The 4G Master Node then initiates the signalling which is used to move the S1-U connection from the 4G Master Node to the 5G Secondary Node. This is done by sending an S1AP: *E-RAB Modification Indication* to the MME. The content of this message is presented in Table 335. The 'E-RAB to be Modified List' provides the Transport Layer Address and Downlink GTP TEID provided by the 5G Secondary Node within the X2AP: *SGNB Addition Request Acknowledge*

Information Elements		Presence
MME UE S1AP Identity		Mandatory
eNB UE S1AP Identity		Mandatory
E-RAB to be Modified List	E-RAB ID	Mandatory
	Transport Layer Address	Mandatory
	DL GTP TEID	Mandatory
E-RAB not to be Modified List	E-RAB ID	Mandatory
	Transport Layer Address	Mandatory
	DL GTP TEID	Mandatory
CSG Membership Info		Optional
Tunnel Information for BBF		Optional
Secondary RAT Usage Report List		Optional

Table 335 – Content of S1 Application Protocol (S1AP) *E-RAB Modification Indication*

★ The MME forwards the new downlink Transport Layer Address and GTP TEID to the Serving Gateway using a GTPv2-C: *Modify Bearer Request*. The Serving Gateway acknowledges the request using a GTPv2-C: *Modify Bearer Response*. These GTPv2-C messages are specified within 3GPP TS 29.274

★ The Serving Gateway sends a GTPv1-U: *End Marker* packet to the 4G Master Node after stopping the downlink packet flow towards the 4G Master Node. This packet is then forwarded across the X2 interface towards the 5G Secondary Node. The *End Marker* packet identifies the point at which the packet flow is switched across to the new S1-U connection towards the 5G Secondary Node. This information is used to support the re-ordering process at the 5G Secondary Node. The *End Marker* packet is specified within 3GPP TS 29.281

★ The Serving Gateway subsequently forwards all downlink data towards the 5G Secondary Node. The PDCP layer within the 5G Secondary Node can forward the downlink data for transmission across the 5G air-interface. Alternatively, the PDCP layer can forward the downlink data across the X2 interface towards the 4G Master Node. In that case, the 4G Master Node becomes responsible for delivering the downlink data using the 4G air-interface. The algorithm used to select the downlink data path is dependent upon the network implementation. It may be driven by downlink coverage conditions, i.e. data is transferred across the 4G air-interface when the 5G coverage becomes relatively poor. Alternatively, it may be driven by downlink buffer occupancy, i.e. data is transferred across the 4G air-interface if the 5G Secondary Node transmit buffers become relatively full. This could be caused by downlink coverage conditions or air-interface congestion

★ Assuming that the UE is configured with uplink RLC entities for both the 4G Master Node and the 5G Secondary Node, the UE can be configured with the *ul-DataSplitThreshold* presented in Table 336 (provided to the UE within the 5G *RadioBearerConfig* parameter structure illustrated in Figure 452). This information element belongs to the *PDCP-Config* parameter structure, i.e. the PDCP layer within the UE is responsible for splitting uplink data between the two paths. A default value of 'infinity' is assumed if the *ul-DataSplitThreshold* is excluded. The value of 'infinity' means that only the primary RLC entity is used for transmission so the uplink data is not split. The primary RLC entity is identified by the *primaryPath* information element which points towards a specific cell group. Otherwise, the UE is permitted to split the stream of uplink packets between the primary and secondary RLC entities when the total PDCP and RLC data volume pending initial transmission exceeds the value of *ul-DataSplitThreshold*

extract from *PDCP-Config*			
moreThanOneRLC	primaryPath	cellGroup	0 to 3
		logicalChannel	1 to 32
	ul-DataSplitThreshold	0, 100, 200, 400, 800, 1600, 3200, 6400, 12800, 25600, 51200, 102400, 204800, 409600, b819200, b1228800, 1638400, 2457600, 3276800, 4096000, 4915200, 5734400, 6553600 bytes, infinity	
	pdcp-Duplication	BOOLEAN	

Table 336 – Data Volume Threshold for splitting uplink data

★ 3GPP References: TS 36.331, TS 38.331, TS 36.413, TS 36.423, TS 29.274, TS 29.281. TS 37.340

15.3 RRC CONNECTION SETUP

★ The RRC Connection Setup procedure is used to make the transition from RRC Idle mode to RRC Connected mode. The UE must make this transition before transferring any application data, or completing any signalling procedures

★ The RRC Connection Setup procedure is always initiated by the UE but can be triggered by either the UE or the network. For example, the UE triggers RRC Connection Setup if the end-user starts an application to browse the internet, or to send an email. Similarly, the UE triggers RRC Connection Setup if the UE moves into a new Tracking Area and has to complete a Tracking Area Update. The network triggers the RRC Connection Setup procedure by sending a Paging message. This could be used to allow the delivery of an incoming SMS or notification of an incoming voice call

★ The RRC Connection Setup procedure configures Signalling Radio Bearer (SRB) 1 and allows subsequent signalling to use the Dedicated Control Channel (DCCH) rather than the Common Control Channel (CCCH) used by SRB 0. The initial Non-Access Stratum (NAS) message is transferred to the Base Station as part of the RRC Connection Setup procedure. The Base Station subsequently forwards this message to the AMF

★ The signalling for the RRC Connection Setup procedure is shown in Figure 453. It is based upon a 3-way handshake between the UE and Base Station. This figure also illustrates the initial NAS message being forwarded to the AMF

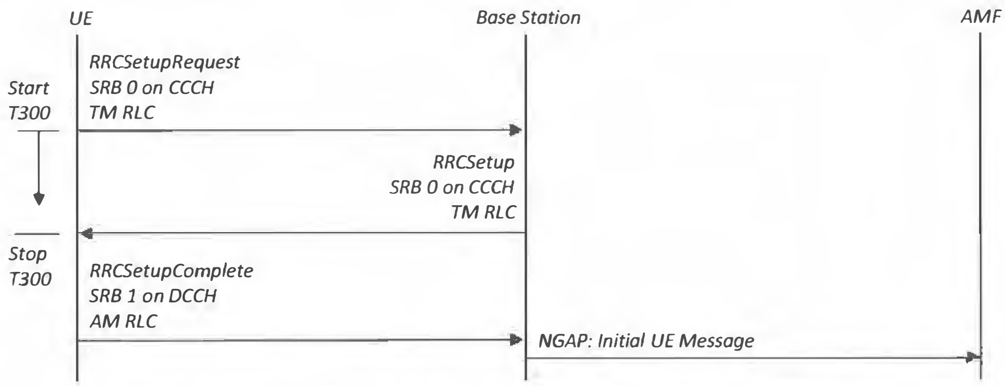


Figure 453 – RRC Connection Setup signalling procedure (classical Base Station architecture)

★ The *RRCSetupRequest* is sent on the PUSCH as MSG3 during the contention based Random Access procedure (shown in Figure 360, section 13.1.1). It is transferred using SRB 0 on the Common Control Channel (CCCH) because SRB 1 has not been established at this stage. The Resource Block allocation for the *RRCSetupRequest* is provided within the Random Access Response message (MSG2)

★ The content of the *RRCSetupRequest* is shown in Table 337. It includes a UE identity and an establishment cause. There is no scope for the UE to report any measurements within the *RRCSetupRequest*. In contrast, the UMTS (3G) version of the *RRCConnectionRequest* allows the UE to report CPICH measurements which can be used for open loop power control calculations

<table>
<tr><th colspan="3">RRCSetupRequest</th></tr>
<tr><td rowspan="3">ue-Identity</td><td colspan="2">CHOICE</td></tr>
<tr><td>ng-5G-S-TMSI-Part1</td><td>randomValue</td></tr>
<tr><td>BIT STRING {39 bits}</td><td>BIT STRING {39 bits}</td></tr>
<tr><td>establishmentCause</td><td colspan="2">emergency, highPriorityAccess, mt-Access, mo-Signalling, mo-Data, mo-VoiceCall, mo-VideoCall, mo-SMS, mps-PriorityAccess, mcs-PriorityAccess</td></tr>
</table>

Table 337 – *RRCSetupRequest* message

★ The content of the *RRCSetupRequest* has been carefully specified to limit the message size to 48 bits. In general, it is important for MSG3 to be small because it cannot be segmented, i.e. it is transferred using Transparent Mode RLC which does not support segmentation. The payload illustrated in Table 337 indicates a message size of 39 bits for the UE identity plus 4 bits for the establishment cause (there are 10 cause values which can be encoded using 4 bits). This generates a total of 43 bits. 3GPP TS 38.331 also specifies 1 'spare' bit within the payload which is not shown in Table 337. In addition, it is necessary to include 1 bit to signal the choice between the two types of UE identity. Similarly, it is necessary to include 2 bits to signal the choice between four potential CCCH messages: {*RRCSetupRequest*, *RRCResumeRequest*, *RRCReestablishmentRequest*, *RRCSystemInfoRequest*}. Finally, 1 bit is included to signal the choice between the existing set of four CCCH messages and a message extension which can be used to introduce new messages in the future

★ The UE adds an 8 bit MAC header to the *RRCSetupRequest* so the total message size is 48 + 8 = 56 bits. It should be noted that this corresponds to the smallest value that can be configured for *ra-Msg3SizeGroupA*. This means that the UE always selects a 'Group A' PRACH preamble when sending an *RRCSetupRequest* (this statement is applicable when the Base Station configures 'Group A' and 'Group B' PRACH preambles, otherwise the message size does not impact the preamble selection procedure)

★ If the UE has already registered with the 5G Core Network using a previous RRC Connection, and the AMF has already allocated a 5G-S-TMSI then the UE identity within the *RRCSetupRequest* can be signalled using the 39 least significant bits from the 5G-S-TMSI (the structure of the 5G-S-TMSI is presented in section 18.5. It has a total size of 48 bits). The 39 least significant bits include the 5G-TMSI, the AMF Pointer and 1 bit from the AMF Set Identity. The complete 5G-S-TMSI is not included within the *RRCSetupRequest* because it would make the message size too large. The set of 39 bits are sufficient to minimise the probability of multiple UE using the same UE identity. The remaining 9 bits can be included within the *RRCSetupComplete* message. Otherwise, the UE populates the UE identity field with a random number within the range 0 to 2^{39}-1

★ The establishment cause within the *RRCSetupRequest* is selected using a mapping which is based upon the combination of Access Identity and Access Category. Table 339 presents this mapping for a New Radio (NR) Base Station connected to the 5G Core Network. 3GPP TS 24.501 specifies a second mapping for an EUTRA Base Station connected to the 5G Core Network

Access Identity	Access Category	RRC Establishment Cause
0	0 (= MT access)	mt-Access
	1 (= delay tolerant)	*not applicable* *
	2 (= emergency)	emergency
	3 (= MO signalling)	mo-Signalling
	4 (= MO MMTel voice)	mo-VoiceCall
	5 (= MO MMTel video)	mo-VideoCall
	6 (= MO SMS and SMSoIP)	mo-SMS
	7 (= MO data)	mo-Data
1	any category	mps-PriorityAccess
2		mcs-PriorityAccess
11, 15		highPriorityAccess
12, 13, 14		

* UE selects a second Access Category within the range 3 to 7 that is used to identify the RRC Establishment cause

Table 338 – Mapping from Access Identity and Access Category to RRC Establishment Cause (NR connected to 5G CN)

★ The UE starts the T300 timer after transmitting the *RRCSetupRequest*. The value of T300 is broadcast within SIB 1. The RRC Connection Setup procedure fails if T300 expires before the UE receives the *RRCSetup* message. The RRC layer does not support re-transmissions of MSG3 within a specific connection setup attempt. However, HARQ re-transmissions of MSG3 can be triggered at the MAC layer while T300 is running. The Base Station triggers HARQ re-transmissions of MSG3 using DCI Format 0_0 to provide a new uplink resource allocation on the PUSCH. The CRC bits belonging to the DCI are scrambled using the Temporary C-RNTI. The Contention Resolution timer is re-started after a HARQ re-transmission of MSG3, but T300 is not re-started

★ Random access contention can occur after sending the *RRCSetupRequest*. Contention occurs when multiple UE select the same PRACH occasion and the same PRACH preamble. Contention requires the UE to repeat transmission of the PRACH preamble and the subsequent *RRCSetupRequest*. This increases the delay associated with connection establishment but does not cause the overall procedure to fail unless the maximum number of preamble transmissions has been reached

★ The Base Station can multiplex the *RRCSetup* message within the same PDSCH transmission as the 'UE Contention Resolution Identity' MAC Control Element. The *RRCSetup* message is transferred using SRB 0 on the downlink CCCH. The *RRCSetup* message provides configuration information for SRB 1. This allows subsequent signalling to use the Dedicated Control Channel (DCCH). SRB 2 is always configured after security activation so the *RRCSetup* message does not include any information regarding SRB 2

★ Table 339 presents the high level content of the *RRCSetup* message. The message is divided into two main sections: Radio Bearer configuration and Master Cell Group configuration. The Radio Bearer configuration provides information regarding the PDCP layer, whereas the Master Cell Group configuration provides information regarding the RLC, MAC and Physical layers. This structure is particularly useful when using the Centralised Unit (CU) – Distributed Unit (DU) split Base Station architecture because it allows the CU to generate the Radio Bearer configuration and the DU to generate the Master Cell Group configuration

★ The RLC layer configuration links a logical channel identity to the SRB identity. It also provides the RLC configuration (only shown as *rlc-Config* within Table 339). The RLC configuration specifies the set of Acknowledged Mode RLC parameters for SRB 1, e.g. uplink and downlink Sequence Number lengths, maximum number of re-transmissions, re-assembly timer and Status Report polling configuration. The *mac-LogicalChannelConfig* provides uplink prioritisation information to ensure that SRB 1 is prioritised appropriately relative to other logical channels

★ The MAC layer information can be used to configure Discontinuous Reception (DRX), Scheduling Requests, Buffer Status Reporting (BSR), Timing Advance Groups (TAG) and Power Headroom (PHR) reporting. The Physical layer configuration can be used to provide information regarding HARQ acknowledgements and power control. It can also be used to allocate RNTI values (other than the C-RNTI which has already been allocated during the Random Access procedure)

★ The Master Cell Group configuration also provides the Special Cell (spCell) parameter set which includes the *spCellConfigDedicated* parameter structure. This relatively large parameter structure configures the PDCCH, PDSCH and PUSCH in combination with other parameters linked to the serving cell

RRCSetup						
radioBearerConfig	srb-ToAddModList	SEQUENCE {1 to 2 instances}				
		srb-Identity	1 to 3			
		pdcp-Config	t-Reordering	0, 1, 2, 3, 4, 5, 8, 10, 15, 20, 30, 40, …, 2750 ms		
masterCellGroup	cellGroupId	0 to 3				
	rlc-BearerToAddModList	SEQUENCE {1 to 32 instances}				
		logicalChannelIdentity	1 to 32			
		servedRadioBearer	CHOICE			
			srb-Identity	1 to 3	drb-Identity	1 to 32
		rlc-Config				
		mac-LogicalChannelConfig				
	mac-CellGroupConfig	drx-Config				
		schedulingRequestConfig				
		bsr-Config				
		tag-Config				
		phr-Config				
	physicalCellGroup Config	harq-ACK-SpatialBundlingPUCCH	true			
		harq-ACK-SpatialBundlingPUSCH	true			
		p-NR-FR1	-30 to 33 dBm			
		pdsch-HARQ-ACK-Codebook	semiStatic, dynamic			
		tpc-SRS-RNTI, tpc-PUCCH-RNTI, tpc-PUSCH-RNTI, sp-CSI-RNTI, cs-RNTI, mcs-C-RNTI,				
		p-UE-FR1	-30 to 33 dBm			
		xScale	0, 6 dB			
	spCellConfig	servCellIndex	0 to 31			
		rlf-TimersAndConstants				
		rlmInSyncOutOfSyncThreshold				
		spCellConfigDedicated				

Table 339 – *RRCSetup* message (high level content)

★ Upon receiving the *RRCSetup* message, the UE stops the T300 timer and makes the transition to RRC Connected mode. The UE then requires an uplink resource allocation to transmit the *RRCSetupComplete* message on the PUSCH. This requires the UE to send a Scheduling Request unless the Base Station provides a proactive grant. After receiving the uplink resource allocation on the PDCCH, the UE is able to transmit the *RRCSetupComplete*. The content of the *RRCSetupComplete* is shown in Table 340

RRCSetupComplete			
selectedPLMN-Identity	1 to 12		
registeredAMF	plmn-Identity	mcc	3 digits
		mnc	2 or 3 digits
	amf-Identifier	BIT STRING {24 bits}	
guami-Type	native, mapped		
s-NSSAI-List	SEQUENCE {1 to 8 instances}		
	S-NSSAI	sst	BIT STRING {8 bits}
		sst-SD	BIT STRING {32 bits}
dedicatedNAS-Message	OCTET STRING		
ng-5G-S-TMSI-Value	CHOICE		
	ng-5G-S-TMSI	ng-5G-S-TMSI-Part2	
	BIT STRING {48 bits}	BIT STRING {9 bits}	

Table 340 – *RRCSetupComplete* message

★ The selected PLMN identity defines a pointer to a PLMN listed within SIB1, i.e. the UE selects a PLMN for its connection request when a cell belongs to more than a single PLMN

- The registered AMF field is optional, and is included after a UE has registered. The AMF is identified using its Globally Unique AMF Identifier (GUAMI). The GUAMI is a combination of the PLMN identity and the AMF Identifier. The AMF Identifier is a concatenation of the AMF Region Identity, the AMF Set Identity and the AMF Pointer
- The GUAMI type field indicates whether the GUAMI is native (derived from the 5G-GUTI previously allocated to the UE), or mapped (derived from an EPS GUTI allocated by the 4G Core Network). A mapped GUAMI allows information to be retrieved from the MME
- The Single Network Slice Selection Assistance Information (S-NSSAI) allows the UE to request a specific set of Network Slices. Each Network Slice is specified in terms of its Slice/Service Type (SST) and Slice Differentiator (SD). The UE is permitted to request up to 8 Network Slices
- Inclusion of the registered AMF and the requested Network Slices helps the Base Station to select an appropriate AMF for the UE's signalling connection towards the 5G Core Network
- The UE also includes its initial Non-Access Stratum (NAS) message within the *RRCSetupComplete*. NAS messages are specified within 3GPP TS 24.501. Example initial NAS messages include Registration Request, De-registration Request and Service Request
- The final part of the *RRCSetupComplete* provides the 9 Most Significant Bits belonging to the 5G-S-TMSI (the 39 Least Significant Bits were already provided within the *RRCSetupRequest* (assuming a 5G-S-TMSI has already been allocated to the UE). The *RRCSetupComplete* also supports the inclusion of a complete 5G-S-TMSI but this option is not used if the UE has sent an *RRCSetupRequest* (it can be used if the UE has received an *RRCSetup* in response to a *RRCResumeRequest*)
- The Base Station extracts the NAS message from the *RRCSetupComplete* and forwards it to the appropriate AMF using the NG Application Protocol (NGAP) *Initial UE Message*. Forwarding this message does not form part of the RRC Connection Setup procedure but is described in this section for completeness. The content of the NGAP *Initial UE Message* is shown in Table 341
- The Base Station allocates the 'RAN UE NGAP Identity' to allow the Base Station to identify the UE within NGAP signalling procedures. The 'AMF UE NGAP Identity' (not included within the *Initial UE Message*) allows the AMF to identify the UE within NGAP signalling procedures
- The 'User Location Information' specifies the location of the UE in terms of Cell Global Identity (CGI) and Tracking Area Identity (TAI). The 'RRC Establishment Cause' is set equal to the cause value within the *RRCSetupRequest*

Information Elements	Presence
RAN UE NGAP Identity	Mandatory
NAS PDU	Mandatory
User Location Information	Mandatory
RRC Establishment Cause	Mandatory
5G-S-TMSI	Optional
AMF Set Identity	Optional
UE Context Request	Optional
Allowed NSSAI	Optional

Table 341 – Content of NG Application Protocol (NGAP) *Initial UE Message*

- The 'AMF Set Identity' is included if the NGAP: *Initial UE Message* has been re-routed. The AMF selected by the Base Station may determine that it cannot support the UE, e.g. due to not supporting the set of requested Network Slices. In this case, the AMF may forward the initial NAS message directly to another AMF. Alternatively, the AMF can return the initial NAS message to the Base Station within an NGAP: *Reroute NAS Request*. This message provides the Base Station with a new target AMF Set Identity and a corresponding set of Allowed NSSAI (which are then also included within the NGAP: *Initial UE Message* when it is re-routed)
- The NGAP: *Initial UE Message* can also include a 'UE Context Request' flag to indicate that the Base Station would like the AMF to start the Initial Context Setup procedure
- Figure 454 illustrates the signalling associated with the RRC Connection Setup procedure when the Base Station rejects the *RRCSetupRequest*. The reject message is returned to the UE using SRB 0 on the CCCH logical channel. The Base Station may reject the connection establishment request as a result of congestion

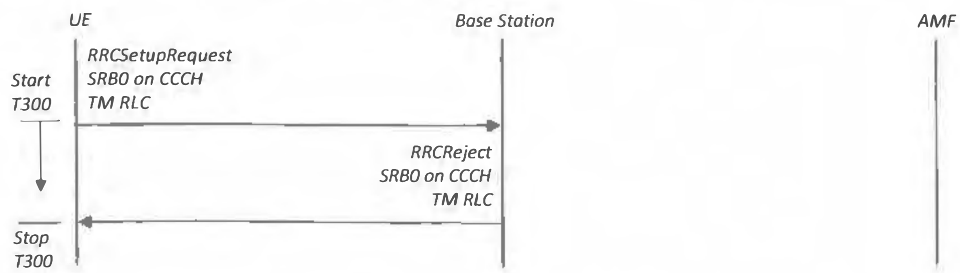


Figure 454 – Signalling associated with *RRCReject* message

★ The content of the *RRCReject* message is presented in Table 342. Inclusion of the *waitTime* is optional so the Base Station may send an empty message. If the *waitTime* is included, the UE starts timer T302 with its expiry value set equal to the *waitTime*. With the exception of Access Categories 0 and 2, all connection attempts are access barred until T302 expires. Access Categories 0 and 2 correspond to mobile terminated access and emergency access respectively. In the case of mobile terminated access, the network is responsible for controlling access by preventing the transmission of paging messages if necessary. T302 is stopped if the UE completes cell reselection so in that case, the UE is permitted to attempt an RRC Connection Setup with the new serving cell

RRCReject	
waitTime	1 to 16 seconds

Table 342 – *RRCReject* message

★ Figure 455 illustrates the RRC Connection Setup procedure assuming a Centralised Unit (CU) – Distributed Unit (DU) split Base Station architecture. This architecture requires F1 Application Protocol (F1AP) signalling between the CU and DU

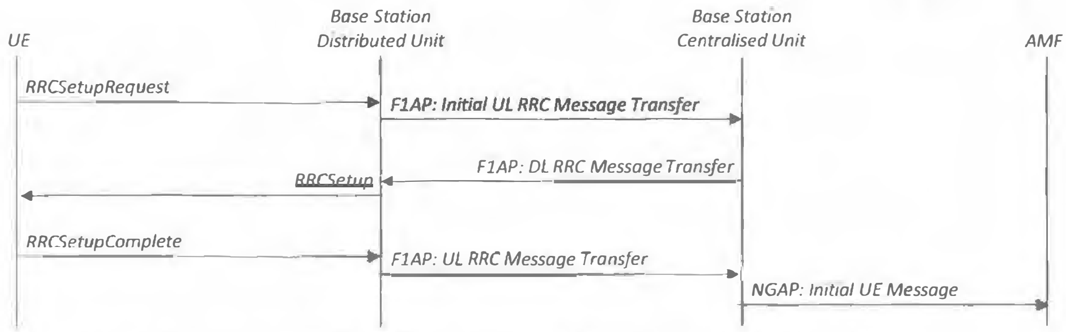


Figure 455 – RRC Connection Setup signalling procedure (CU-DU Split Base Station architecture)

★ The *RRCSetupRequest* is forwarded to the CU using an F1AP: *Initial UL RRC Message Transfer*. This F1AP message is shown in Table 343. The DU allocates the 'gNB-DU UE F1AP Identity' to allow the DU to identify the UE within subsequent F1AP signalling messages. The Cell Global Identity (CGI) is included to allow the CU to forward it to the AMF within the NGAP: *Initial UE Message* (part of the 'User Location Information'). The DU also specifies the C-RNTI which has been allocated to the UE during the Random Access procedure

Information Elements	Presence
gNB-DU UE F1AP Identity	Mandatory
NR CGI	Mandatory
C-RNTI	Mandatory
RRC Container	Mandatory
DU to CU RRC Container	Optional
SUL Access Indication	Optional
Transaction Identity	Mandatory

Table 343 – Content of F1 Application Protocol (F1AP) *Initial UL RRC Message Transfer*

★ The 'RRC Container' encapsulates the *RRCSetupRequest* received from the UE. The 'DU to CU RRC Container' provides the CU with the *CellGroupConfig* parameter structure which the CU subsequently uses to generate the *masterCellGroup* section of the *RRCSetup* message, i.e. the CU hosts the RRC layer and is responsible for generating the *RRCSetup* message but some of the content originates from the DU

★ The 'SUL Access Indication' is used as a flag to specify that the UE has accessed the cell using a Supplemental Uplink carrier

★ The 'Transaction Identity' is used to differentiate between all ongoing parallel procedures of the same type

★ The F1AP: *DL RRC Message Transfer* includes the 'gNB-DU UE F1AP Identity' allocated by the DU, and also a 'gNB-CU UE F1AP Identity' allocated by the CU. The F1AP message also specifies the SRB associated with the encapsulated RRC message. In the case of the *RRCSetup*, this is always SRB 0. The DU can use this information to generate the MAC header which includes the Logical Channel Identity (LCID). The F1AP message can also request the DU to provide an RRC Delivery Status report for the downlink transmission. The F1AP: *RRC Delivery Report* provides the highest in-sequence successfully delivered PDCP Sequence Number in combination with the PDCP Sequence Number of the downlink RRC message for which the report is generated

★ The F1AP: *UL RRC Message Transfer* includes the SRB Identity and the encapsulated RRC message. It does not include any other fields except for the 'gNB-DU UE F1AP Identity' allocated by the DU, and the 'gNB-CU UE F1AP Identity' allocated by the CU

★ 3GPP References: TS 38.331, TS 38.413, TS 38.473, TS 24.501, TS 23.501, TS 23.502

15.4 INITIAL CONTEXT SETUP

★ The Initial Context Setup procedure can be completed after the UE has established an RRC Connection and has thus already configured SRB 1. The Initial Context Setup procedure is used to:

- o create a UE context at the Base Station
- o activate ciphering and integrity protection
- o configure SRB 2
- o configure one or more Data Radio Bearers (DRB)

★ Figure 456 illustrates the Initial Context Setup procedure in combination with the RRC Connection Setup procedure assuming a Centralised Unit (CU) – Distributed Unit (DU) split Base Station architecture. This architecture requires F1 Application Protocol (F1AP) signalling between the CU and DU. The RRC Connection Setup procedure and the NGAP: *Initial UE Message* are described in section 15.3

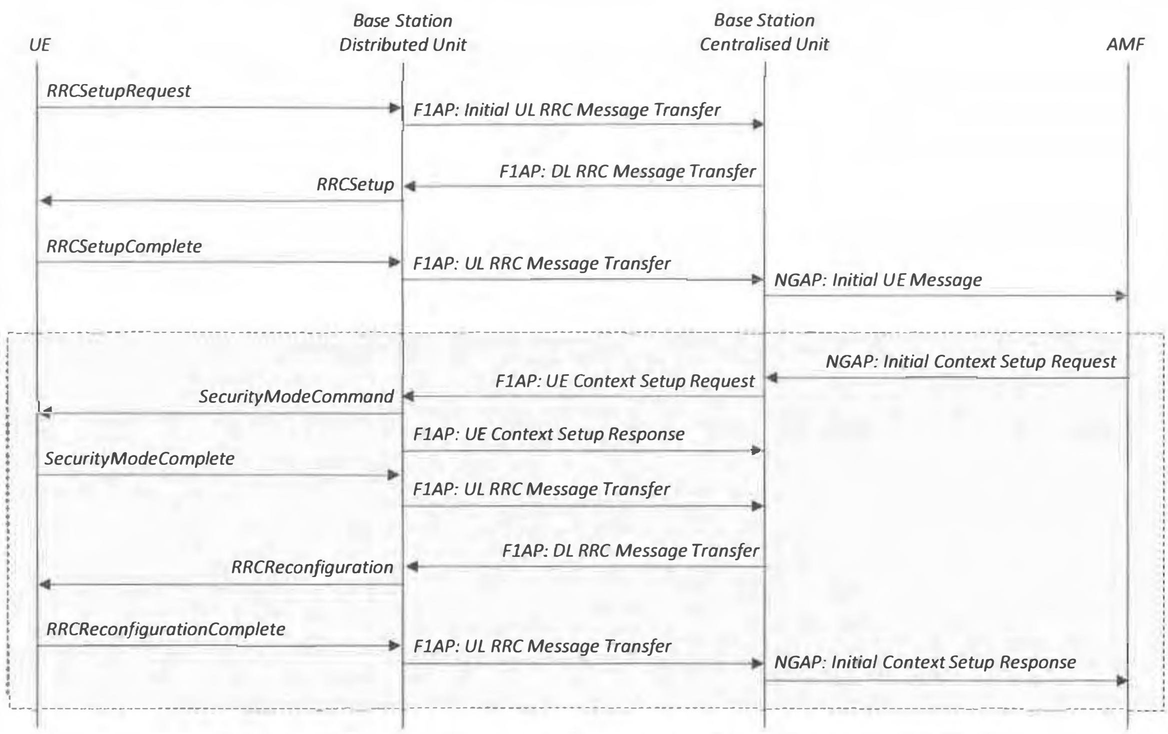


Figure 456 – Initial Context Setup signalling (CU-DU Split Base Station architecture)

★ The Base Station uses the 'UE Context Request' flag within the NGAP: *Initial UE Message* to request that the AMF starts the Initial Context Setup procedure. The content of the NGAP: *Initial Context Setup Request* is presented in Table 344

★ The 'Old AMF' identity is included if the UE's control plane signalling connection has been re-routed from one AMF to another AMF. The AMF originally selected by the Base Station may determine that it cannot support the UE, e.g. due to not supporting the set of requested Network Slices. In this case, the original AMF may forward the initial NAS message directly to another AMF. The new AMF then becomes responsible to completing the Initial Context Setup procedure

★ The 'UE Aggregate Maximum Bit Rate' (UE-AMBR) is included if the 'PDU Session Resource Setup Request List' is included. The UE-AMBR is a subscription parameter which is retrieved from the User Data Management (UDM) Network Function. It defines the maximum permitted bit rate summed across all non-GBR QoS Flows. It is not applicable to GBR QoS Flows

★ The 'Core Network Assistance Information' includes the 'UE Identity Index' which the Base Station uses to calculate the UE's Paging Frame. The AMF derives the 'UE Identity Index' using the expression '5G-S-TMSI mod 1024'. This generates a bit string of length 10. The 'Core Network Assistance Information' can also include a UE specific paging DRX cycle duration, a Mobile Initiated Connection Only (MICO) flag and an expected UE behaviour in terms of mobility. The AMF also uses this field to specify the periodic registration update timer for the UE

★ The 'PDU Session Resource Setup Request List' can be used to request the allocation of resources for one or more PDU sessions. For example, this field can be used to request the resources for a default PDU Session for transferring data and a default PDU Session for transferring IMS signalling. The 'PDU Session NAS PDU' is transparent to the Base Station and can be forwarded to the UE within the subsequent *RRCReconfiguration* message. The 'PDU Session Resource Setup Request Transfer' field provides the Base Station with information regarding the GTP-U tunnel to be used when transferring uplink user plane data towards the UPF. It also specifies the set of QoS Flows belonging to the PDU Session, the PDU Session type (IPv4, IPv6, IPv4v6, Ethernet, Unstructured) and the security requirement in terms of ciphering and integrity protection. In addition, a PDU Session Aggregate Maximum Bit Rate can be specified

- The 'UE Security Capabilities' provides the Base Station with information regarding the UE capability in terms of ciphering and integrity protection. This assumes that the AMF has stored UE capability information previously obtained from the UE. The 'Security Key' allows the Base Station to derive the keys for both ciphering and integrity protection. These fields provide the Base Station with sufficient information to start the RRC Security Mode procedure

Information Elements		Presence
AMF UE NGAP Identity		Mandatory
RAN UE NGAP Identity		Mandatory
Old AMF		Optional
UE Aggregate Maximum Bit Rate		Conditional
Core Network Assistance Information		Optional
Globally Unique AMF Identifier		Mandatory
PDU Session Resource Setup Request List	SEQUENCE {1 to 256 instances}	Optional
	PDU Session Identity	Mandatory
	PDU Session NAS PDU	Optional
	S-NSSAI	Mandatory
	PDU Session Resource Setup Request Transfer	Mandatory
Allowed NSSAI		Mandatory
UE Security Capabilities		Mandatory
Security Key		Mandatory
Trace Activation		Optional
Mobility Restriction List		Optional
UE Radio Capability		Optional
Index to RAT/Frequency Selection Priority (RFSP)		Optional
Masked IMEISV		Optional
NAS-PDU		Optional
Emergency Fallback Indicator		Optional
RRC Inactive Transition Report Request		Optional
UE Radio Capability for Paging		Optional
Redirection for Voice EPS Fallback		Optional

Table 344 – Content of NG Application Protocol (NGAP) *Initial Context Setup Request*

- The 'Mobility Restriction List' can be used to specify a set of Equivalent PLMN which the UE is permitted to access. It can also be used to specify restricted Radio Access Technologies (RAT), Forbidden Area Information and Service Area Information. Forbidden Area Information can specify Forbidden Tracking Area Codes, whereas Service Area Information can specify Not Allowed Tracking Area Codes. The former impacts cell reselection behaviour whereas the latter does not impact cell reselection behaviour

- The 'UE Radio Capability' provides the Base Station with the *UERadioAccessCapabilityInformation* RRC message. It is assumed that the Radio Access Network has previously retrieved this information from the UE and it has then been forwarded to the AMF. The AMF stores the UE Capability information to avoid having to re-request it each time the UE enters RRC Connected mode

- The 'Index to RAT/Frequency Selection Priority' (RFSP) can be used in the same way as the 'Subscriber Profile ID (SPID) for RAT/Frequency Priority' belonging to the 4G system. Both define a pointer within the range 1 to 256 which is linked to the user's subscription. The Base Station can use the value to configure UE specific mobility rules, e.g. to allocate a specific set of Absolute Priorities for Idle mode cell reselection, or for selecting a specific set of target carriers for inter-frequency handover

- The 'Masked IMEISV' can be used to identify a UE model, without identifying the individual UE. The Base Station can use this information if there is a requirement to apply specific rules to some UE models. The 'Masked IMEISV' has the last 4 digits of the Serial Number (SNR) set to 1 to avoid exposing the full UE identity

- The 'Emergency Fallback Indicator' can be used to indicate that either EPS Fallback or RAT Fallback can be performed for the purposes of an emergency call

- The 'RRC Inactive Transition Report Request' can be used to request the Base Station to forward an NGAP: *RRC Inactive Transition Report* if the UE is subsequently moved to the RRC Inactive state. This allows the AMF to adjust its behaviour to account for the RRC Inactive state. For example, it may be necessary to increase supervision timers to account for the increased delay associated with contacting the UE (it is necessary to send an RRC: *Paging* message to the UE and then move the UE back to RRC Connected mode before transferring any downlink signalling or data)

★ The 'UE Radio Capability for Paging' provides the Base Station with the *UERadioPagingInformation* RRC message. It is assumed that the Radio Access Network has previously retrieved this information from the UE and it has then been forwarded to the AMF. The information specifies the set of operating bands which the UE supports for the paging procedure

★ The 'Redirection for Voice EPS Fallback' field can be used to specify that both the UE and AMF support EPS Fallback for the IMS voice service

★ The Base Station CU uses the NGAP: *Initial Context Setup Request* to generate the F1AP: *UE Context Setup Request* which is then forwarded to the DU. This F1AP message requests the DU to setup resources for both SRB 2 and the set of DRB required by the PDU Sessions listed within the NGAP message. It also provides the DU with UE capability information and a transport network layer address for the uplink GTP-U tunnel between the DU and CU

★ The F1AP: *UE Context Setup Request* also includes an RRC Container which encapsulates the RRC: *SecurityModeCommand*, i.e. this message is generated by the CU but is forwarded to the DU for scheduling and transmission towards the UE. The content of the *SecurityModeCommand* is presented in Table 345. It specifies the ciphering and integrity protection algorithms to be used for Access Stratum security

SecurityModeCommand		
rrc-TransactionIdentifier	0 to 3	
securityAlgorithmConfig	cipheringAlgorithm	nea0, nea1, nea2, nea3
	integrityProtAlgorithm	nia0, nia1, nia2, nia3

Table 345 – *SecurityModeCommand* message

★ The UE responds with a *SecurityModeComplete* message which serves as a simple acknowledgement without any information content. The Base Station DU forwards the *SecurityModeComplete* to the CU within an F1AP: *UL RRC Message Transfer*

★ The DU also generates a response for the F1AP: *UE Context Setup Request*. This response specifies the SRB and DRB which have been successfully setup. It can also specify any SRB or DRB have it has failed to setup. In addition, the DU uses this message to provide the CU with a transport network layer address for the downlink GTP-U tunnel between the CU and DU

★ The CU then proceeds to generate the *RRCReconfiguration* message which is used to configure SRB 2 and the set of DRB at the UE. This message is forwarded to the DU from where it is scheduled and transmitted to the UE using SRB 1. The UE responds with an *RRCReconfigurationComplete* which is returned to the CU

★ The overall procedure is completed by the CU forwarding an NGAP: *Initial Context Setup Response* to the AMF. The content of this message is presented in Table 346. It is used to provide a list of PDU Session resources which the Base Station has successfully setup and a list of PDU Session resources which the Base Station has failed to setup

Information Elements		Presence
AMF UE NGAP Identity		Mandatory
RAN UE NGAP Identity		Mandatory
PDU Session Resource Setup Response List	SEQUENCE {1 to 256 instances}	Optional
	PDU Session Identity	Mandatory
	PDU Session Resource Setup Response Transfer	Mandatory
PDU Session Resource Failed to Setup List	SEQUENCE {1 to 256 instances}	Optional
	PDU Session Identity	Mandatory
	PDU Session Resource Setup Unsuccessful Transfer	Mandatory
Criticality Diagnostics		Optional

Table 346 – Content of NG Application Protocol (NGAP) *Initial Context Setup Response*

★ The 'PDU Session Resource Setup Response Transfer' field is provided for each of the successful PDU Session resources. This field is transparent to the AMF and is forwarded to the SMF. It provides a transport network layer address for the downlink GTP-U tunnel between the UPF and the Base Station CU

★ The 'PDU Session Resource Setup Unsuccessful Transfer' field is provided for each of the PDU Session resources which the Base Station failed to setup. This field is transparent to the AMF and is forwarded to the SMF. It provides a cause for the failed setup procedure

★ 3GPP References: TS 38.401, TS 38.331, TS 38.413, TS 38.473

15.5 Xn BASED HANDOVER

- The Xn based handover procedure allows the primary serving cell to be changed from one Base Station to another Base Station, when those Base Stations are connected using an Xn interface. An 'N2 based' handover can be used when the Xn interface is not available (N2 is the logical Reference Point between the Base Station and AMF so this corresponds to using NGAP signalling across the NG-C interface for the handover procedure)
- Figure 457 illustrates the signalling procedure for an Xn based handover. This example assumes that the handover procedure has been triggered by an RRC: *MeasurementReport* from the UE. Alternatively, the handover could be triggered by the Base Station. For example, a load based handover could be triggered by the Base Station although this may also involve UE measurement reporting to verify the coverage of the target cell
- The overall handover procedure is divided into three phases: Handover Preparation, Handover Execution and Handover Completion. The first two phases only involve the Radio Access Network, whereas the third phase also involves the Core Network. Network statistics typically allow the performance of each phase to be quantified. Overall handover performance should be based upon a combination of all three phases

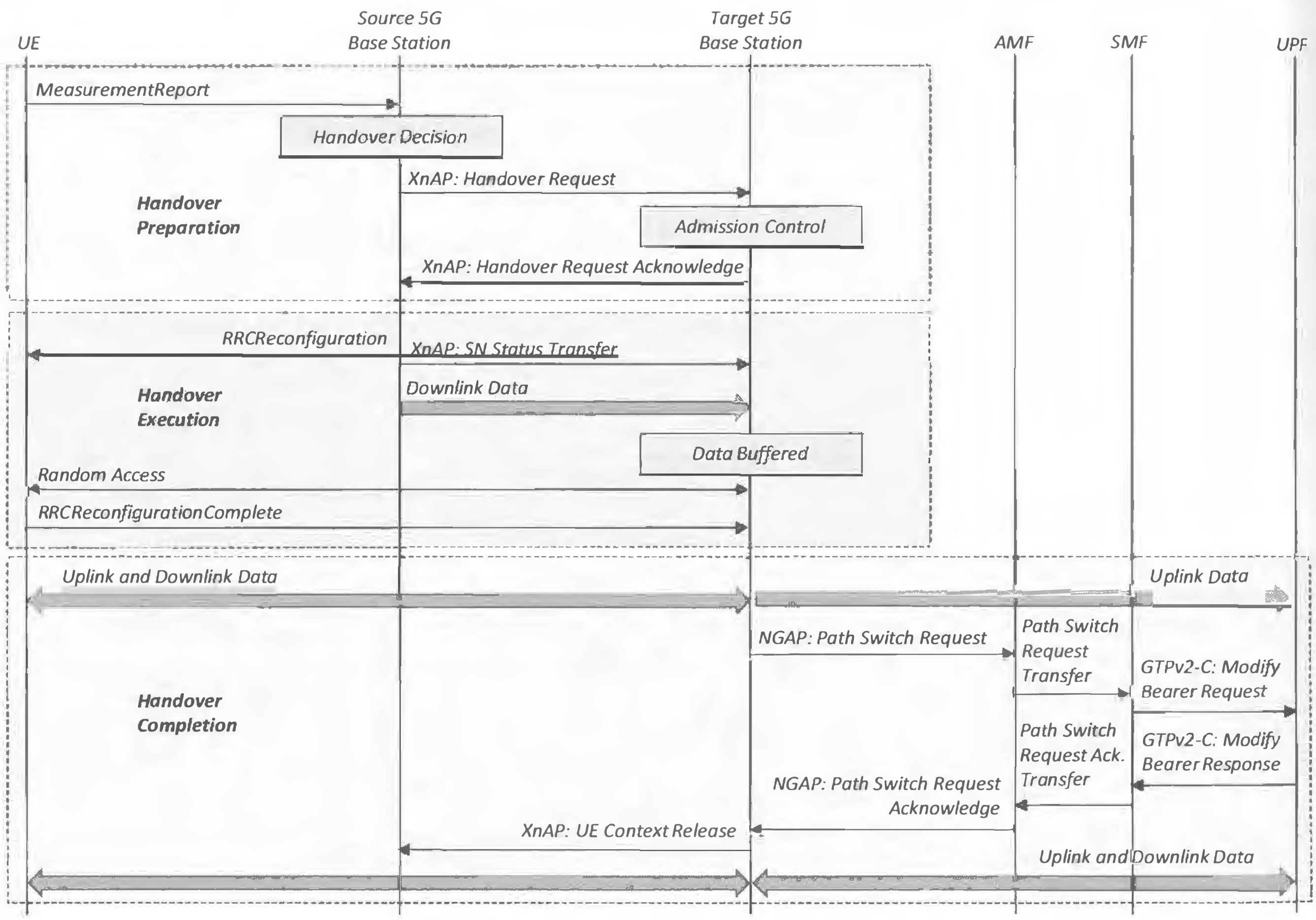


Figure 457 – Signalling procedure for an Xn based Handover

- The content of the XnAP: *Handover Request* is presented in Table 347. The source Base Station allocates the 'Source NG-RAN Node UE XnAP Identity' to the UE associated signalling procedure across the Xn interface
- The 'Cause' value is typically set to 'Handover Desirable for Radio Reasons' if the handover has been triggered by an Event A3 measurement report. Alternatively, it may be set to 'Time Critical Handover' if the handover has been triggered by Event A5. There is also a cause value of 'Reduce Load in Serving Cell' which can be used for load based handover procedures, and a value of 'Resource Optimisation Handover' which can be used when distributing load across neighbouring cells
- The 'Target Cell Global Identity' is extracted from the database of neighbour relations at the source Base Station. In general, the UE will identity the target cell within an RRC *MeasurementReport* using a Physical layer Cell Identity (PCI). The Base Station is then responsible for mapping that PCI onto a specific target cell. This mapping requires that all neighbour relations belonging to a specific cell have a unique PCI, i.e. optimal PCI planning avoids the possibility of PCI confusion
- The 'Globally Unique AMF Identity' (GUAMI) provides the target Base Station with the identity of the AMF which is being used to serve the UE

Information Elements		Presence
Source NG-RAN Node UE XnAP Identity		Mandatory
Cause		Mandatory
Target Cell Global Identity		Mandatory
GUAMI		Mandatory
UE Context Information	NG-C UE associated Signalling Reference	Mandatory
	Signalling TNL association address at source NG-C side	Mandatory
	UE Security Capabilities	Mandatory
	AS Security Information	Mandatory
	Index to RAT/Frequency Selection Priority	Optional
	UE Aggregate Maximum Bit Rate	Mandatory
	PDU Session Resources to be Setup List	Mandatory
	RRC Context	Mandatory
	Location Reporting Information	Optional
	Mobility Restriction List	Optional
Trace Activation		Optional
Masked IMEISV		Optional
UE History Information		Mandatory
UE Context Reference at the S-NG-RAN node	Global NG-RAN Node ID	Optional
	S-NG-RAN node UE XnAP ID	Optional

Table 347 – Content of Xn Application Protocol (XnAP) *Handover Request*

★ The 'UE Context Information' provides the target Base Station with information regarding the PDU Sessions to be relocated during the Handover procedure. The 'NG-C UE associated Signalling Reference' is provided to allow the target Base Station to address the connection when sending the NGAP: *Path Switch Request* to the AMF during the Handover Completion phase. The 'Signalling TNL association address at source NG-C side' provides an IP address for the AMF signalling connection. The 'PDU Session Resources to be Setup List' provides the IP address and GTP-U TEID for the uplink data transfer towards the UPF. It also specifies the PDU Session and the associated set of QoS Flows. The 'RRC Context' includes the *HandoverPreparationInformation* message specified by 3GPP TS 38.331

★ The target Base Station applies its Admission Control checks after receiving the XnAP: *Handover Request*. These checks may account for the availability of radio resources, hardware resources and transport resources. The target Base Station can then proceed to complete the Handover Preparation phase by returning the XnAP: *Handover Request Acknowledge* presented in Table 348

Information Elements	Presence
Source NG-RAN node UE XnAP ID	Mandatory
Target NG-RAN node UE XnAP ID	Mandatory
PDU Session Resources Admitted List	Mandatory
PDU Session Resources Not Admitted List	Optional
Target NG-RAN Node To Source NG-RAN Node Transparent Container	Mandatory
UE Context Kept Indicator	Optional
Criticality Diagnostics	Optional

Table 348 – Content of Xn Application Protocol (XnAP) *Handover Request Acknowledge*

★ The 'PDU Session Resources Admitted List' includes transport layer information (IP address and GTP-U TEID) which allows the source Base Station to start forwarding user plane data across the Xn interface. The 'Target NG-RAN Node To Source NG-RAN Node Transparent Container' includes the *HandoverCommand* message specified by 3GPP TS 38.331. This message encapsulates the *RRCReconfiguration* message which is to be sent to the UE. The *RRCReconfiguration* message can include one or more dedicated PRACH preambles to allow Contention Free access to a beam belonging to the target cell

★ The source Base Station extracts the *RRCReconfiguration* message and transmits it to the UE. The source Base Station also forwards an XnAP: *SN Status Transfer* message to the target Base Station (presented in Table 349). This message is used to provide the target Base Station with information regarding the Sequence Number status at the PDCP layer. The 'UL COUNT' value specifies the Sequence Number of the first missing uplink SDU, whereas the 'DL COUNT' value specifies the next Sequence Number to be allocated to a downlink SDU. The 'Receive Status of UL PDCP SDU' can be used to provide a bitmap where each '0' corresponds to a missing PDCP SDU and the bit position corresponds to a Sequence Number which follows the first missing uplink SDU

Information Elements			Presence
Source NG-RAN node UE XnAP ID			Mandatory
Target NG-RAN node UE XnAP ID			Mandatory
DRBs Subject To Status Transfer List	SEQUENCE {1 to 32 instances}		Mandatory
	DRB Identity		Mandatory
	Receive Status Of PDCP SDU		Optional
	UL COUNT Value	PDCP Sequence Number	Mandatory
		Hyper Frame Number	Mandatory
	DL COUNT Value	PDCP Sequence Number	Mandatory
		Hyper Frame Number	Mandatory

Table 349 – Content of Xn Application Protocol (XnAP) *SN Status Transfer*

★ The downlink data which is forwarded across the Xn interface is buffered at the target Base Station until the UE completes the Random Access procedure and forwards the *RRCReconfigurationComplete* message. At this stage, the UE is connected to the target Base Station and the Handover Execution phase has been completed. The target Base Station is able to forward uplink data towards the UPF but downlink data is still sent to the source Base Station from where it is forwarded across the Xn interface

★ The Handover Completion phase is responsible for requesting the UPF to move the downlink data path from the source Base Station to the target Base Station. The target Base Station initiates this phase by sending an NGAP: *Path Switch Request* to the AMF. The content of this message is presented in Table 350

Information Elements		Presence
RAN UE NGAP ID		Mandatory
Source AMF UE NGAP ID		Mandatory
User Location Information		Mandatory
UE Security Capabilities		Mandatory
PDU Session Resource to be Switched in Downlink List	SEQUENCE {1 to 256 instances}	Mandatory
	PDU Session ID	Mandatory
	Path Switch Request Transfer	Mandatory
PDU Session Resource Failed to Setup List	SEQUENCE {1 to 256 instances}	Optional
	PDU Session ID	Mandatory
	Path Switch Request Setup Failed Transfer	Mandatory

Table 350 – Content of NG Application Protocol (NGAP) *Path Switch Request*

★ The 'Path Switch Request Transfer' and 'Path Switch Request Setup Failed Transfer' fields are transparent to the AMF. These fields are forwarded to the SMF because the SMF is responsible for managing the UPF. The AMF forwards these fields by encapsulating them within an 'Update SM Context' service request message which is forwarded using an HTTP POST method. This service request procedure is specified within 3GPP TS 29.502

★ The 'Path Switch Request Transfer' field specifies the downlink transport layer information for the target Base Station (IP address and GTP-U TEID). The SMF uses a GTPv2-C: *Modify Bearer Request* to forward this information to the UPF. The UPF acknowledges the request using a GTPv2-C: *Modify Bearer Response*. These GTPv2-C messages are specified within 3GPP TS 29.274

★ The SMF provides an acknowledgement to the AMF to indicate that the service request has been completed, and this acknowledgement is forwarded to the target Base Station using an NGAP: *Path Switch Request Acknowledge* message. At this stage, the connection has completely moved across to the target Base Station in both the uplink and downlink directions. This means that the source Base Station is now able to release the resources it has been using for the connection. The target Base Station triggers the release procedure by sending an XnAP: *UE Context Release* message

★ 3GPP References: TS 38.331, TS 38.413, TS 38.423, TS 38.300, TS 29.502, TS 29.274

15.6 RRC CONNECTION RELEASE

★ The RRC Connection Release procedure can be used to:
  - o release an RRC Connection by moving a UE from RRC Connected to RRC Idle
  - o suspend an RRC Connection by moving a UE from RRC Connected to RRC Inactive
  - o release an RRC Connection by moving a UE from RRC Inactive to RRC Idle

★ The Base Station is permitted to move a UE from RRC Connected to RRC Inactive if it has already setup SRB 2 and at least one Data Radio Bearer (DRB)

★ Figure 458 illustrates a Base Station initiating an RRC Connection Release procedure to move a UE from RRC Connected to RRC Idle. This procedure could be triggered by the expiry of a UE specific inactivity timer. The *RRCRelease* message instructs the UE to move to RRC Idle. The UE is permitted up to 60 ms to acknowledge this message at the MAC and RLC layers before following the instruction to move to RRC Idle. The Base Station uses the NGAP: *UE Context Release Request* message to request the AMF to initiate the NGAP UE Context Release procedure. This releases the UE context at the Base Station, while the AMF maintains the UE context as long as the UE remains registered with the 5G Core Network

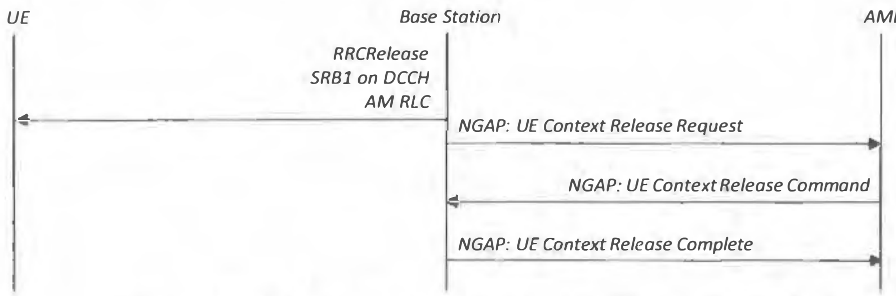


Figure 458 – RRC Connection Release to RRC Idle (Base Station initiated)

★ Figure 459 illustrates an AMF initiating an NGAP UE Context Release procedure which results in the UE being moved to RRC Idle. This procedure could be triggered after the completion of a NAS Mobility Registration Update

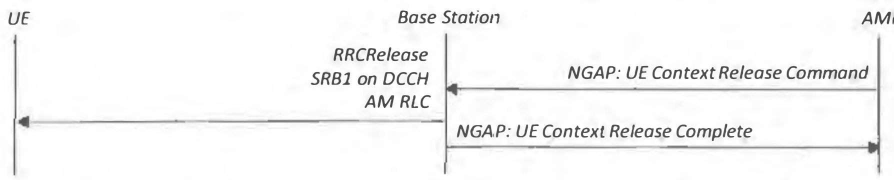


Figure 459 – RRC Connection Release to RRC Idle (Core Network initiated)

★ Table 351 presents the content of the *RRCRelease* message. The *redirectedCarrierInfo* allows the Base Station to instruct the UE to complete an RRC Release with Redirection when moving towards either RRC Idle or RRC Inactive. RRC Release with Redirection specifies the target carrier for cell selection. The Base Station can redirect the UE towards an NR carrier or an E-UTRA (LTE) carrier. In the case of NR, the UE is provided with the NR-ARFCN belonging to the SS/PBCH Blocks, the subcarrier spacing of the SS/PBCH Blocks and the timing of the SS/PBCH Blocks. In the case of EUTRA, the UE is provided with the ARFCN and the Core Network type

★ The *cellReselectionPriorities* field allows the Base Station to allocate dedicated Absolute Priorities for cell reselection in RRC Idle and RRC Inactive. Priorities can be specified for up to 8 E-UTRA carriers and up to 8 NR carriers. The T320 timer can be used to limit the time that the dedicated Absolute Priorities remain valid. The UE reverts to using the Absolute Priorities broadcast by the System Information when T320 expires

★ Inclusion of the *suspendConfig* indicates that the UE should move to RRC Inactive rather than RRC Idle. The UE is allocated an Inactive-RNTI (I-RNTI) which can be used to identify both the UE and the serving Base Station while the UE remains within the allocated RAN Notification Area (RNA). The *suspendConfig* parameter set is described in greater detail within section 1.8.3, while the I-RNTI is described in section 18.7. Figure 460 illustrates the use of an *RRCRelease* message to move a UE to RRC Inactive. In this example it is assumed that the AMF requested notification of the RRC state transition within the NGAP: *Initial Context Setup Request*

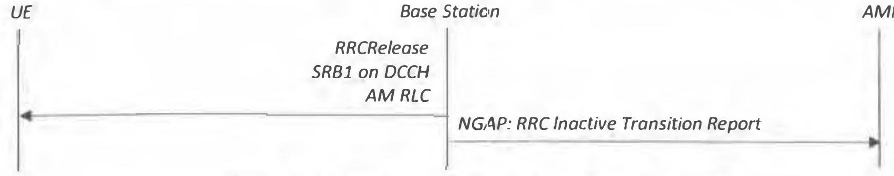


Figure 460 – RRC Connection Release to RRC Inactive

RRCRelease								
redirectedCarrierInfo	CHOICE							
	nr				eutra			
	carrierFreq	0 to 3279165			eutraFrequency	0 to 262143		
	ssbSubcarrierSpacing	15, 30, 120, 240 kHz			cnType	epc, fiveGC		
	smtc	periodicityAndOffset	CHOICE					
			5 subframes	0 to 4				
			10 subframes	0 to 9				
			20 subframes	0 to 19				
			40 subframes	0 to 39				
			80 subframes	0 to 79				
			160 subframes	0 to 159				
		duration	1, 2, 3, 4, 5 subframes					
cellReselectionPriorities	freqPriorityListEUTRA	SEQUENCE {1 to 8 instances}						
		carrierFreq	0 to 262143					
		cellReselectionPriority	0, 1, 2, 3, 4, 5, 6, 7					
		cellReselectionSubPriority	0.2, 0.4, 0.6, 0.8					
	freqPriorityListNR	SEQUENCE {1 to 8 instances}						
		carrierFreq	0 to 3279165					
		cellReselectionPriority	0, 1, 2, 3, 4, 5, 6, 7					
		cellReselectionSubPriority	0.2, 0.4, 0.6, 0.8					
	t320	5, 10, 20, 30, 60, 120, 180 min						
suspendConfig	fullI-RNTI	BIT STRING {40 bits}						
	shortI-RNTI	BIT STRING {24 bits}						
	ran-PagingCycle	32, 64, 128, 256 radio frames						
	ran-Notification AreaInfo	CHOICE						
		cellList	1 to 8 instances of PLMN-RAN-AreaCell	plmn-Identity	1 to 32 instances of CellIdentity	BIT STRING (36 bits)		
		ran-AreaConfigList	1 to 8 instances of PLMN-RAN-AreaConfig	plmn-Identity	1 to 16 instances of RAN-AreaConfig	TAC	1 to 32 instances of RAN-AreaCode	0 to 255
	t380	5, 10, 20, 30, 60, 120, 360, 720 mins						
	nextHopChaining Count	0 to 7						
deprioritisationReq	deprioritisationType	frequency, nr						
	deprioritisationTimer	5, 10, 15, 30 min						
waitTime	1 to 16 seconds							

Table 351 – *RRCRelease* message

- ★ The *deprioritisationReq* field allows either the current RF carrier to be deprioritised, or the set of all NR RF carriers to be deprioritised. Deprioritisation impacts the cell reselection procedure and means that the UE assumes an Absolute Priority for the targeted RF carrier(s) which is lower than any of the remaining carriers. The UE continues to apply deprioritisation if the UE moves to another Radio Access Technology (RAT). Deprioritisation information is discarded upon expiry of the T325 timer which is set equal to the value of the *deprioritisationTimer*
- ★ If the *waitTime* is included, the UE starts timer T302 with its expiry value set equal to the *waitTime*. With the exception of Access Categories 0 and 2, all connection attempts are access barred until T302 expires. Access Categories 0 and 2 correspond to mobile terminated access and emergency access respectively. In the case of mobile terminated access, the network is responsible for controlling access by preventing the transmission of paging messages if necessary. T302 is stopped if the UE completes cell reselection so in that case, the UE is permitted to attempt an RRC Connection Setup with the new serving cell
- ★ 3GPP References: TS 38.331, TS 38.304, TS 38.413

16 RADIO NETWORK PLANNING

16.1 OPERATING BAND

★ In many cases, there will be a one-to-one relationship between the allocated spectrum and the operating band. In these cases, there is only a single operating band which can be selected

★ In some cases, operating bands overlap so multiple operating bands can be associated with a single spectrum allocation. For example, a TDD spectrum allocation from 3300 to 3400 MHz can be associated with operating band n77 (3300 to 4200 MHz) or operating band n78 (3300 to 3800 MHz)

★ The network implementation may allow multiple operating bands to be configured, e.g. SIB1 is capable of broadcasting a list of operating bands rather than just a single operating band

★ If the network implementation supports a single operating band per channel then it will be necessary to select one of the candidate operating bands. This selection could be based upon the requirement for specific band combinations. Band combinations are specified between LTE and NR for the Non-Standalone Base Station architecture. Band combinations are also specified for NR Carrier Aggregation and Dual Connectivity

★ All of the required band combinations should be identified and checks should be completed to determine whether or not all combinations have been specified by 3GPP. Checks should also be completed to determine whether or not the network equipment and UE support all band combinations. This may lead to one operating band being more attractive than another operating band. For example, operating band n77 may support all of the required band combinations, while operating band n78 may not support all of the required band combinations

16.2 NR-ARFCN & GSCN

★ It is necessary to identify center frequencies for both the channel bandwidth and the set of SS/PBCH Blocks. Initial deployments are likely to use a single set of SS/PBCH Blocks requiring a single center frequency. More advanced deployments may use multiple sets of SS/PBCH Blocks requiring multiple center frequencies, e.g. when a channel bandwidth is configured to use multiple Bandwidth Parts. Figure 461 illustrates a single set of SS/PBCH Blocks within a channel bandwidth

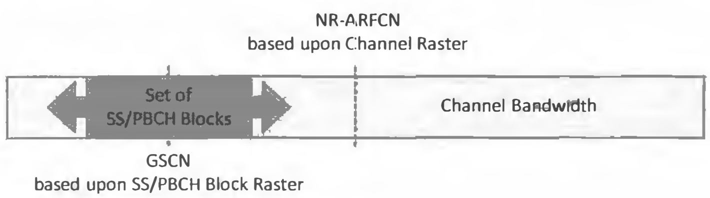


Figure 461 – NR-ARFCN for Channel Bandwidth & GSCN for SS/PBCH Blocks

★ The New Radio - Absolute Radio Frequency Channel Number (NR-ARFCN) identifies the center frequency of the channel (as described in section 2.5.1). The steps associated with selecting an appropriate NR-ARFCN include:

- o identify the channel raster(s) for the selected operating band. Many operating bands within Frequency Range 1 are restricted to using a 100 kHz raster to provide coexistence with LTE (which also uses a 100 kHz raster). Other operating bands support two channel rasters. For example, operating bands n77 and n78 support the 15 kHz and 30 kHz channel rasters. When two channel rasters are specified for an operating band, the larger raster is applicable when the channel only uses a subcarrier spacing which equals the larger raster
- o identify the target center frequency in MHz. In general, the target center frequency should be positioned towards the center of the allocated spectrum while occupying a position belonging to the channel raster
- o calculate the NR-ARFCN using the equation presented in section 2.5.1

★ The Global Synchronisation Channel Number (GSCN) identifies the center frequency for a set of SS/PBCH Blocks (as described in section 2.5.2). The two main requirements associated with selecting a center frequency are:

- o the Resource Blocks occupied by the SS/PBCH Blocks must be fully within the channel bandwidth
- o the SS/PBCH Blocks must be subcarrier aligned with the Resource Blocks belonging to the channel bandwidth. Orthogonality will be lost if the two transmissions are not subcarrier aligned

★ In addition, it is necessary to identify a strategy for the general position of the SS/PBCH Blocks, i.e. should the SS/PBCH Blocks be placed within the lower section, middle section or upper section of the channel bandwidth? Placing the SS/PBCH Blocks towards the center of the channel bandwidth means that SS-RSRP and SS-RSRQ measurements are completed at the center of the channel. These measurements may be more representative of 'average' channel conditions when compared to measurements completed using the lower or upper sections of the channel. Placing the SS/PBCH Blocks towards the center of the channel bandwidth also provides a solution analogous to LTE which always uses the center of the channel for the Synchronisation Signals and PBCH. A counter argument could be based upon the measurement of frequency multiplexed CSI Reference Signals. If the SS/PBCH Blocks occupy the center of the channel bandwidth, the number of contiguous Resource Blocks available to frequency multiplexed CSI Reference Signals will be reduced (the channel bandwidth will be segmented by the SS/PBCH Blocks). This may have some impact upon measurement accuracy

★ As an example, consider a spectrum allocation from 2300 to 2340 MHz within operating band n40. Operating band n40 uses a 100 kHz channel raster so it is possible to place the center frequency at 2320 MHz. The NR-ARFCN can be calculated as:

$$\text{NR-ARFCN} = N_{\text{REF-Offs}} + (\text{Center Frequency} - F_{\text{REF-Offs}}) / \Delta F_{\text{Global}}$$

$$\text{NR-ARFCN} = 0 + (2320 \text{ MHz} - 0) / 5 \text{ kHz} = 464\,000$$

★ The resultant NR-ARFCN is a multiple of 20 which confirms that the center frequency belongs to the 100 kHz channel raster

★ Assuming that the SS/PBCH Blocks are to be positioned towards the center of the channel bandwidth then candidate center frequencies can be identified using the following equation which is applicable to operating bands below 3 GHz:

$$\text{Center Frequency} = N \times 1200 \text{ kHz} + M \times 50 \text{ kHz} \qquad \text{where, } N = 1 \text{ to } 2499 \text{ and } M = 1, 3 \text{ or } 5$$

★ Setting N = 1933, generates candidate center frequencies of 2319.65, 2319.75 and 2319.85 MHz for M = 1, 3 and 5 respectively. It is then necessary to check which of these candidates provides subcarrier alignment with the channel bandwidth. The first candidate has an offset of 350 kHz relative to the center of the channel bandwidth. This is not an integer multiple of 15 kHz so is not subcarrier aligned. Similarly, the second candidate has an offset of 250 kHz which is not an integer multiple of 15 kHz so is not subcarrier aligned. The third candidate has an offset of 150 kHz which is an integer multiple of 15 kHz. Thus, in this example, the third candidate should be selected. The GSCN can then be calculated as:

$$\text{GSCN} = 3 \times N + (M - 3) / 2 = 3 \times 1933 + (5 - 3) / 2 = 5800$$

★ The appropriate value of 'M' changes as the center frequency of the channel bandwidth increments in steps of 100 kHz. This results from 100 kHz not being an integer multiple of 15 kHz. The preceding example has illustrated that M = 5 should be selected, but if the center frequency of the channel bandwidth is incremented to 2320.1 MHz then the combination of N = 1933 and M = 1 provides subcarrier alignment

★ Subcarrier alignment is less complex for operating bands above 3 GHz because the 100 kHz channel raster is not used. In these cases, the 'M' variable is not required when calculating the SS/PBCH center frequency and the corresponding GSCN

16.3 SLOT FORMAT

★ Section 2.2 describes the use of semi-static and dynamic Slot Formats for TDD. Initial 5G network deployments are likely to focus upon using semi-static Slot Formats due to the challenges associated with cross-link interference that can be generated when using dynamic Slot Formats

★ In some countries, the national regulator may specify the Slot Format to be used within each 5G operating band. In other countries, operators may agree to use a common Slot Format. In these cases, it is not necessary for the Radio Network Planning team to select a Slot Format. However, the Slot Format has implications upon other aspects of Radio Network Planning so it is important to complete an initial impact assessment

★ This impact assessment should include:

- o SS/PBCH Block restrictions
- o PRACH Format, Root Sequence and Configuration Index restrictions
- o Cell Range restriction
- o Latency and Throughput dependencies

★ Figure 462 illustrates an example 5G Slot Format which is based upon 4G Uplink/Downlink Subframe Configuration 2. For the purposes of this example, it is assumed that 5G is using the 30 kHz subcarrier spacing so there are two 5G slots within the duration of each 4G subframe

★ Considering the SS/PBCH, it is important to note that there are 3 downlink slots at the start of the radio frame. Referring to Table 56 within Section 3.4, it can be seen that when using the 30 kHz subcarrier spacing, SS/PBCH transmissions can potentially start during symbols {4, 8, 16, 20, 32, 36, 44, 48} or during symbols {2, 8, 16, 22, 30, 36, 44, 50}. In the case of Figure 462, the 3 downlink slots allow starting symbols of {4, 8, 16, 20, 32, 36} or {2, 8, 16, 22, 30, 36}, i.e. it is only possible to transmit 6 SS/PBCH rather than the complete set of 8 SS/PBCH. In terms of beamforming, this restricts the cell to having 6 SS/PBCH beams rather than 8 SS/PBCH beams, i.e. a smaller set of wider beams is required when compared to a cell which supports 8 SS/PBCH beams

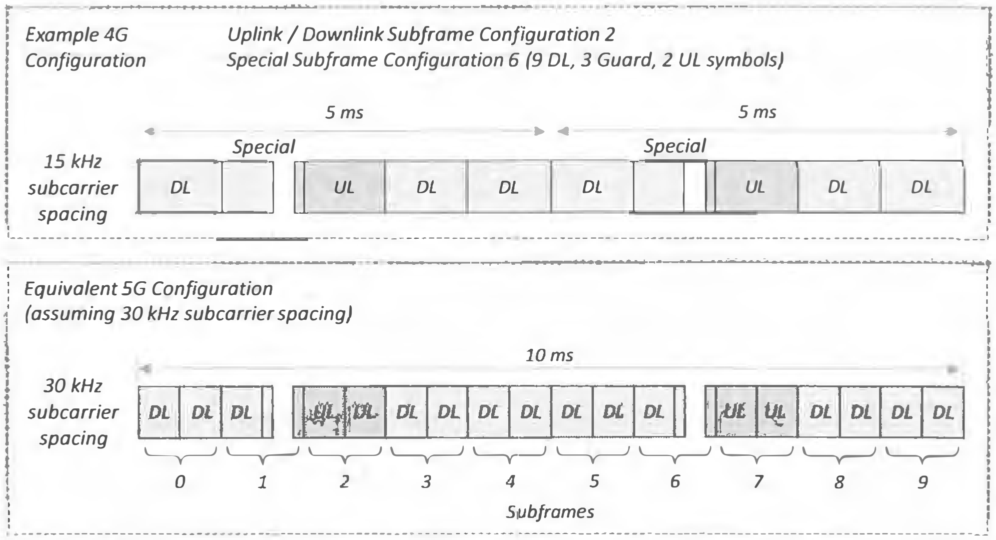


Figure 462 – 5G Slot Format based upon 4G Uplink/Downlink Subframe Configuration 2

★ Considering the PRACH Format, it is important to note that there are 2 consecutive uplink subframes which provide an uplink duration of 1 ms. This means that there is scope to transmit 'Long' PRACH Preamble Formats 0 and 3 (presented in Table 167, Section 7.2.3) which both have durations of 1 ms. However, it is not possible to select 'Long' PRACH Preamble Format 1 nor Format 2 which both have durations exceeding 1 ms. Having the option to select a 'Long' PRACH Preamble Format means that cells can benefit from an increased cell range and an increased number of PRACH Root Sequences (838 Root Sequences rather than 138 Root Sequences). Having an increased number of Root Sequences means that the re-use pattern will be larger and there will be a reduced risk of collision

★ Considering the PRACH Configuration Index, it is important to study the timing of the uplink slots. The PRACH Configuration Index defines the timing of the PRACH opportunities and these opportunities must coincide with the uplink slots. For example, 3GPP TS 38.211 specifies PRACH Configuration Indices 9, 14 and 19 that allow the transmission of PRACH Format 0 during subframes 2 and 7. These Configuration Indices could thus be selected for deployment but all other Configuration Indices linked to PRACH Format 0 should be excluded

★ Figure 463 illustrates the same Slot Format as Figure 462 but the Radio Frame is configured to start 3 ms later, i.e. the Radio Frame starts immediately after an uplink slot. This solution increases the number of downlink slots at the start of the Radio Frame and so increases the number of SS/PBCH Blocks which can be accommodated. In this case, the complete set of 8 SS/PBCH Blocks can be accommodated by the first 4 downlink slots. In addition, this solution changes the subframe numbering associated with the uplink slots, i.e. the uplink subframes are now numbers 4 and 9 rather than 2 and 7. This changes the set of PRACH Configuration Indices which can be supported. 3GPP TS 38.211 specifies PRACH Configuration Indices 0 to 7, 12 and 17 that allow the transmission of PRACH Format 0 during subframes 4 and 9

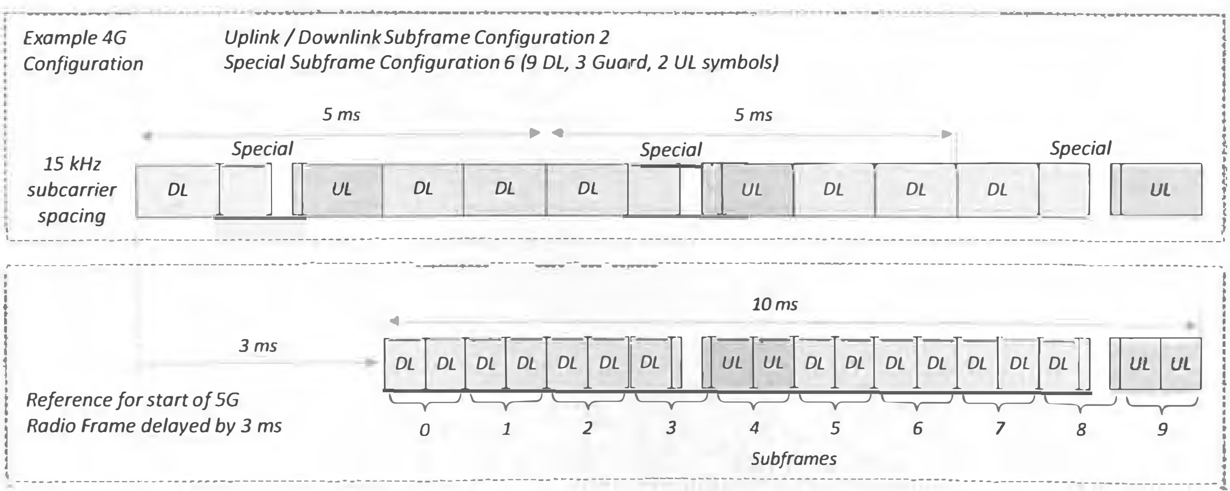


Figure 463 – 5G Slot Format based upon 4G Uplink/Downlink Subframe Configuration 2 (with delayed start of Radio Frame)

★ Figure 464 illustrates an example Slot Format which distributes the uplink slots across the Radio Frame. In this example, there are 3 downlink slots at the start of the Radio Frame so it is possible to accommodate up to 6 SS/PBCH Blocks. Each uplink slot has a duration of 0.5 ms so 'Long' PRACH Preamble Formats cannot be accommodated. Instead, it is necessary to use 'Short' PRACH Preamble Formats (described in Section 7.2.4). These PRACH Preambles are restricted to supporting relatively small cell ranges and allow the use of only 138 Root Sequences. These factors indicate that the Slot Format illustrated in Figure 464 is more appropriate for small cells or microcells

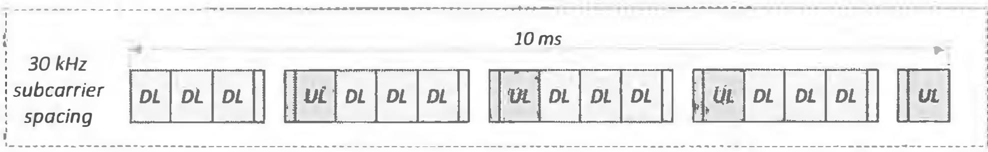


Figure 464 – 5G Slot Format with distributed uplink slots

★ A benefit associated with the Slot Format illustrated in Figure 464 is reduced latency. There is a reduced average waiting time for an uplink slot because the uplink slots are distributed across the Radio Frame. This is beneficial in terms of transferring uplink data but is also beneficial in terms of returning acknowledgements after receiving downlink data

★ The guard period belonging to the Slot Format can impact the maximum cell range. The guard period is required to accommodate the round trip propagation delay in addition to the transceiver switching delay at both the Base Station and UE. Figure 465 illustrates the uplink / downlink transmission timing observed by the UE and Base Station for a UE which is positioned at cell edge

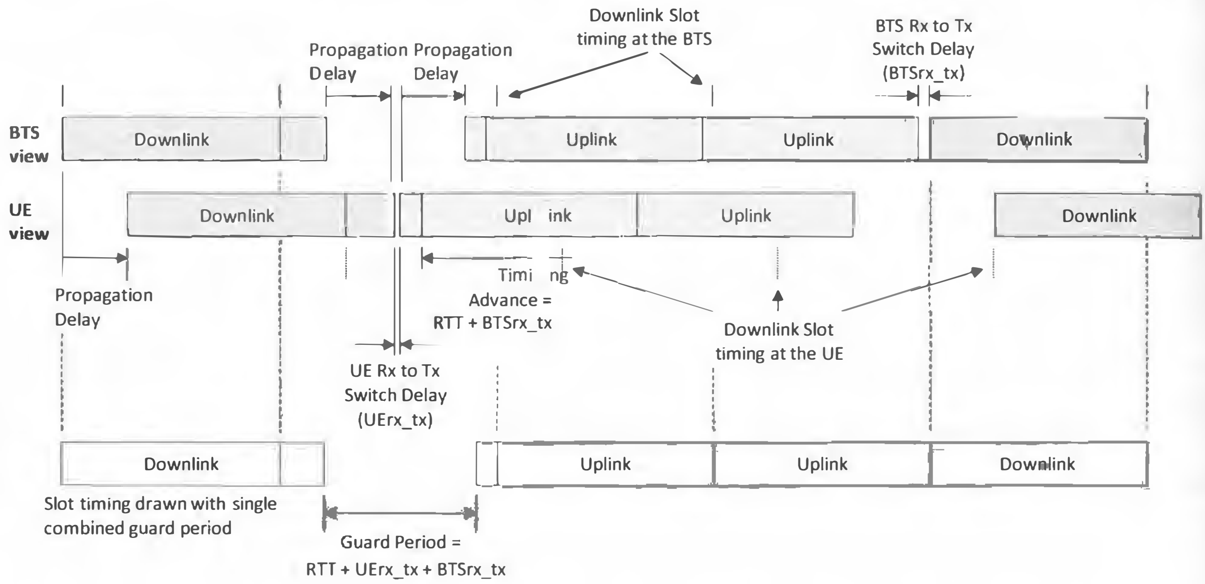


Figure 465 – Uplink / Downlink Guard Period accommodating round trip propagation delay plus transceiver switching delays

★ Downlink slots are received by the UE after experiencing the propagation delay. Timing Advance determines the point in time that the UE starts to transmit in the uplink direction. Timing Advance is relative to the downlink slot timing received by the UE. Timing Advance is described in section 13.2. Timing Advance cannot instruct the UE to start transmitting immediately after the downlink transmission has finished. It must allow some time for the UE to switch from receiving to transmitting. This typically requires 10 to 40 microseconds

★ Uplink radio frames are received by the Base Station after experiencing the propagation delay. The Timing Advance instruction must be large enough to ensure that there is time for the Base Station to switch from receiving to transmitting after the uplink transmission has finished. This typically requires 10 to 20 microseconds

★ The maximum cell range is determined by the duration of the guard period after subtracting the UE and Base Station switching times

★ Table 352 presents the maximum cell range associated with a range of guard periods assuming a total of 40 microseconds for both the UE and Base Station switching times. These figures assume the normal cyclic prefix (14 symbols per slot)

Number of Guard Symbols	Subcarrier Spacing			
	15 kHz	30 kHz	60 kHz	120 kHz
1	4.7	-	-	-
2	15.4	4.7	-	-
3	26.1	10.1	2.0	-
4	36.9	15.4	4.7	-
5	47.6	20.8	7.4	0.7
6	58.3	26.1	10.1	2.0
7	69.0	31.5	12.8	3.4

Number of Guard Symbols	Subcarrier Spacing			
	15 kHz	30 kHz	60 kHz	120 kHz
8	79.7	36.9	15.4	4.7
9	90.4	42.2	18.1	6.1
10	101.1	47.6	20.8	7.4
11	111.9	52.9	23.5	8.7
12	122.6	58.3	26.1	10.1
13	133.3	63.6	28.8	11.4
14	144.0	69.0	31.5	12.8

Table 352 – Maximum Cell Ranges (km) associated with Guard Periods of 1 to 14 symbols

- The maximum cell range is larger for the smaller subcarrier spacings due to the longer symbol durations. Guard periods longer than 14 symbols could be configured to support larger cell ranges
- The entries within Table 352 without a cell range result correspond to guard periods which are too short to accommodate the 40 microseconds transceiver switching delay
- Throughput requirements should also be considered when evaluating a Slot Format. The ratio between the uplink and downlink slots will impact the ratio between the uplink and downlink throughputs. The ratio is also likely to impact link budget requirements. If there is a specific cell edge average throughput requirement, reducing the number of slots will make that average throughput requirement more difficult to achieve. It will be necessary to increase the instantaneous throughputs to compensate for the reduced number of slots. Increasing the instantaneous throughput requirement will increase the SINR requirement and make the link budget more stringent
- Distributing uplink slots across the Radio Frame will increase the requirement for guard periods which generate an overhead from the perspective of uplink and downlink throughputs. For example, the Slot Format in Figure 464 requires twice as many guard periods relative to the Slot Format in Figure 463

16.4 ANTENNA SOLUTION

- When using Frequency Range 2, it is likely that an active antenna array is necessary to ensure that link budget requirements are satisfied, i.e. the primary requirement for beamforming is to improve coverage rather than spectral efficiency
- When using Frequency Range 1, there is increased potential for a choice of antenna solutions. Passive antenna can be used in combination with Remote Radio Heads (RRH) or RF Modules. Alternatively, active antenna can be used with transceivers organised either in a single row to allow beamforming in the azimuth direction, or in multiple rows to allow beamforming in both the azimuth and elevation directions
- Selection of an appropriate antenna solution requires consideration of commercial, technical and practical aspects. Passive antenna are likely to be lower cost and may be more practical in terms of size and weight. Passive antenna may be used with or without a beamforming solution. When using beamforming, the beams are likely to be relatively coarse when compared to an active antenna. For example, a passive antenna solution could be based upon an 8Tx8Rx architecture which uses 4 columns of cross-polar antenna elements. A typical minimum active antenna configuration includes 8 columns of cross-polar antenna elements to generate a 16Tx16Rx architecture. Doubling the number of cross-polar columns allows the beams to be more directional in the horizontal plane (beamforming principles are described in Section 1.21) Larger active antenna configurations could be based upon 32Tx32Rx or 64Tx64Rx architectures. The 32Tx32Rx architecture could be based upon 2 rows of 16 transceivers whereas the 64Tx64Rx architecture could be based upon 4 rows of 16 transceivers
- In all cases, it is necessary to become familiar with the antenna gain pattern offered by a specific solution. Figure 466 compares a typical 3-sector 65° beamwidth passive antenna solution with an active antenna solution. In the case of the active antenna solution, the beams are intended to represent SS/PBCH Block beams. The addition of refined CSI Reference Signal beams is illustrated later in this section
- In the case of the active antenna, the beamwidth of the envelope of beams can be controlled by selecting a specific set of beamforming coefficients. Figure 466 illustrates a first example where the beamwidth of the envelope has been set to 120° for a 3-sector Base Station configuration, and a second example where the beamwidth of the envelope has been set to 90° for a 4-sector Base Station configuration. Both examples assume the use of 8 SS/PBCH Block beams within a cell. This means that the beams are more closely packed when distributing the beams across 90° rather than 120°. Alternatively, a reduced number of beams could be configured as the beamwidth of the envelope is reduced, e.g. in the case of a 6-sector configuration using a 60° envelope beamwidth

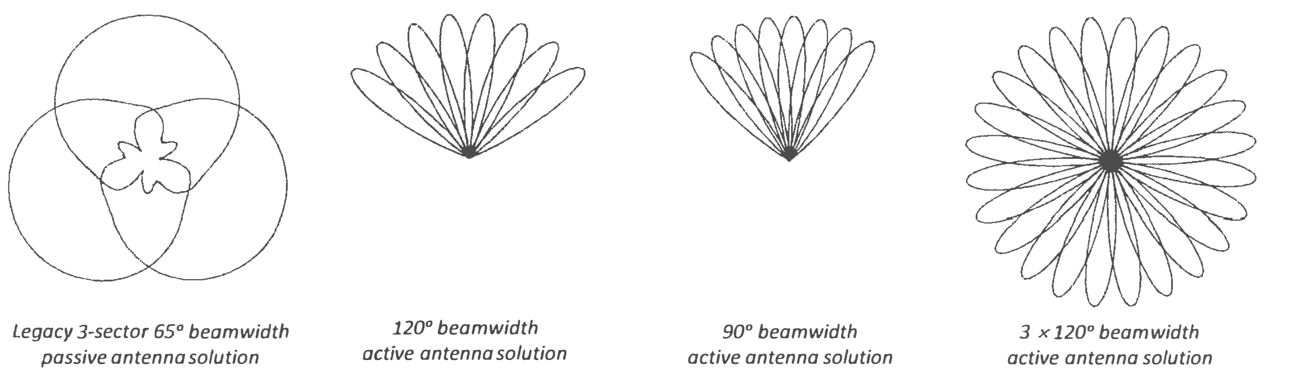


Figure 466 – Example passive and active antenna gain patterns

★ Figure 467 compares a set of SS/PBCH Block beams with a set of CSI Reference Signal beams. Within this context, the CSI Reference Signal is used for beam refinement. It is assumed that there are 4 CSI Reference Signal beams for each SS/PBCH Block beam. It is also assumed that all transceivers belonging to the active antenna are organised in a single row. This means that the 4 CSI Reference Signal beams associated with each SS/PBCH Block beam are distributed in a horizontal row (rather than a 2×2 grid or a vertical column). Figure 467 illustrates that the CSI Reference Signal beams offer a high resolution for beam selection and help to avoid any nulls between beams

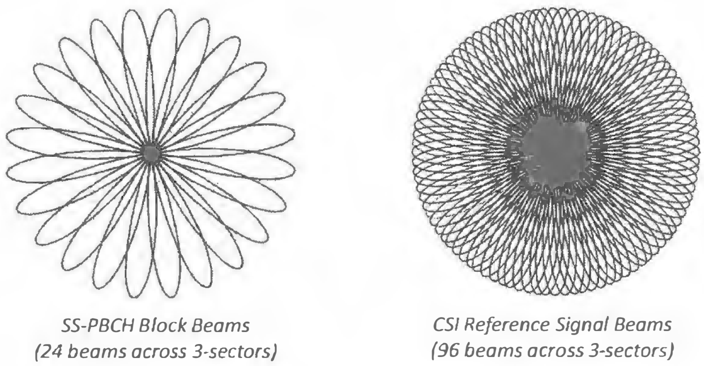


Figure 467 – Example SS/PBCH Block and CSI Reference Signal beams

★ In addition to studying the antenna gain patterns in the horizontal plane, it is important to also consider the vertical plane and the requirement for downtilt. Legacy passive antenna use a combination of mechanical and electrical downtilts. These downtilts help to ensure that RF transmissions do not overshoot into neighbouring cell coverage areas. Capacity limited regions with high site densities are likely to require increased downtilt relative to low traffic regions with lower site densities. Active antennas can use a combination of mechanical and electrical/beamforming downtilts. If the active antenna has multiple rows of transceivers, the beamforming downtilt is controllable and the active antenna can generate multiple rows of beams with a range of downtilts. Figure 468 illustrates two example beam patterns. The 8×1 beam pattern could be generated by a 16Tx16Rx active antenna with a single row of transceivers, whereas the 4×2 beam pattern could be generated by a 64Tx64Rx active antenna with multiple rows of transceivers

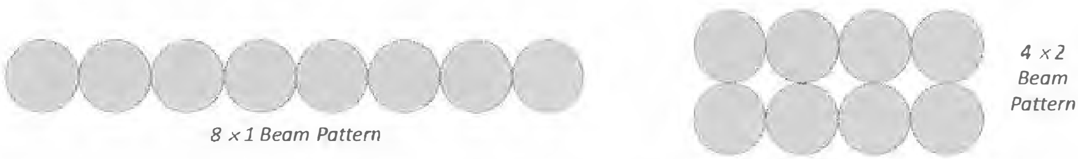


Figure 468 – 8×1 and 4×2 beam patterns

★ Figure 469 illustrates the downtilts belonging to single row and double row beam patterns. The vertical profile of the single row beam pattern is similar to a legacy passive cross polar panel antenna. The cell edge is defined by the angle of the upper 3 dB beamwidth. The vertical profile of the double row beam pattern illustrates the different beamforming downtilts provided by each row of beams. In this case, the cell edge is defined by the angle of the 3 dB beamwidth belonging to the upper row of beams. The lower row of beams provides coverage towards base of the antenna. Once the beam pattern has been selected and the beamforming downtilts identified, the mechanical downtilt can be determined

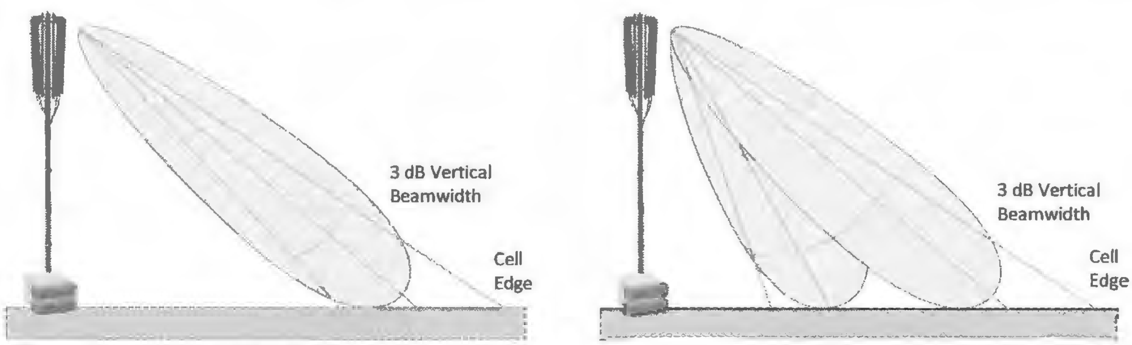


Figure 469 – Downtilts associated with single row and double row beam patterns

★ If the active antenna is being added to an existing Base Station site then the cell edge provided by the active antenna can be aligned with the cell edge provided by the existing legacy antenna. However, it may be appropriate to adjust the downtilt to account for differences in the operating bands, e.g. if a higher operating band is used with higher air-interface attenuation then there may be scope to reduce the downtilt to improve coverage

16.5 DOWNLINK TRANSMIT POWER

★ National regulators may specify a maximum permitted total EIRP per MHz. Operators are then responsible for ensuring that the limit is not exceeded

★ In the case of passive antenna deployments without beamforming, the EIRP per transmit path can be calculated by adding the antenna gain to the maximum commissioned transmit power and subtracting any cable/connector losses. The result must then be increased by the number of transmit paths, e.g. a 3 dB increase for 2×2 MIMO and a 6 dB increase for 4×4 MIMO. In this case, the antenna gain is fixed and is dependent upon the antenna model (in general, dependent upon the horizontal and vertical half power beamwidths). A typical antenna with 65° horizontal beamwidth could have a gain of 18 dBi. If Each transmit path is commissioned to operate with a maximum of 46 dBm and the cable/connector losses sum to 1 dB, then the maximum EIRP would be 63 dBm. If the Base Station is configured with 4 transmit paths to support 4×4 MIMO then this power would be increased to 69 dBm. This transmit power could be distributed across a 40 MHz channel bandwidth. A national regulator may specify an upper limit of 65 dBm per 5 MHz which corresponds to 74 dBm per 40 MHz

★ In the case of active antenna deployments with beamforming, the general principles of the calculation are the same but the antenna gain depends upon the beamforming weights applied to the transmitted signal, i.e. the antenna gain becomes a function of both the software and hardware. An active antenna using digital beamforming in Frequency Range 1 may be equipped with 64 transmit paths, and each transmit path could be commissioned to operate with a maximum of 26 dBm. In this case, the maximum total transmit power would be 26 + 10×LOG(64) = 44 dBm. The antenna gain generated by the active antenna could be 25 dBi for a directional beam, leading to an EIRP of 69 dBm

★ These examples serve to illustrate that a passive antenna solution with a high transmit power capability and moderate antenna gain can generate the same EIRP as an active antenna with a moderate transmit power capability and high antenna gain. It is possible that the transmit power of the active antenna could be increased but it may be restricted by the maximum EIRP regulatory requirements. The active antenna solution benefits the system by radiating the power across a narrower beamwidth and thus helps to reduce intercell interference which can have a significant impact upon system performance

★ It should be noted that the example above assumes that all of the downlink power is radiated using a single beam. In the case of digital beamforming, the Base Station could transmit from all beams simultaneously and then the downlink power is shared across the beams (the potential to allocate all of the downlink power to a single beam will depend upon the implementation of dynamic power sharing across beams). If the active antenna is configured with 8 beams and all beams are simultaneously active, then the transmit power per beam would be reduced by 10×LOG(8) = 9 dB

★ It may be permitted to include TDD duty cycles when calculating the maximum EIRP. For example, if 60% of slots are downlink then the average EIRP is 10×LOG(1/0.6) = 2.2 dB lower than the instantaneous EIRP

16.6 PCI ALLOCATION

★ Physical layer Cell Identity (PCI) planning for NR is similar to PCI planning for LTE and scrambling code planning for UMTS

- o NR has 1008 PCI which are organised into 336 groups of 3
- o LTE has 504 PCI which are organised into 168 groups of 3
- o UMTS has 512 scrambling codes organised into 64 groups of 8

★ The most important requirements for planning PCI are to remain 'Collision Free' and 'Confusion Free':

- o Collision Free: the physical separation between cells using the same PCI should be sufficiently great to ensure that a UE never simultaneously receives the same PCI from more than a single cell. This is achieved by maximising the re-use distance between cells which are allocated the same PCI. Planning should be simplified for NR relative to LTE because there are twice as many PCI values available to allocate. In the case of Frequency Range 2, site densities may be much higher but propagation losses will help to restrict dominance areas and prevent overshooting into neighbouring coverage areas
- o Confusion Free: the physical separation between cells using the same PCI should be sufficiently great to avoid neighbour ambiguity at a Base Station, i.e. the Base Station should be able to link a specific PCI to a specific neighbouring cell without ambiguity. This means that a cell should not have multiple neighbours using the same PCI

★ In addition, there are arguments (described below) for further PCI planning rules. These rules imply that UE should not be able to simultaneously receive multiple PCI with equal:

- o 'PCI mod 3' values
- o 'PCI mod 4' values
- o 'PCI mod 30' values

For example, the 'PCI mod 3' rule means that neighbouring cells should not be allocated PCI of 22 and 28 because they both have 'PCI mod 3' values of 1

- ★ The requirement for a 'PCI mod 3' rule is based upon the relationship between the PCI and the sequence transmitted by the Primary Synchronisation Signal (PSS). There are 3 different sequences which are re-used across the network and the sequence is determined by the value of 'PCI mod 3'. This means that cells which have the same 'PCI mod 3' result will transmit the same PSS. Simulations have shown that cell acquisition times can increase when a UE receives the same PSS from multiple cells. Receiving the PSS from multiple cells can cause the UE to make misleading channel estimates which are subsequently applied when attempting to detect the Secondary Synchronisation Signal (SSS)
- ★ In the case of LTE, there is an additional argument for the 'PCI mod 3' rule based upon the subcarriers occupied by the Cell specific Reference Signal (CRS). When cells are configured to transmit the CRS using 2 or more antenna ports, and those cells have equal 'PCI mod 3' results then the CRS transmissions collide (assuming time synchronisation between cells). These collisions can have a negative impact upon reported CQI values and consequently lead to lower allocated throughputs
- ★ The requirement for a 'PCI mod 4' rule is based upon the subcarriers occupied by the Demodulation Reference Signal (DMRS) for the PBCH. Subcarriers are allocated to the DMRS using a 'PCI mod 4' calculation. This leads to the DMRS occupying 25 % of subcarriers and means that there will be DMRS to DMRS interference if neighbouring cells have equal 'PCI mod 4' values. If neighbouring cells have unequal 'PCI mod 4' values then there will be PBCH to DMRS and DMRS to PBCH interference. The latter interference scenario is preferred although the impact is likely to be relatively small
- ★ The requirement for a 'PCI mod 30' rule is based upon the allocation of sequences to the PUSCH Demodulation Reference Signal (DMRS) when Transform Precoding is enabled. The full set of sequences is divided into 30 groups. The impact of intercell interference is reduced if different groups are allocated to neighbouring cells. The allocated group is based upon a 'PCI mod 30' calculation unless a value for *nPUSCH-Identity* is configured within the *DMRS-UplinkConfig*. When using a 'PCI mod 30' calculation, ensuring that neighbouring cells do not have equal 'PCI mod 30' values is analogous to ensuring that neighbouring cells use different uplink Reference Signal sequences. If the 'PCI mod 30' rule cannot be satisfied for practical reasons, group hopping can be enabled to help reduce the impact of any group collisions
- ★ If the 'PCI mod 3' rule is satisfied then the 'PCI mod 30' rule will also be satisfied. If a 3-sector Base Station is allocated a PCI Group, i.e. a set of 3 consecutive PCI values, then both the 'PCI mod 3' and 'PCI mod 4' rules will be satisfied across the cells of that Base Station
- ★ Figure 470 illustrates an example deployment of 3-sector Base Stations, where each Base Station has been allocated a single group of PCI. An ideal hexagonal cell layout is assumed for the purposes of this example. The 'PCI mod 3' rule is satisfied between all direct neighbours. The 'PCI mod 4' rule is satisfied between neighbours belonging to the same Base Station, but is not satisfied between neighbours belonging to different Base Stations

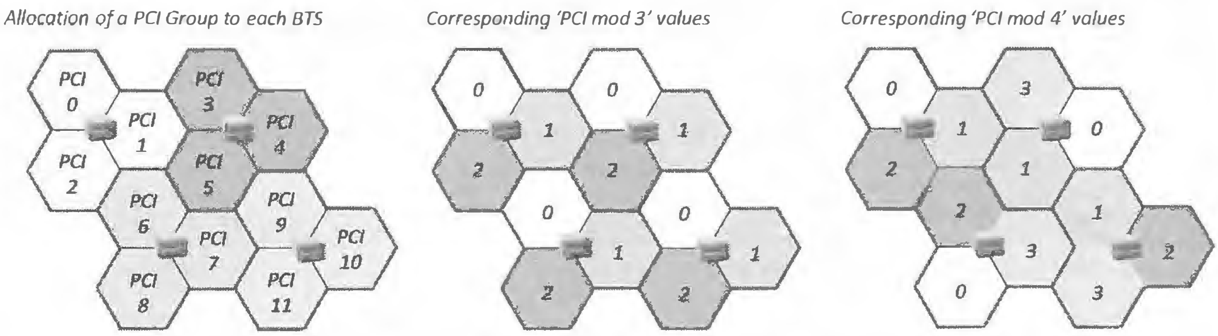


Figure 470 – 'PCI mod 3' and 'PCI mod 4' results when allocating PCI groups to 3-sector BTS

- ★ In practice, Base Stations will not have an ideal hexagonal cell layout. The situation is further complicated by heterogeneous network architectures where a single macrocell could be neighboured with many micro, pico or femto cells. In those cases, the 'PCI mod 3' rule may be satisfied intra-BTS but not inter-BTS
- ★ If Base Stations have 6 sectors then PCI planning can be based upon allocating 2 PCI groups to each Base Station. If all sites were 6-sector then the maximum re-use pattern at a Base Station level would reduce from 336 to 168
- ★ In addition to the PCI planning rules described above, a range of PCI can be excluded from the network plan to allow for future network expansion, or the introduction of Femto cells. Femto cells could be allocated a subset of the total PCI. The size of the subset would depend upon the expected density of the Femto cell deployment. Femto cells typically allocate their own PCI from an allocated range after being switched-on and scanning for the PCI used by neighbouring Base Stations
- ★ Additional rules for PCI planning are required at locations close to international borders where there may be another 5G operator using the same RF carrier. These rules are often specified by regulatory organisations. For example, in Europe the Electronic Communications Committee (ECC) within the European Conference of Postal and Telecommunications Administrations (CEPT) has specified ECC Recommendation (08)02. This document states that coordination can be avoided if signal strengths across the international border are below specific thresholds. Otherwise, it recommends that co-channel PCI should be coordinated between neighbouring 5G systems in border areas

16.7 CYCLIC PREFIX

- The Cyclic Prefix represents a guard period at the start of each symbol which provides protection against multi-path delay spread. The cyclic prefix also represents an overhead which should be minimised. The cyclic prefix is described in section 2.8
- 3GPP TS 38.211 specifies the normal cyclic prefix for all subcarrier spacings, and the extended cyclic prefix for the 60 kHz subcarrier spacing. Specifying the extended cyclic prefix for the 60 kHz subcarrier spacing allows it to be used within both Frequency Range 1 and Frequency Range 2
- The extended cyclic prefix increases the duration of each symbol because the duration of the cyclic prefix increases while duration of the payload remains constant. The extended cyclic prefix decreases the number of symbols within each slot from 14 symbols to 12 symbols, i.e. physical layer air-interface capacity is reduced
- The normal cyclic prefix can be used for the majority of deployment scenarios. It should be noted that the normal cyclic prefix at 15 kHz can tolerate a larger delay spread than the extended cyclic prefix at 60 kHz. Thus, when using Frequency Range 1, the normal cyclic prefix at 15 kHz can also be considered as a solution to tolerate increased delay spreads. Table 52 and Table 53 within section 2.8 present the normal and extended cyclic prefix durations and their equivalent distances
- The duration of the cyclic prefix should be greater than the multi-path delay spread. The delay spread depends upon the cell range as well as the propagation environment and the presence of any distant reflectors
- Small cells, microcells and indoor solutions typically have delay spreads in the order of 10 to 100 ns, so can use the normal cyclic prefix. Macrocells within urban and suburban areas typically have delay spreads in the order of 1 or 2 μs. This means that macrocells can use the normal cyclic prefix when assuming that macrocells are deployed using Frequency Range 1, i.e. a lower operating band with a lower subcarrier spacing and a longer cyclic prefix duration. Rural areas have a low delay spread when the environment is open and there is line-of-sight propagation. However, the delay spread can also become high as a result of the larger cell range and potentially the presence of any distant reflectors

16.8 CSI REFERENCE SIGNAL

- The CSI Reference Signal is a flexible multi-purpose signal as described in section 3.7.4. The requirement for planning will depend upon the use-case and the network implementation. The example presented within this section is based upon the transmission of CSI Reference Signals for Beam Management, i.e. using them to support beam refinement during the 'P-2' phase of Beam Management
- The network implementation may provide a choice of CSI Reference Signal densities. Table 120 in section 3.7.4 illustrates that densities of 3, 1 and 0.5 Resource Elements per Resource Block are supported. Figure 471 illustrates examples of CSI Reference Signals configured with densities of 3 and 1 Resource Elements per Resource Block. Configuring a higher density allows the UE to complete its measurements with increased accuracy. Configuring a lower density increases the scope for frequency multiplexing

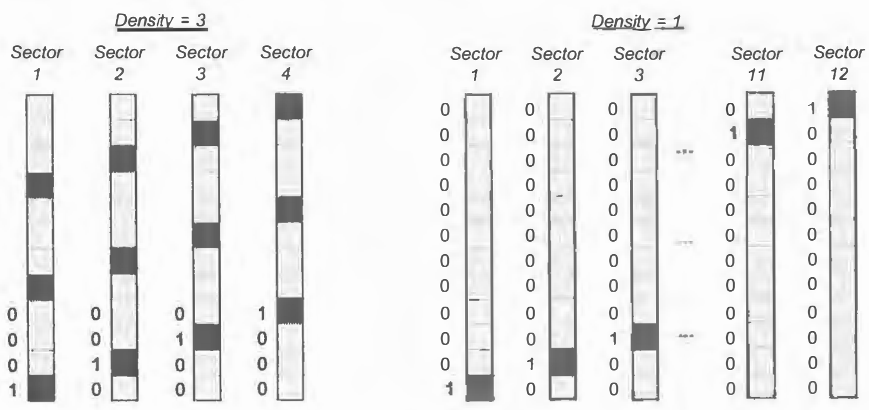


Figure 471 – Multiplexing of CSI Reference Signals with densities of 3 and 1 Resource Elements per Resource Block

- If Base Stations are deployed with 3 or 4 sectors then the density of 3 Resource Elements per Resource Block can be selected. This helps to maximise the accuracy of UE measurements and provides sufficient scope for frequency multiplexing around the sectors of the Base Station. Frequency multiplexing avoids CSI RS to CSI RS interference between sectors
- If Base Stations are configured with more than 4 sectors then the density of 3 could still be used but with re-use of the frequency multiplexing positions. Alternatively, the density of 1 could be used to allow up to 12 multiplexing positions

16.9 PHASE TRACKING REFERENCE SIGNAL

★ The Phase Tracking Reference Signal (PTRS) is described in section 3.7.6 for the downlink and in section 7.5.4 for the uplink. In terms of Radio Network Planning, the network implementation may allow configuration of the subcarriers occupied by the PTRS. It is preferable for neighbouring cells to use different subcarriers to avoid PTRS to PTRS interference

★ Table 353 presents the PTRS subcarrier offset for each combination of DMRS Antenna Port, DMRS Configuration Type and *resourceElementOffset*. This table is applicable to the downlink but the same table exists for the uplink with the exception that DMRS antenna ports 1000 to 1005 are replaced by DMRS antenna ports 1 to 5

★ The subcarrier offsets have been specified to ensure that the PTRS uses the same subcarriers as the DMRS. For example, antenna ports 1000 and 1001, with DMRS Configuration Type 1 use even numbered subcarriers for the DMRS, whereas antenna ports 1002 and 1003 use odd numbered subcarriers. The PTRS has not been specified to be used with the DMRS 'Double Symbol' configuration. This means that antenna ports 1004 to 1007 are not applicable when using Configuration Type 1, and antenna ports 1006 to 1011 are not applicable when using Configuration Type 2

DMRS Antenna Port	k_{ref}^{RE}							
	DMRS Configuration Type 1 *resourceElementOffset*				DMRS Configuration Type 2 *resourceElementOffset*			
	00	01	10	11	00	01	10	11
1000	0	2	6	8	0	1	6	7
1001	2	4	8	10	1	6	7	0
1002	1	3	7	9	2	3	8	9
1003	3	5	9	11	3	8	9	2
1004	-	-	-	-	4	5	10	11
1005	-	-	-	-	5	10	11	4

Table 353 – PTRS Subcarrier Offset as a function of the DMRS antenna port, DMRS Configuration Type and *resourceElementOffset*

★ Figure 472 illustrates the subcarriers occupied by the PTRS when *resourceElementOffset* is configured with values of '00', '01', '10' and '11' (assuming DMRS Antenna Port 1000 and Configuration Type 1). PTRS to PTRS interference is avoided if neighbouring cells are configured with different *resourceElementOffset* values. The set of 4 values restricts the size of the re-use pattern so it is likely that PTRS to PTRS interference will exist between some neighbouring cells. An example strategy could involve configuring each sector belonging to a specific Base Station with different *resourceElementOffset* values. This would at least avoid PTRS to PTRS interference between sectors belonging to the same Base Station

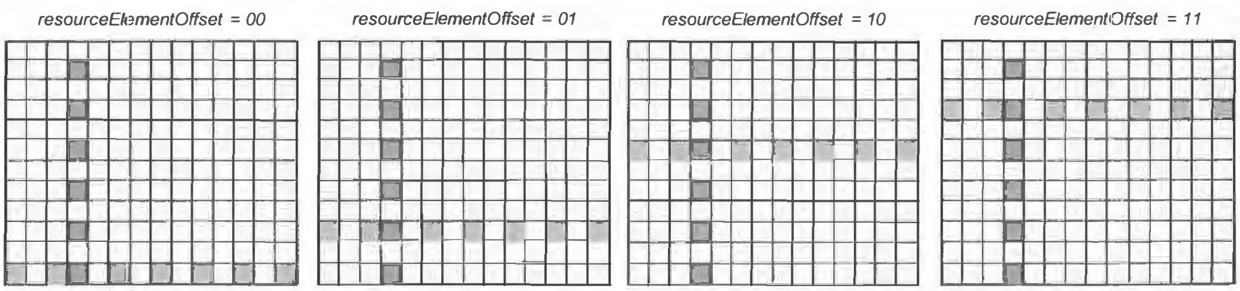


Figure 472 – PTRS Subcarrier Offsets for DMRS Antenna Port 1000 (DMRS Configuration Type 1)

★ Table 353 illustrates that different combinations of DMRS Antenna Port and *resourceElementOffset* can lead to equal subcarrier offsets. For example, {Antenna Port 1000; *resourceElementOffset* = '01'} and { Antenna Port 1001; *resourceElementOffset* = '00'} both use a subcarrier offset of '2' when assuming Configuration Type 1. The downlink PTRS is transmitted using only a single antenna port so a UE which is configured for 2×2 MIMO and is using DMRS antenna ports 1000 and 1001 will receive the PTRS on only one of those antenna ports

★ The PTRS is transmitted within every 2nd Resource Block or every 4th Resource Block depending upon the size of the PDSCH/PUSCH Resource Block allocation (see Table 127 for the downlink, and Table 226 for the uplink). This allows frequency multiplexing of the Resource Blocks used by the PTRS. The Resource Block offset is randomised by calculating its value from the RNTI belonging to the UE which is receiving the resource allocation. This means that neighbouring cells using the same PTRS subcarrier offset can avoid PTRS to PTRS interference if the RNTI calculations lead to different Resource Block offsets. This frequency multiplexing will be randomised according to the UE which are scheduled at any point in time, i.e. some resource allocations may lead to PTRS to PTRS interference while other resource allocations may avoid PTRS to PTRS interference

16.10 PRACH PLANNING

16.10.1 PRACH FORMAT

★ The PRACH Format must be selected from either:

  - the set of long PRACH Formats (0, 1, 2, 3), or
  - the set of short PRACH Formats (A1, A2, A3, B1, B4, A1/B1, A2/B2, A3/B3, C0, C2)

  Formats 'B2' and 'B3' are always used in combination with Formats 'A2' and 'A3' respectively

★ Long PRACH formats are described in section 7.2.3, while short PRACH Formats are described in section 7.2.4

★ Figure 473 summarises the criteria used to select the PRACH Format. The Frequency Range should be considered as the first criteria - operating bands within Frequency Range 2 only support the short PRACH Formats. In contrast, operating bands within Frequency Range 1 support both the long and short PRACH Formats

★ The Slot Format should be considered as the second criteria when selecting a PRACH Format. If using FDD, the Slot Format does not restrict the PRACH Format because continuous uplink transmission is permitted. If using TDD, the Slot Format can restrict the choice of PRACH Format. For example, if the 30 kHz subcarrier spacing is used in combination with the following Slot Format pattern {D, D, D, F, U, D, D, D, F, U}, the maximum number of contiguous uplink slots is 1. This leads to a maximum uplink transmission period of 0.5 ms (based upon the 30 kHz subcarrier spacing and ignoring uplink symbols within the Flexible slot). Long PRACH Formats have a minimum period of 1 ms so in this case, it would be necessary to configure a Short PRACH Format. Alternatively, if the 30 kHz subcarrier spacing is used in combination with the following Slot Format pattern {D, D, D, D, D, D, D, F, U, U}, the maximum number of contiguous uplink slots is 2. This leads to a maximum uplink transmission period of 1 ms so it becomes possible to select long PRACH Formats 0 and 3 (see Table 167 for the durations associated with each of the long PRACH Formats)

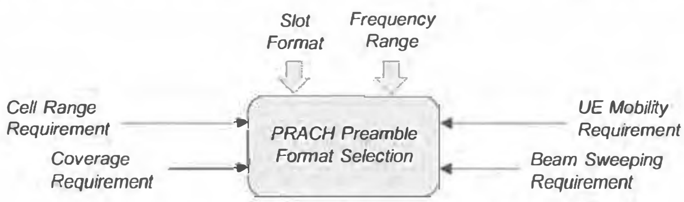


Figure 473 – Criteria used to select the PRACH Preamble Format

★ The cell range requirement is also an important criteria when selecting a PRACH Format. Long PRACH Formats support maximum cell ranges between 14 and 100 km, whereas, short PRACH Formats are restricted to supporting cell ranges up to 9.3 km. The majority of short PRACH Formats support maximum cell ranges below 5 km. Table 167 presents the maximum cell ranges for the long PRACH Formats, while Table 173 presents the maximum cell ranges for the short PRACH Formats. In all cases, the precise maximum cell range depends upon the assumed propagation channel delay spread

★ The coverage requirement can be used as an input when selecting a repetition level for the PRACH sequence. Within this context, coverage requirement refers to deep indoor coverage rather than long range coverage, i.e. improving coverage within the existing cell range rather than extending the maximum cell range

  - in the case of the long PRACH Formats, the 'Sequence Duration' column within Table 167 indicates that PRACH Format 1 benefits from 2 transmissions of the sequence, while PRACH Formats 2 and 3 benefit from 4 transmissions of the sequence. PRACH Format 2 is intended to provide the best coverage performance because it is based upon the transmission of 4×800 μs sequences (PRACH Format 3 uses a higher subcarrier spacing and is intended for high mobility scenarios)
  - in the case of the short PRACH Formats, the 'Sequence Duration' column within Table 173 indicates the repetition level for each PRACH Format. For example, PRACH Format A1 benefits from 2 transmissions of the sequence, while Format B4 benefits from 12 transmissions of the sequence

★ The UE mobility requirement can be used as a criteria when selecting the subcarrier spacing. Long PRACH Formats 0, 1 and 2 use a subcarrier spacing of 1.25 kHz while long PRACH Format 3 uses a subcarrier spacing of 5 kHz. The larger subcarrier spacing is more robust in the presence of Doppler frequency offsets. Short PRACH Formats can be configured to use subcarrier spacings of 15, 30, 60 or 120 kHz. These larger subcarrier spacings are more robust in the presence of Doppler frequency offsets. However, the smaller cell ranges associated with the short PRACH Formats will require more frequent handovers if deployed at locations with high UE mobility

★ Short PRACH Formats are more suitable for Base Stations configured with large beam sweeping patterns. The short duration of each PRACH occasion allows the Base Station to rapidly sweep through the set of beam positions, i.e. minimising latency. Operating bands within Frequency Range 2 can support up to 64 SS/PBCH beams and in this case it is mandatory to use a short PRACH Format. In the case of Frequency Range 1, PRACH latency can become significant if long PRACH preambles are used in combination with the maximum of 8 SS/PBCH beams. In this case, latency can be reduced by allowing multiple beams to share a single PRACH occasion, i.e. the set of 64 PRACH preambles can be shared across beams. Alternatively, latency can be reduced by frequency multiplexing PRACH occasions

16.10.2 PRACH CONFIGURATION INDEX

★ The PRACH Configuration Index must be selected from one of three tables specified by 3GPP TS 38.211:

- o Frequency Range 1, Paired Spectrum (FDD) and Supplementary Uplink, or
- o Frequency Range 1, Unpaired Spectrum (TDD), or
- o Frequency Range 2, Unpaired Spectrum (TDD)

Each table includes 256 rows which are grouped according to the PRACH Preamble Format. Once the relevant table and PRACH Preamble Format have been identified, the number of rows available for selection is typically reduced to within the range of 15 to 30

★ Table 171 and Table 172 present the rows which are applicable to long PRACH Formats 0 to 3. Table 177, Table 178 and Table 179 present a subset of the rows which are applicable to the short PRACH Formats

★ Figure 474 illustrates the criteria used to select the PRACH Configuration Index. The PRACH Preamble Format should be considered as the first criteria because it identifies the set of rows available for selection

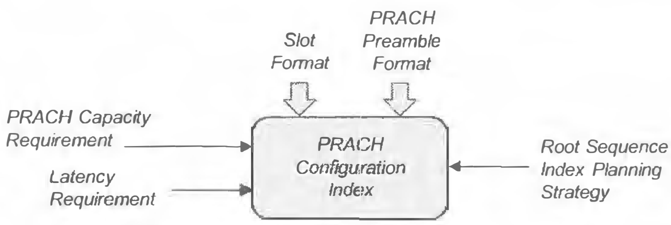


Figure 474 – Criteria used to select the PRACH Configuration Index

★ The Slot Format should be considered as the second criteria because it may further restrict the set of rows available for selection. If using FDD, the Slot Format does not restrict the PRACH Configuration Index because all slots are available for uplink transmission. If using TDD, the Slot Format can restrict the choice of PRACH Configuration Indices because the Configuration Index defines the timing of the PRACH opportunities and these opportunities must coincide with the timing of the uplink slots

★ Figure 475 illustrates an example TDD Slot Format which allows uplink transmission during subframes 2 and 7. If using PRACH Format 0, there are only 3 PRACH Configuration Indices available for selection. These are visible within Table 172 as PRACH Configuration Indices 9, 14 and 19

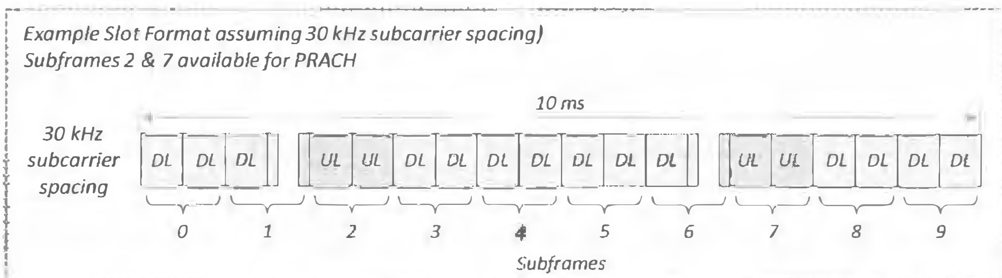


Figure 475 – Example Slot Format with subframes 2 and 7 available for PRACH transmission

★ The PRACH capacity and latency requirements should also be considered when selecting a PRACH Configuration Index. For example, PRACH Configuration Index 0 within Table 172 provides a low capacity and high latency because there is a single PRACH occasion every 160 ms (assuming PRACH occasions are not frequency multiplexed). The benefit of this configuration is a low PRACH overhead. PRACH Configuration Index 7 provides a moderate capacity and latency because there is a single PRACH occasion every 10 ms. PRACH Configuration Index 27 provides a high capacity and low latency because there are five PRACH occasions every 10 ms

★ The PRACH Root Sequence Index planning strategy can also impact the selection of the PRACH Configuration Index. Section 16.10.5 describes 2 alternative strategies:

- o all neighbouring cells are allocated a common PRACH Configuration Index, but a different Root Sequence Index
- o all cells belonging to a specific Base Station (or Distributed Unit if using the CU/DU Split Base Station architecture) are allocated a common Root Sequence Index, but a different combination of PRACH Configuration Index and PRACH Frequency Offset

★ The latter strategy helps to reduce the probability of Root Sequence collisions by increasing the Root Sequence re-use distance, i.e. Root Sequences are allocated 'per Base Station' rather than 'per cell'. The PRACH Configuration Index can be used to provide isolation in the time domain. When using the example shown in Figure 475, sector 1 could be allocated Configuration Index 14 to use subframe 2, sector 2 could be allocated Configuration Index 9 to use subframe 7, while sector 3 could also be allocated Configuration Index 9 but with a different PRACH Frequency Offset to provide isolation in the frequency domain

16.10.3 ZERO CORRELATION ZONE

★ Selecting a Zero Correlation Zone is a prerequisite to planning the PRACH Root Sequence Indices

★ Each PRACH occasion allows the use of 64 preamble sequences. These preamble sequences allow multiple UE to share the same set of time and frequency domain resources when transmitting their PRACH preambles

★ 3GPP TS 38.211 specifies that preamble sequences are generated from a set of 838 Root Sequences when using a long PRACH Format and from a set of 138 Root Sequences when using a short PRACH format. Each preamble sequence is generated from its Root Sequence by applying a cyclic shift. The Zero Correlation Zone determines the size of the cyclic shift and the number of preamble sequences which can be generated from each Root Sequence. The key trends associated with selecting large and small Zero Correlation Zones are:

- large Zero Correlation Zones:
  - large cyclic shifts used to generate preamble sequences from each Root Sequence. This leads to a larger maximum permitted propagation delay and thus, a larger cell range
  - fewer preamble sequences can be generated from each Root Sequence, so each cell requires an increased number of Root Sequences. This reduces the Root Sequence re-use pattern size and increases the potential for Root Sequence collisions
- small Zero Correlation Zones:
  - small cyclic shifts used to generate preamble sequences from each Root Sequence. This leads to a smaller maximum permitted propagation delay and thus, a smaller cell range
  - more preamble sequences can be generated from each Root Sequence, so each cell requires fewer Root Sequences. This increases the Root Sequence re-use pattern size and decreases the potential for Root Sequence collisions

★ It is beneficial to generate as many preamble sequences as possible from the same Root Sequence because these sequences are orthogonal to one another. Preamble sequences generated from different root sequences are not orthogonal

★ Figure 476 summarises the criteria used to select the Zero Correlation Zone. The combination of PRACH Preamble Format, PRACH subcarrier spacing and UE mobility requirement determines the look-up table used to select the Zero Correlation Zone

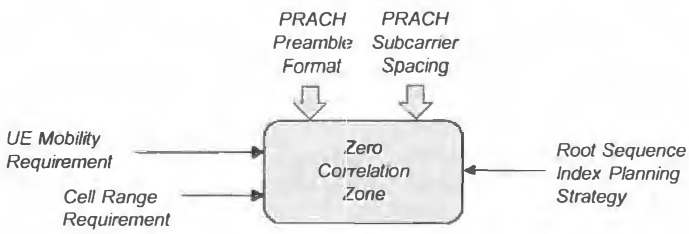


Figure 476 – Criteria used to select the Zero Correlation Zone

★ Table 169 in section 7.2.3 presents the relationship between Zero Correlation Zone, Root Sequence Index re-use pattern size and cell range when using a long PRACH Format with the 1.25 kHz subcarrier spacing, i.e. PRACH Formats 0, 1 or 2. Table 170 presents the same relationship when using a long PRACH Format with the 5 kHz subcarrier spacing, i.e. PRACH Format 3. Both of these tables are applicable to low/medium mobility scenarios, i.e. they assume the 'unrestricted' set of cyclic shifts rather than the 'restricted' set of cyclic shifts. The High Speed Flag described in section 16.10.4 is used to select between the 'unrestricted' and 'restricted' sets of cyclic shifts. The 'restricted' sets of cyclic shifts are intended for high mobility scenarios

★ The appropriate Zero Correlation Zone is identified by selecting the smallest value which satisfies the maximum cell range requirement. This approach ensures that the cell range is sufficient while helping to maximise the Root Sequence re-use pattern size. It is important to ensure that the selected cell range caters for any overshooting of RF transmissions in the live network. If a cell radiates beyond its maximum cell range then UE which are located outside the maximum cell range will experience failed PRACH procedures

★ This results from the increased propagation delay appearing similar to an increased cyclic shift, i.e. both increased propagation delay and increased cyclic shift cause the Base Station to receive a signal which appears delayed in time. If the maximum cell range is exceeded, the increased propagation delay causes preamble 'X' to appear similar to preamble 'Y' (because preambles are generated by applying cyclic shifts to the Root Sequence). This means that the Base Station will provide a Random Access Response for preamble 'Y' while the UE is monitoring for a response to preamble 'X', i.e. the MSG1 to MSG3 success rate will become poor

★ Table 175 in section 7.2.4 presents the relationship between Zero Correlation Zone and Root Sequence Index re-use pattern size when using a short PRACH Format. In this case, the re-use pattern sizes are significantly smaller because there are only 138 Root Sequences available. Table 176 presents the relationship between Zero Correlation Zone and cell range when using subcarrier spacings of 15, 30, 60 or 120 kHz. These cell ranges are relatively small due to the reduced symbol duration associated with the higher subcarrier spacings. The reduced symbol duration leads to a reduced maximum permitted round trip delay associated with each cyclic shift

16.10.4 HIGH SPEED FLAG

★ The high speed flag is only applicable to the long PRACH Formats, i.e. it cannot be applied when using Frequency Range 2. It is configured using the *restrictedSetConfig* information element presented in Table 354. Configuring a value of 'unrestrictedSet' indicates support for low to medium mobility scenarios, while configuring values of 'restrictedSetTypeA' or 'restrictedSetTypeB' indicates support for high and very high mobility scenarios respectively

extract from *RACH-ConfigCommon*	
restrictedSetConfig	unrestrictedSet, restrictedSetTypeA, restrictedSetTypeB

Table 354 – Configuration of the High Speed Flag

★ 3GPP has introduced the concept of 'Restricted Sets' to mitigate the impact of the Doppler frequency offsets which can be experienced when travelling at high speed. Frequency offsets have a negative impact upon PRACH performance by generating additional peaks in the auto-correlation function. The use of Restricted Sets reduces the number of cyclic shifts which can be applied to each Root Sequence to ensure that there is no ambiguity between the wanted auto-correlation peaks and the unwanted auto-correlation peaks

★ The Unrestricted Sets are intended for use with frequency offsets which do not exceed half of the subcarrier spacing. 'Type A' Restricted Sets are intended for use with frequency offsets which do not exceed the subcarrier spacing, whereas 'Type B' Restricted Sets are intended for use with frequency offsets which do not exceed twice the subcarrier spacing

★ Figure 242 in section 7.2.1 illustrates an example of restricting the set of cyclic shifts to mitigate the impact of a frequency offset. Different Root Sequences exhibit different patterns of unwanted auto-correlation peaks. This leads to different Root Sequences supporting different numbers of permitted cyclic shifts

★ When using the Unrestricted set of cyclic shifts, the number of preamble sequences generated from each Root Sequence is constant. This makes it relatively easy to group the Root Sequences when allocating them to individual cells. When using a Restricted set of cyclic shifts, the number of preamble sequences generated from each Root Sequence is no longer constant and this complicates the allocation of Root Sequences. In addition, the use of Restricted cyclic shifts reduces the number of preamble sequences which can be generated from each Root Sequences. This reduces the Root Sequence re-use pattern size and increases the potential for Root Sequence collisions

16.10.5 ROOT SEQUENCE INDEX

★ Root Sequences are used to generate the set of 64 PRACH preambles belonging to each PRACH occasion. The number of preambles which can be generated from each Root Sequence depends upon the Zero Correlation Zone. Figure 477 illustrates an example based upon cells which require 10 Root Sequences to generate their 64 PRACH preambles. The means that each cell is allocated 10 Root Sequences

★ The RRC signalling protocol is used to specify the <u>first</u> Root Sequence belonging to each cell. This is done using the *prach-RootSequenceIndex* within the *RACH-ConfigCommon* parameter structure (Table 255), which can be broadcast within SIB1 or provided to the UE using dedicated signalling. The UE and Base Station use consecutive additional Root Sequence Indices to generate the complete set of 64 PRACH preambles

Figure 477 – Example PRACH Root Sequences used by neighbouring cells

★ The allocated Root Sequence Index and the consecutive additional Root Sequence Indices refer to 'logical' Root Sequence Indices. 3GPP TS 38.211 provides a look-up table to map logical Root Sequence Indices onto physical Root Sequence Indices. This mapping means that the actual physical Root Sequences are not consecutive. However, from the perspective of Radio Network Planning and UE signalling it is only necessary to consider the logical values

★ Root Sequence Indices should be allocated to cells with a re-use distance which ensures that a specific cell never receives PRACH transmissions from a UE which is using the same Root Sequence within another cell. Root Sequence Index collisions generate unnecessary PRACH load and poor PRACH performance. If multiple cells using the same Root Sequence receive a PRACH preamble from a UE, then both cells will respond with a MSG2 transmission. The UE will respond to one of those cells with MSG3, while the other cell will record a failure between MSG1 and MGS3. This increased PRACH load and poor PRACH performance may not impact the end-user experience but nevertheless this scenario should be minimised in live network deployments

* Figure 478 illustrates the criteria used to allocate the set of Root Sequence Indices. The PRACH Preamble Format should be considered as the first criteria because it determines the total number of Root Sequences available for planning. Long PRACH Formats support 838 Root Sequences, whereas short PRACH Formats support only 138 Root Sequences

* Generating a Root Sequence Index plan is relatively challenging when only 138 Root Sequences are available (after accounting for the fact that each cell will normally require multiple Root Sequences). In the case of Frequency Range 2, the higher air-interface attenuation helps to avoid Root Sequence Index collisions. In the case of Frequency Range 1, the deployment of small cells with restricted coverage areas can help to avoid Root Sequence Index collisions. Otherwise, the deployment of macrocells in Frequency Range 1 will be simplified if long PRACH Formats are configured to allow the use of 838 Root Sequences

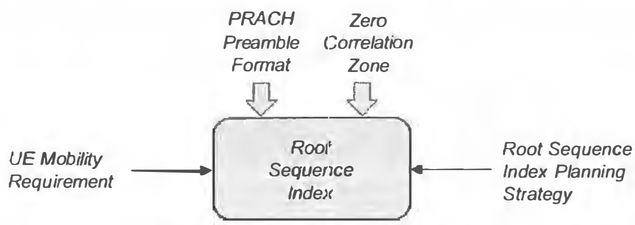


Figure 478 – Criteria used to plan the PRACH Root Sequence Indices

* The Root Sequence Index Planning strategy determines the solution for multiplexing PRACH resources across a group of cells. Two example strategies are illustrated in Figure 479. The first strategy allocates the same Root Sequence Index to all cells belonging to the same Base Station. Those cells are then isolated in the time and frequency domains by configuring different combinations of *prach-ConfigurationIndex* and *msg1-FrequencyStart*. This strategy increases the Root Sequence re-use distance and reduces the potential for Root Sequence collisions. A potential drawback associated with this strategy is the introduction of PUSCH to PRACH inter-cell interference, i.e. relatively high power PUSCH transmissions in one cell can generate interference towards PRACH transmissions in a neighbouring cell

* This first strategy could be extended by allocating the same Root Sequence to a cluster of Base Stations, assuming that all cells within that cluster are allocated different combinations of *prach-ConfigurationIndex* and *msg1-FrequencyStart*.

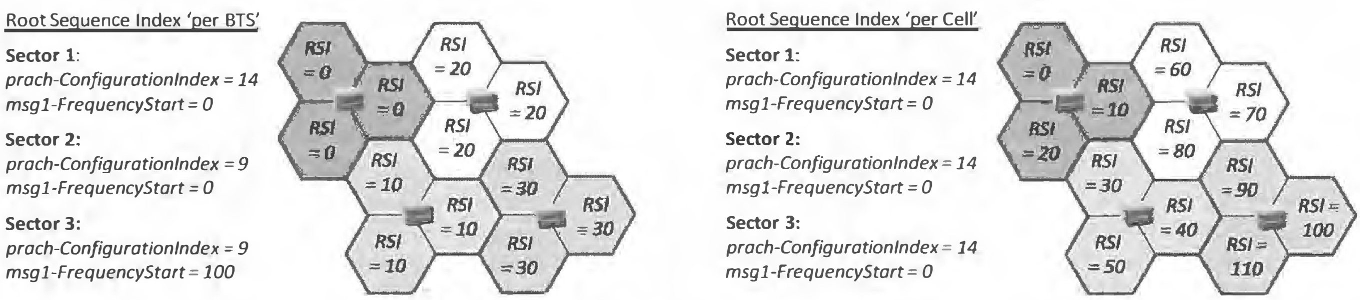


Figure 479 – PRACH Root Sequence Index planning strategies

* The second strategy illustrated in Figure 479 allocates a different Root Sequence Index to each cell within the re-use distance. This allows each cell to be configured with the same PRACH time and frequency resources, i.e. cells are multiplexed in the code domain rather than the time and frequency domains. This approach has the potential benefit of maintaining only PRACH to PRACH inter-cell interference

* This second example highlights the potential challenge associated with Root Sequence Index planning when only 138 Root Sequences are available, i.e. a cluster of only four 3-sector Base Stations have already consumed 120 Root Sequences. A fifth Base Station would have to start re-using some of the already allocated Root Sequences and there would be a risk of inadequate isolation between cells using the same Root Sequence

* If Root Sequence planning becomes challenging due to a small re-use distance, it is possible to increase the re-use distance by restricting the number of PRACH preambles belonging to each PRACH occasion. For example, the number of Root Sequences required per cell can be reduced by a factor of 2 if the number of preambles per PRACH occasion is restricted to 32 rather than 64. This solution reduces PRACH capacity but allows easier Root Sequence planning

* The UE mobility requirement can have a significant impact upon Root Sequence Index planning. If the mobility requirement forces the use of a 'Restricted' set of cyclic shifts then Root Sequence planning becomes more challenging in terms of:

  o the number of PRACH preamble sequences which can be generated from each Root Sequence is reduced so the Root Sequence re-use distance becomes smaller and there is increased potential for collisions

  o the number of PRACH preamble sequences generated from each Root Sequence is no longer constant. This means that instead of allocating evenly spaced Root Sequences, e.g. 0, 10, 20, 30,... etc, it will be necessary to allocate unevenly spaced Root Sequences, e.g. 0, 10, 26, 38, etc

16.10.6 PRACH FREQUENCY OFFSET

★ The PRACH frequency offset determines the position of the PRACH occasions in the frequency domain. A cell can be configured to use a single PRACH occasion in the frequency domain, or can be configured to use up to 8 frequency multiplexed PRACH occasions. Frequency multiplexed PRACH occasions occupy a contiguous set of Resource Blocks

★ The RRC signalling protocol is used to specify the frequency domain position of the first Resource Block belonging to the first PRACH occasion. This is done using the *msg1-FrequencyStart* information element. The number of frequency multiplexed PRACH occasions is specified using the *msg1-FDM* information element. Both of these information elements are presented in Table 355. They can be provided to the UE in SIB1 or can be provided using dedicated signalling

extract from *RACH-ConfigGeneric*	
msg1-FDM	1, 2, 4, 8
msg1-FrequencyStart	0 to 274

Table 355 – Frequency domain parameters for the PRACH

★ Figure 480 illustrates the principle of frequency multiplexing PRACH occasions. *msg1-FrequencyStart* specifies a Resource Block within the active uplink Bandwidth Part. The number of Resource Blocks occupied by each PRACH occasion depends upon the subcarrier spacings of both the PRACH and the PUSCH. The PRACH occupies 6 Resource Blocks when using the 1.25 kHz subcarrier spacing if the PUSCH uses the 15 kHz subcarrier spacing

★ In all cases, the PRACH does not fully occupy the set of allocated Resources Blocks, i.e. there is a guard band either side of the PRACH transmission. Table 168 in section 7.2.3 presents the bandwidth occupied by a PRACH transmission when using a long PRACH Format. Similarly, Table 174 in section 7.2.4 presents the bandwidth occupied by a PRACH transmission when using a short PRACH Format

Long PRACH Preamble Formats
839 Subcarriers

		Resource Blocks Occupied by PRACH		
PRACH Subcarrier Spacing	Occupied Bandwidth	15 kHz PUSCH	30 kHz PUSCH	60 kHz PUSCH
1.25 kHz	1048.75 kHz	6	3	2
5 kHz	4195 kHz	24	12	6

Short PRACH Preamble Formats
139 Subcarriers

		Resource Blocks Occupied by PRACH			
PRACH Subcarrier Spacing	Occupied Bandwidth	15 kHz PUSCH	30 kHz PUSCH	60 kHz PUSCH	120 kHz PUSCH
15 kHz	2085 kHz	12	6	3	-
30 kHz	4170 kHz	24	12	6	-
60 kHz	8340 kHz	-	-	12	6
120 kHz	16680 kHz	-	-	24	12

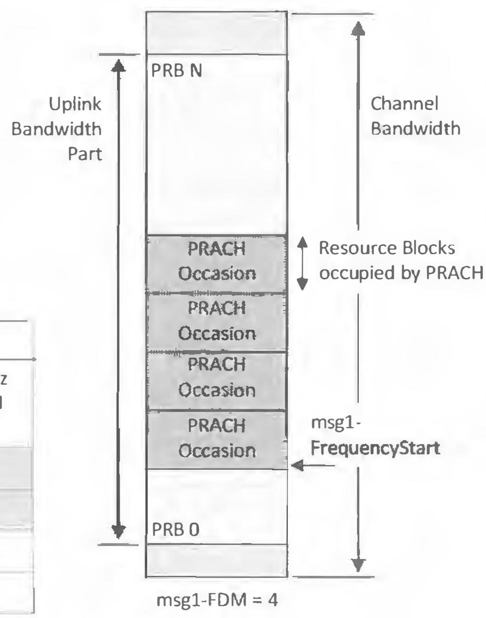


Figure 480 – Frequency multiplexing of PRACH occasions

★ The main objective when configuring the PRACH frequency offset (*msg1-FDM*) is to avoid fragmentation of the Resource Blocks available to the PUSCH, i.e. the PRACH should be positioned to one side of the Bandwidth Part. The Packet Scheduler is permitted to allocate non-contiguous Resource Blocks for the PUSCH but with certain restrictions. These restrictions mean that it remains preferable to avoid fragmentation of the Resource Blocks available to the PUSCH:

- o when using Frequency Range 2, it is mandatory to allocate contiguous Resource Blocks for the PUSCH
- o when using Frequency Range 1, it is mandatory to allocate contiguous Resource Blocks for the PUSCH when Transform Precoding is enabled (the DFT-S-OFDM waveform is used)
- o when using Frequency Range 1, it is permitted to allocate non-contiguous Resource Blocks for the PUSCH when Transform Precoding is disabled (the CP-OFDM waveform is used). However, the non-contiguous Resource Blocks must satisfy the conditions for being categorised as 'almost contiguous' (described in section 7.4.4.2)

16.11 NEIGHBOUR PLANNING

★ Cell specific neighbour definitions are not required for cell reselection unless it is necessary to either blacklist a specific cell or apply a measurement power offset to a specific cell. Measurement power offsets can be used to make individual cells appear either more or less attractive for cell reselection

★ SIB3, SIB4 and SIB5 can be used to broadcast cell specific information for intra-frequency, inter-frequency and inter-system cell reselection. SIB4 and SIB5 also broadcast the carriers available for inter-frequency and inter-system cell reselection. The release 15 version of the 3GPP specifications allows inter-system reselection towards LTE but not towards UMTS, CDMA2000 nor GSM

★ Within the LTE system, SIB24 is used to broadcast carrier information for cell reselection towards NR

★ Cell specific neighbour definitions are required when completing intra-frequency, inter-frequency and inter-system handovers. They are also required when adding a Secondary Cell Group serving cell, or when completing serving cell change procedures, e.g. changing the primary SCG cell for an EN-DC Non-Standalone Base Station connection. Similar to cell reselection, the release 15 version of the 3GPP specifications provides support for inter-system handovers towards LTE, but not towards UMTS, CDMA2000 nor GSM

★ Table 356 summarises the requirement for neighbour relations as a function of the Base Station architecture. The EN-DC configuration is assumed for the Non-Standalone Base Station architecture

Neighbour Category	EN-DC Non-Standalone Base Station	Standalone NR Base Station
LTE to NR	X2 setup with Secondary Node Addition of primary SCG cell	inter-system handover
NR to LTE	not necessary	inter-system handover
NR to NR	change of primary SCG cell	intra-frequency and inter-frequency handovers
LTE to LTE	intra-frequency and inter-frequency handovers	not applicable

Table 356 – Summary of neighbour relation requirements

★ In the case of an EN-DC Non-Standalone Base Station:

  o an LTE Base Station to NR Base Station neighbour relation is required to allow the setup of an X2 connection between the two Base Stations. This neighbour relation links a pair of Base Stations rather than a pair of cells. If each NR Base Station is co-sited with an LTE Base Stations then a neighbour relation should be configured from the LTE Base Station towards the co-sited NR Base Station. In an ideal RF environment, this single neighbour relation would be sufficient because the co-sited NR cells would always be dominant. In reality, the RF environment may lead to neighbouring NR Base Stations providing dominance. In this case, neighbour relations should also be configured from the LTE Base Station towards neighbouring NR Base Stations

  o an LTE cell to NR cell neighbour relation is required to add the primary Secondary Cell Group (SCG) cell, i.e. when a UE is connected to a specific LTE cell, there is a requirement to add a specific NR cell for the EN-DC connection. If NR Base Stations are co-sited with LTE Base Stations then the minimum requirement would be to configure a neighbour relation with the co-sector NR cell. It would also be recommended to configure neighbour relations with NR cells belonging to the adjacent sectors. This would allow EN-DC connections to operate across sectors in case the LTE and NR antenna have different azimuths. If X2 connections have been setup with neighbouring NR Base Stations then LTE cell to NR cell neighbour relations should also be configured towards those neighbouring NR Base Stations

  o NR to LTE neighbour relations are not necessary for EN-DC connections, based upon the assumption that the Master Node (the LTE Base Station) is responsible for initiating the setup of the X2 connections between the NR and LTE Base Stations. The LTE Base Station is required to add NR cells for the EN-DC connection but the NR Base Station is not required to add LTE cells

  o NR cell to NR cell neighbour relations can be used to change the primary SCG cell. This cell change could be either intra-BTS or inter-BTS. As a minimum, neighbour relations should be defined towards the adjacent NR sectors. It may be beneficial to also define neighbour relations towards the NR cells belonging to neighbouring Base Stations

  o LTE to LTE neighbour relations are required for the EN-DC Base Station configuration to allow handovers between primary serving cells. However, it is not necessary to configure new neighbour relations for this purpose if the LTE network already has a set of neighbours configured

★ PCI checks should be completed during the neighbour addition process to ensure that the PCI plan does not generate PCI collisions nor PCI confusion

★ It is possible to configure neighbour relations using Self Organising Network (SON) functionality, e.g. a UE based Automatic Neighbour Relations (ANR) function can be used to populate a set of neighbour relations without the requirement for any manual planning. UE based ANR generates neighbour lists based upon measurement reports from the UE. Otherwise, neighbours must be defined by the planner, or generated by a planning tool. UE based ANR may not be possible for the Non-Standalone Base Station architecture. For example, in the case of EN-DC, if the NR Base Station does not broadcast SIB1 then the UE will be unable to report a Cell Global Identity. In addition, if the NR Base Station is not connected to the MME then the MME will be unable to retrieve the transport layer address for X2 setup between the LTE and NR Base Stations

16.12 CELL & BTS IDENTITY PLANNING

* Cells are identified at a global level using their NR Cell Global Identity (NCGI)
  * the Mobile Country Code (MCC) and Mobile Network Code (MNC) uniquely identify the operator's network
  * the NR Cell Identity (NCI) uniquely identifies a cell within the operator's network
* The NCGI and NCI structures are illustrated in Figure 481

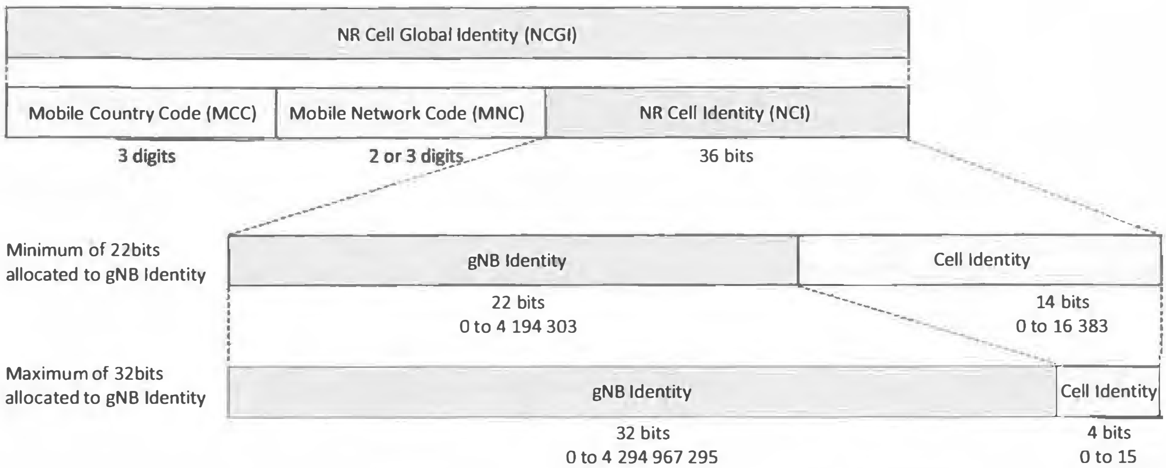


Figure 481 – Structure of New Radio Cell Global Identifier (NCGI)

* The NCI has a total size of 36 bits. These 36 bits are shared between the gNB Identity and the Cell Identity. The gNB Identity can be configured to use between 22 and 32 bits. This leaves between 14 and 4 bits for the Cell Identity
* Allocating 22 bits for the gNB Identity provides a range from 0 to 4 194 304. This range is likely to be sufficient for the majority of networks. Networks which include large numbers of small cells and/or Femto cells may require a larger gNB Identity range. Identities can be allocated to allow certain information to be deduced from the allocated value. For example, values 0 to 50 000 could be used for macrocells, while values 50 001 to 250 000 could be allocated for Femto cells
* Within the context of the RRC Inactive state, there may be some benefit in restricting the number of bits used by the gNB Identity, e.g. using only 16 bits and setting the remaining bits to '0'. The RRC Inactive state relies upon the I-RNTI to identify both the Base Station which hosts the UE context, and the UE within that Base Station. The full I-RNTI has a length of 40 bits, while the short I-RNTI has a length of 24 bits. If 16 bits within the I-RNTI are used to identify the Base Station which hosts the UE context, and if only 16 bits have been used within the gNB Identity, then the gNB Identity can be used directly within the I-RNTI. This helps to avoid the requirement to plan additional Base Station identities specifically for the RRC Inactive state
* Allocating 22 bits for the gNB Identity allows 14 bits to be used for the Cell Identity. These 14 bits provide a range from 0 to 16 383 to identify a cell belonging to a specific Base Station. It is unlikely that a single Base Station will support this number of cells although the number of cells per Base Station can become high when using the Centralised Unit (CU) / Distributed Unit (DU) Split Base Station architecture, e.g. a single Centralised Unit may support 150 Distributed Units and each Distributed Unit could support 6 or more cells
* The Cell Identity can be allocated to allow certain information to be deduced from the allocated value. For example, the first 3 bits could be used to identify the sector, the next 3 bits could be used to identify the carrier and the remaining 8 bits could be used to identify the Distributed Unit (if using the CU/DU Split Base Station architecture)
* The MCC, MNC and NCI are broadcast within SIB1 (see Table 147 in section 6.2). The structure of SIB1 allows a single channel to support multiple PLMN Identities (MCC/MNC) and multiple Cell Identities (NCI). This approach provides additional flexibility for network sharing deployment scenarios. It means that each operator can independently plan its own Cell Identities

16.13 RAN NOTIFICATION AREA PLANNING

- Enabling the RRC Inactive state requires:
    - the definition of RAN Notification Areas (RNA)
    - the allocation of Base Station identities which can be included within the I-RNTI

  The RRC Inactive state and RAN Notification Areas are described in section 1.8.3

- A RAN Notification Area defines the area within which a UE can move while RRC Inactive without having to inform the network that the best serving cell has changed. The network does not have knowledge of the UE location within the RNA so paging messages must be broadcast by all cells belonging to the RNA. The Base Station which released the UE to RRC Inactive hosts the UE context, the NG signalling connection towards the AMF and the GTP-U tunnel towards the UPF. The UE context is retrieved and the Core Network connections are moved if the UE returns to RRC Connected Mode using a different Base Station
- A large RNA provides benefits in terms of reduced signalling load due to UE mobility, i.e. the UE is less likely to cross an RNA boundary and be required to send an *RRCResumeRequest* message to complete an RNA update procedure. A small RNA provides benefits in terms of reduced paging load
- A small RNA also benefits from requiring fewer Xn connections although the requirement for Xn connections depends upon the Base Station architecture. If using the Centralised Unit (CU) / Distributed Unit (DU) Split Base Station architecture then an RNA can include a large number of cells belonging to a single Base Station, i.e. a large number of cells can be hosted by a single Centralised Unit. In this case, the RRC Inactive state can be used with a minimal requirement for Xn interfaces
- A RAN Notification Area can be configured as:
    - a collection of Cell Identities, or
    - a collection of Tracking Area Code (TAC) and RAN Area Code (RAC) combinations
- In both cases, it is necessary to identity RNA boundaries. A simplistic solution could be based upon allocating each Base Station to a separate RNA. In the case of the CU/DU Split Base Station architecture, this could result in more than 100 cells belonging to each RNA. In the case of the classical Base Station architecture, this could result in only 3 cells belonging to each RNA
- In general RNA boundaries should avoid crossing high mobility routes to help minimise the requirement for RNA updates due to mobility. A single RNA could be planned to include all cells within a town center, or all cells providing coverage to a sports stadium
- An I-RNTI is allocated to a UE when it moves to the RRC Inactive state. This I-RNTI identifies both the UE and the Base Station which hosts the UE context. 3GPP supports both a full I-RNTI which occupies 40 bits and a short I-RNTI which occupies 24 bits. The short I-RNTI is relatively restrictive in terms of the number of bits available to identify both the Base Station and UE but it minimises the size of the *RRCResumeRequest* message, i.e. it helps to maximise the coverage performance of MSG3
- The allocation of Base Station identities which can be included within the I-RNTI will depend upon the network implementation and the existing strategy for defining the gNB Identity within the NR Cell Identity. For example, if 16 bits from the full I-RNTI are used to identity the Base Station, and if the gNB Identity within the NR Cell Identity has been allocated using only 16 bits, then those 16 bits can be copied and directly inserted into the I-RNTI. This example scenario is illustrated in Figure 482

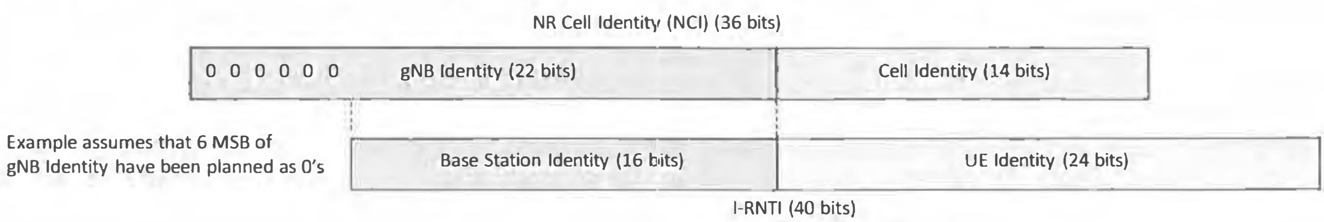


Figure 482 – Generating the I-RNTI from a sub-section of gNB Identity

- 3GPP specifies the total size of a full and short I-RNTI but does not specify the number of bits which are used to identify the Base Station (the allocation of 16 bits within Figure 482 is only an example)
- If a solution similar to that shown in Figure 482 is not adopted then it may be necessary to generate a second Base Station identity specifically for the purposes of the I-RNTI and the RRC Inactive state

16.14 TRACKING AREA PLANNING

★ Networks based upon the EN-DC Non-Standalone Base Station architecture do not require 5G Tracking Areas. UE use LTE for RRC Idle mode so UE extract the 4G Tracking Area Identity from the LTE SIB1. This Tracking Area is used for registration with the MME

★ Networks based upon the Standalone Base Station architecture require 5G Tracking Areas. In this case, UE use NR for RRC Idle mode so UE extract the 5G Tracking Area Identity from the NR SIB1. This Tracking Area is used for registration with the AMF. The UE reports its current Tracking Area within the NAS: Registration Request message. The AMF is permitted to provide the UE with a list of Tracking Area Identities within the NAS: Registration Accept message. Including more than a single Tracking Area Identity allows the UE to roam outside the current Tracking Area without triggering a Tracking Area update procedure

★ The release 8 version of LTE, allows SIB1 to broadcast up to 6 PLMN Identities for the purposes of Network Sharing but all PLMN share the same Tracking Area Code (TAC) and the same Cell Identity. The release 14 version of the 3GPP specifications allows the LTE SIB1 to broadcast separate TAC and Cell Identities for each PLMN. This provides increased flexibility and reduces the requirement for co-ordination amongst operators sharing the same channel

★ In the case of 5G, SIB1 is permitted to broadcast up to 12 PLMN Identities. Each of these PLMN can be configured with separate TAC and Cell Identities, i.e. 5G has adopted the solution introduced for 4G within the release 14 version of the 3GPP specifications

★ Figure 483 illustrates the structure of a 5G System Tracking Area Identity (TAI). The Mobile Country Code (MCC) and Mobile Network Code (MNC) are concatenated with a 5G System Tracking Area Code (TAC). The 5G System TAC has a length of 3 bytes in contrast to a 4G TAC which has a length of 2 bytes. The increased length provides greater flexibility and increased potential for cell level Tracking Area definitions

5GS Tracking Area Identity (TAI)

Mobile Country Code (MCC)	Mobile Network Code (MNC)	5GS Tracking Area Code (TAC)
3 digits	2 or 3 digits	3 bytes

Reserved Values
TAC = 00 00 00
TAC = FF FF FE

Figure 483 – 5G System Tracking Area Identity (TAI)

★ The set of 24 bits belonging to the TAC provide a range from 0 to 16 777 215, which can be expressed in hexadecimal notation as 00 00 00 to FF FF FF. The values 00 00 00 and FF FF FE are reserved to indicate that a Tracking Area Identity has been deleted

★ The main drawback associated with planning large Tracking Areas is an increased paging load. Large Tracking Areas capture increased volumes of UE and each cell within a Tracking Area may have to broadcast all Paging messages for all UE which are registered within that Tracking Area

★ The network implementation may support solutions which help to reduce the paging load. For example, a hierarchical paging solution could restrict the first paging attempt to only the cell that the UE was last connected. If there is no response to the first paging attempt, the network could then broadcast the paging message across a larger area. This type of solution is effective at reducing paging load but can increase latency for UE which are moving throughout the Tracking Area. Hierarchical paging solutions can be disabled for delay sensitive connections but enabled for other connections

★ The main benefit associated with planning large Tracking Areas is a reduced requirement for Tracking Area updates triggered by mobility (Tracking Area updates are initiated by sending a NAS: Registration Request message with the Registration Type set to 'mobility registration updating'). Reducing the number of Tracking Area updates helps to reduce the network signalling load. It can also help to reduce paging failures caused by the short delay between a UE crossing a Tracking Area boundary and the UE completing its registration with the new Tracking Area, i.e. there is a risk of paging messages being broadcast across a Tracking Area after the UE has moved into a different Tracking Area

★ Tracking Area Identity lists can be used to reduce the number of Tracking Area updates triggered by mobility. Smaller Tracking Areas can be combined to increase the area across which a UE can move without triggering a Tracking Area update. This can potentially be done dynamically to help manage the trade-off between paging load and Tracking Area update signalling load

★ New networks with relatively low traffic levels can be planned with large Tracking Areas. These Tracking Areas can then be split as traffic levels and paging loads increase over time. In general, Tracking Area boundaries should be planned to avoid crossing high mobility routes and areas with high traffic densities

★ 5G networks which are deployed over an existing 4G network can re-use the 4G Tracking Area plan. The same Tracking Area Codes can be re-used across both 4G and 5G. Alternatively, the 5G Tracking Area Codes could be given a fixed offset to allow easier differentiation

16.15 THROUGHPUT EXPECTATIONS

★ It is often necessary to estimate uplink and downlink throughputs before testing or deploying a specific configuration. These estimates can be used to help understand the impact of specific overheads. For example, they can be used to estimate the impact of SS/PBCH Blocks, Random Access occasions and Reference Signal allocations. They can also be used to help guide decisions regarding Transport Network bandwidth requirements

★ Throughput figures can be categorised as end-user connection throughputs and total cell throughputs. Connection throughputs reflect the end-user experience whereas cell throughputs reflect the system capacity. In both cases, there are many variables which impact the result so it is often necessary to re-calculate results for specific scenarios. If Multi-User MIMO is to be enabled then cell throughput calculations will require assumptions regarding the number of UE sharing common Resource Block allocations

★ Both connection throughputs and cell throughputs depend upon the capabilities of the UE and network. For example, an optimistic result will be generated if 8×8 MIMO is assumed while the UE and network support 4×4 MIMO

★ Throughput figures can also be categorised as maximums, averages or percentiles (for example, to quantify the throughput which 90 % of cells achieve, or to quantify the throughput which 90 % of end-users experience). Averages and percentiles are more difficult to calculate because they require knowledge of the radio conditions across the area of a cell, or across a group of cells. In these cases, it can be more appropriate to rely upon system level simulations to generate expectations of network performance. Simulations can be based upon a generic network layout, e.g. a grid of hexagonal cells covering a flat earth radio environment, or they can model specific deployment scenarios with terrain and building vector data. Simulations have the benefit of generating increased quantities of information. They can generate distributions of results rather than just single results, and can be used to identify problem areas when modelling specific deployment scenarios

★ The Slot Format should be identified as a prerequisite to calculating the uplink and downlink throughputs. In the case of FDD, this is simple because the uplink and downlink carriers allow continuous transmission in both directions. In the case of TDD, it is necessary to identify a specific uplink / downlink transmission pattern. This may have already been identified as part of the Slot Format Radio Network Planning activity described in section 16.3. The example calculations presented in this section are based upon the Slot Format illustrated in Figure 484. It is assumed that the 30 kHz subcarrier spacing is used so this example is based upon Frequency Range 1 with digital beamforming

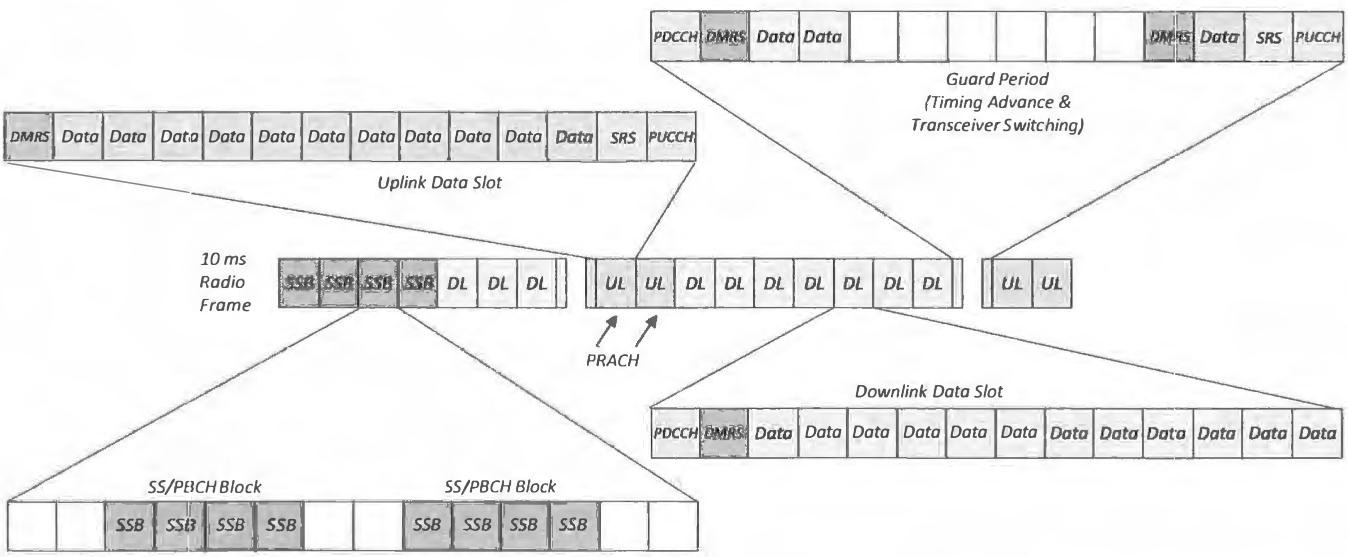


Figure 484 – Example Slot Format for Throughput calculations

★ This Slot Format starts with a series of 7 downlink slots. Up to 4 of these downlink slots can be used by the SS/PBCH, i.e. 1 slot is able to accommodate 2 SS/PBCH Blocks, and Frequency Range 1 supports up to 8 SS/PBCH Blocks (equivalent to 8 beams). Digital beamforming allows one beam to be transmitting the SS/PBCH while another beam is transferring data. Thus, the allocation of 4 slots to the SS/PBCH does not mean that those 4 slots cannot be used to transfer data. If the SS/PBCH has a 10 ms period, the SS/PBCH slots will be present at the start of every radio frame. The overhead generated by the SS/PBCH can be reduced if the transmission period is increased. However, this can increase latency when accessing a cell or when completing measurements

★ The Slot Format then includes a single slot which is allocated primarily for transceiver switching and timing advance. This slot includes a series of 4 downlink symbols, 6 guard period symbols and 4 uplink symbols. The downlink and uplink symbols within this slot can be used for data transfer although the capacity is relatively low when compared to a normal slot

★ The Slot Format includes 2 uplink slots at the end of each 5 ms cycle. The uplink slots must accommodate the PRACH with a period which is determined by the PRACH Configuration Index

16.15.1 DOWNLINK

★ The downlink throughput can be estimated by quantifying the throughput per slot and then averaging over time. Start by considering a downlink data slot which is assumed to have 12 symbols available to the PDSCH after allocating the first symbol for the PDCCH and the second symbol for the PDSCH DMRS. In this example, it is assumed that the PDSCH is not frequency multiplexed with the DMRS so data is not transferred using the second symbol

★ Table 357 quantifies the downlink throughput associated with a downlink data slot. Figures are presented for a range of channel bandwidths and a range of coverage conditions (corresponding to CQI values of 15, 11, 6 and 3). 2×2 MIMO is assumed for this example so there are 2 parallel streams of data towards the UE. The 30 kHz subcarrier spacing is assumed so the slot duration is 0.5 ms

	Channel Bandwidth				
	10 MHz	20 MHz	40 MHz	80 MHz	100 MHz
PRB	24	51	106	217	273
Resource Elements per PRB per Slot	24×12×12 = 3 456	51×12×12 = 7 344	106×12×12 = 15 264	217×12×12 = 31 248	273×12×12 = 39 312
MIMO Order	2×2	2×2	2×2	2×2	2×2
Slot Duration	0.5 ms	0.5 ms	0.5 ms	0.5 ms	0.5 ms
CQI = 15, 256QAM Coding Rate 0.926	102.4 Mbps	217.6 Mbps	452.3 Mbps	925.9 Mbps	1164.9 Mbps
CQI = 11, 64QAM Coding Rate 0.853	70.8 Mbps	150.3 Mbps	312.5 Mbps	639.7 Mbps	804.8 Mbps
CQI = 6, 16QAM Coding Rate 0.602	33.3 Mbps	70.7 Mbps	147.0 Mbps	301.0 Mbps	378.7 Mbps
CQI = 3, QPSK Coding Rate 0.438	12.1 Mbps	25.7 Mbps	53.5 Mbps	109.5 Mbps	137.7 Mbps

Table 357 – Instantaneous Downlink Throughputs calculated for Downlink Data Slot

★ The throughput figures for the 100 MHz channel bandwidth illustrate that high throughputs can be achieved even when the radio conditions are relatively poor, i.e. over 130 Mbps is achieved when using QPSK with a coding rate of 0.438. The 20 MHz figures are comparable to those which can be achieved by LTE when assuming 1 symbol is allocated to the LTE PDCCH

★ Table 358 quantifies the downlink throughput associated with the downlink symbols within a transceiver switching slot. It is assumed that 2 symbols are available to the PDSCH after allocating the first symbol for the PDCCH and the second symbol for the PDSCH DMRS. The calculations are the same as those within Table 357 except that 2 symbols are available rather than 12 symbols

	Channel Bandwidth				
	10 MHz	20 MHz	40 MHz	80 MHz	100 MHz
PRB	24	51	106	217	273
Resource Elements per PRB per Slot	24×12×2 = 576	51×12×2 = 1224	106×12×2 = 2544	217×12×2 = 5208	273×12×2 = 6552
MIMO Order	2×2	2×2	2×2	2×2	2×2
Slot Duration	0.5 ms	0.5 ms	0.5 ms	0.5 ms	0.5 ms
CQI = 15, 256QAM Coding Rate 0.926	17.1 Mbps	36.3 Mbps	75.4 Mbps	154.3 Mbps	194.1 Mbps
CQI = 11, 64QAM Coding Rate 0.853	11.8 Mbps	25.1 Mbps	52.1 Mbps	106.6 Mbps	134.1 Mbps
CQI = 6, 16QAM Coding Rate 0.602	5.5 Mbps	11.8 Mbps	24.5 Mbps	50.2 Mbps	63.1 Mbps
CQI = 3, QPSK Coding Rate 0.438	2.0 Mbps	4.3 Mbps	8.9 Mbps	18.2 Mbps	23.0 Mbps

Table 358 – Instantaneous Downlink Throughputs calculated for Transceiver Switching Slot

★ The longer term average throughput can now be calculated as a weighted average of the figures within Table 357 and Table 358. For example, if it is assumed that downlink data is not transferred during the slot which accommodates the SS/PBCH Block and that the SS/PBCH Block has a period of 10 ms then the average throughput for the 100 MHz channel with CQI = 15 can be calculated as $[(1164.9 \times 13) + (194.1 \times 2)] / 20 = 776.6$ Mbps. Alternatively, if the SS/PBCH Block is assumed to have a period of 20 ms then the equivalent result is $[(1164.9 \times 27) + (194.1 \times 4)] / 40 = 805.7$ Mbps

★ Table 359 presents the longer term average throughputs for each combination of channel bandwidth and radio conditions. Results are provided for both the 10 ms and 20 ms SS/PBCH Block periods. These figures can be interpreted as either an end-user connection throughput or a cell throughput assuming Multi-User MIMO is disabled. In reality, it is unlikely that the CQI = 15 result would correspond to an average cell throughput because it is unlikely that average radio conditions would allow an average CQI = 15

	Channel Bandwidth				
	10 MHz	20 MHz	40 MHz	80 MHz	100 MHz
CQI = 15, 256QAM Coding Rate 0.926	68.3 Mbps 70.8 Mbps	145.1 Mbps 150.5 Mbps	301.5 Mbps 312.8 Mbps	617.3 Mbps 640.4 Mbps	776.6 Mbps 805.7 Mbps
CQI = 11, 64QAM Coding Rate 0.853	47.2 Mbps 48.8 Mbps	100.2 Mbps 104.0 Mbps	208.3 Mbps 216.1 Mbps	426.5 Mbps 442.5 Mbps	536.5 Mbps 556.7 Mbps
CQI = 6, 16QAM Coding Rate 0.602	22.2 Mbps 23.0 Mbps	47.2 Mbps 48.9 Mbps	98.0 Mbps 101.7 Mbps	200.7 Mbps 208.2 Mbps	252.4 Mbps 261.9 Mbps
CQI = 3, QPSK Coding Rate 0.438	8.1 Mbps 8.4 Mbps	17.2 Mbps 17.8 Mbps	35.7 Mbps 37.0 Mbps	73.0 Mbps 75.7 Mbps	91.8 Mbps 95.3 Mbps

* first figure assumes a 10 ms SS/PBCH Block period, while second figure assumes a 20 ms SS/PBCH Block

Table 359 – Downlink Throughputs averaged across SS/PBCH Block transmission period

★ In the case of cell throughput, Multi-User MIMO has the potential to increase the figures presented in Table 359. Operating bands within Frequency Range 1 support up to 8 SS/PBCH Blocks allowing up to 8 SS/PBCH beams. In theory, these 8 beams can be used to simultaneously transfer downlink data towards 8 UE, generating a total of 16 streams when all 8 UE are using 2×2 MIMO. This Multi-User MIMO scenario would ideally increase the figures in Table 359 by a factor of 8. In reality, the increase would be less than a factor of 8 if it is assumed that a double symbol DMRS is used rather than a single symbol DMRS when allowing Multi-User MIMO with a relatively large number of UE. In addition, it is unlikely that Multi-User MIMO will be able to continuously spatially multiplex 8 UE. The number of UE which can be spatially multiplexed will depend upon the number of UE loading the cell and the geographic distribution of those UE across the cell area

★ The calculations presented above have ignored the overheads generated by the CSI Reference Signal, Tracking Reference Signal and Phase Tracking Reference Signal. They have also assumed that no additional DMRS symbols have been configured. The CSI Reference Signal for Beam Refinement can be frequency multiplexed with the SS/PBCH Block. This means that no additional overhead is required because the slot which accommodates the SS/PBCH Block has already been excluded from transferring downlink data. The overheads generated by the remaining Reference Signals can be included once their configurations are known. For example, a Tracking Reference Signal may occupy 3 Resource Elements per Resource Block in the frequency domain, and 4 symbols every 80 ms in the time domain. Based upon the previous example, the corresponding overhead relative to the total number of downlink data Resource Elements is given by $(3 \times 4) / [(12 \times 12 \times 13 \times 8) + (12 \times 2 \times 2 \times 8)] = 0.08$ %, i.e. the overhead generated by a single Tracking Reference Signal is small

16.15.2 UPLINK

★ Similar to the downlink, the uplink throughput can be estimated by quantifying the throughput per slot and then averaging over time. Start by considering an uplink data slot which is assumed to have 11 symbols available to the PUSCH after allocating the first symbol for the PUSCH DMRS and the last two symbols for the SRS and PUCCH. In this example, it is assumed that the PUSCH is not frequency multiplexed with the DMRS so data is not transferred using the first symbol

★ Table 360 quantifies the uplink throughput associated with an uplink data slot. Figures are presented for a range of channel bandwidths and a range of coverage conditions (assuming the same coding rates as were used for the downlink calculations). 2×2 MIMO is assumed for this example so there are 2 parallel streams of data towards the Base Station. The 30 kHz subcarrier spacing is assumed so the slot duration is 0.5 ms

★ The uplink figures in Table 360 are comparable to the downlink figures in Table 357. The uplink figures are less than the downlink figures because it has been assumed that there are only 11 symbols available to the PUSCH, while there are 12 symbols available to the PDSCH. Otherwise, the uplink and downlink calculations are the same. Figures for 256QAM have been included for the uplink although this is an optional UE capability which is indicated by the UE using the *pusch-256QAM* information element

	Channel Bandwidth				
	10 MHz	20 MHz	40 MHz	80 MHz	100 MHz
PRB	24	51	106	217	273
Resource Elements per PRB per Slot	24×12×11 = 3 168	51×12×11 = 6 732	106×12×11 = 13 992	217×12×11 = 28 644	273×12×11 = 36 036
MIMO Order	2×2	2×2	2×2	2×2	2×2
Slot Duration	0.5 ms	0.5 ms	0.5 ms	0.5 ms	0.5 ms
256QAM Coding Rate 0.926	93.9 Mbps	199.5 Mbps	414.6 Mbps	848.8 Mbps	1067.8 Mbps
64QAM Coding Rate 0.853	64.9 Mbps	137.8 Mbps	286.4 Mbps	586.4 Mbps	737.7 Mbps
16QAM Coding Rate 0.602	30.5 Mbps	64.8 Mbps	134.8 Mbps	275.9 Mbps	347.1 Mbps
QPSK Coding Rate 0.438	11.1 Mbps	23.6 Mbps	49.0 Mbps	100.4 Mbps	126.3 Mbps

Table 360 – Instantaneous Uplink Throughputs calculated for Uplink Data Slot

★ Table 361 quantifies the uplink throughput associated with the uplink symbols within a transceiver switching slot. It is assumed that only 1 symbol is available to the PUSCH after allocating the first symbol for the PUSCH DMRS and the last two symbols for the SRS and PUCCH

	Channel Bandwidth				
	10 MHz	20 MHz	40 MHz	80 MHz	100 MHz
PRB	24	51	106	217	273
Resource Elements per PRB per Slot	24×12×1 = 288	51×12×1 = 612	106×12×1 = 1272	217×12×1 = 2604	273×12×1 = 3276
MIMO Order	2×2	2×2	2×2	2×2	2×2
Slot Duration	0.5 ms	0.5 ms	0.5 ms	0.5 ms	0.5 ms
256QAM Coding Rate 0.926	8.5 Mbps	18.1 Mbps	37.7 Mbps	77.2 Mbps	97.1 Mbps
64QAM Coding Rate 0.853	5.9 Mbps	12.5 Mbps	26.0 Mbps	53.3 Mbps	67.1 Mbps
16QAM Coding Rate 0.602	2.8 Mbps	5.9 Mbps	12.3 Mbps	25.1 Mbps	31.6 Mbps
QPSK Coding Rate 0.438	1.0 Mbps	2.1 Mbps	4.5 Mbps	9.1 Mbps	11.5 Mbps

Table 361 – Instantaneous Uplink Throughputs calculated for Transceiver Switching Slot

★ Similar to the downlink, the longer term average throughput can now be calculated as a weighted average of the figures within Table 360 and Table 361. For example, the average throughput for the 100 MHz channel with 64QAM and a coding rate of 0.853 can be calculated as $[(737.7 \times 4) + (67.1 \times 2)] / 20 = 154.3$ Mbps

★ Table 362 presents the longer term average throughputs for each combination of channel bandwidth and radio conditions. These figures can be interpreted as either an end-user connection throughput or a cell throughput assuming Multi-User MIMO is disabled. In reality, it is unlikely that the 256QAM result would correspond to an average cell throughput because it is unlikely that average radio conditions would allow 256QAM

★ In the case of cell throughput, Multi-User MIMO has the potential to increase the figures presented in Table 362. Operating bands within Frequency Range 1 support up to 8 SS/PBCH Blocks allowing up to 8 SS/PBCH beams. In theory, these 8 beams can be used to simultaneously receive uplink data from 8 UE, generating a total of 16 streams when all 8 UE are using 2×2 MIMO. This Multi-User MIMO scenario would ideally increase the figures in Table 362 by a factor of 8. In reality, the increase would be less than a factor of 8 if it is assumed that a double symbol DMRS is used rather than a single symbol DMRS when allowing Multi-User MIMO with a relatively large number of UE. In addition, it is unlikely that Multi-User MIMO will be able to continuously spatially multiplex 8 UE. The number of UE which can be spatially multiplexed will depend upon the number of UE loading the cell and the geographic distribution of those UE across the cell area

	Channel Bandwidth				
	10 MHz	20 MHz	40 MHz	80 MHz	100 MHz
256QAM Coding Rate 0.926	19.6 Mbps	41.7 Mbps	86.7 Mbps	177.5 Mbps	223.3 Mbps
64QAM Coding Rate 0.853	13.6 Mbps	28.8 Mbps	59.9 Mbps	122.6 Mbps	154.3 Mbps
16QAM Coding Rate 0.602	6.4 Mbps	13.6 Mbps	28.2 Mbps	57.7 Mbps	72.6 Mbps
QPSK Coding Rate 0.438	2.3 Mbps	4.9 Mbps	10.3 Mbps	21.0 Mbps	26.4 Mbps

Table 362 – Uplink Throughputs averaged across 10 ms radio frame

★ The calculations presented above have ignored the overheads generated by the PRACH and the Phase Tracking Reference Signal. They have also assumed that no additional DMRS symbols have been configured. The overhead generated by the PRACH depends upon the PRACH Format and the number of PRACH occasions within a specific time window. The Slot Format illustrated in Figure 484 includes 2 consecutive uplink slots, i.e. 1 ms of continuous uplink transmission is permitted. This means that a long PRACH Format can be used to help maximise the supported cell range. PRACH Format 0 occupies 1 ms in the time domain and 3 Resource Blocks in the frequency domain (based upon the PUSCH using a 30 kHz subcarrier spacing). If the PRACH Configuration Index is selected to allow 1 PRACH occasion per 10 ms Radio Frame, then the PRACH occupies 3 × 12 × 14 × 2 = 1008 Resource Elements per Radio Frame

★ Table 363 presents the overhead generated by the PRACH relative to the total number of Resource Elements available to the PUSCH for the transfer of uplink data. These calculations assume that the PRACH occupies 11 symbols per slot rather than 14 symbols per slot because the PUSCH is able to use 11 symbols per slot, i.e. from the perspective of the PUSCH, 11 symbols are lost rather than 14 symbols

★ The overheads presented in Table 363 would increase if the number of PRACH occasions per Radio Frame increases, e.g. PRACH occasions could be time multiplexed across the two pairs of uplink slots, or frequency multiplexed within a single pair of uplink slots. Alternatively, the overheads would decrease if the PRACH occasions occur less frequently, e.g. 1 PRACH occasion per 20 ms rather than 1 PRACH occasion per 10 ms

	Channel Bandwidth				
	10 MHz	20 MHz	40 MHz	80 MHz	100 MHz
PRB	24	51	106	217	273
PUSCH Resource Elements per Radio Frame	3168×4 + 288×2 = 13 248	6732×4 + 612×2 = 28 152	13992×4 + 1272×2 = 58 512	28644×4 + 2604×2 = 119 784	36036×4 + 3276×2 = 150 696
PRACH Resource Elements per Radio Frame	3×12×11×2 = 792	3×12×11×2 = 792	3×12×11×2 = 792	3×12×11×2 = 792	3×12×11×2 = 792
Overhead	6.0 %	2.8 %	1.4 %	0.7 %	0.5 %

Table 363 – PRACH overheads assuming 1 PRACH occasion per 10 ms Radio Frame

17 DYNAMIC SPECTRUM SHARING

- Dynamic Spectrum Sharing allows both 4G and 5G to simultaneously operate within the same spectrum, i.e. the set of Resource Elements is shared between the two technologies. Dynamic Spectrum Sharing is applicable to Frequency Range 1 because existing 4G operating bands are below 6 GHz
- Dynamic Spectrum Sharing allows spectrum to be re-farmed without a step change in its utilisation, i.e. it allows a smooth evolution from one technology to another technology. Figure 485 illustrates an example Base Station which is initially configured with two 4G carriers
  - the first option for re-farming involves the complete replacement of one 4G carrier with a 5G carrier. This approach can lead to a step change in the spectrum utilisation if the re-farming is completed at a time when the penetration of 5G devices is low. The original 4G carrier was heavily loaded whereas the new 5G carrier is unloaded. In addition, the remaining 4G carriers become more congested due to the reduced quantity of 4G spectrum
  - the second option for re-farming is based upon Dynamic Spectrum Sharing. In this case, the 4G system continues to use both carriers but one carrier can also be used by the 5G system. The shared carrier is able to support both 4G and 5G devices. This requires co-ordination of the resources used by each system

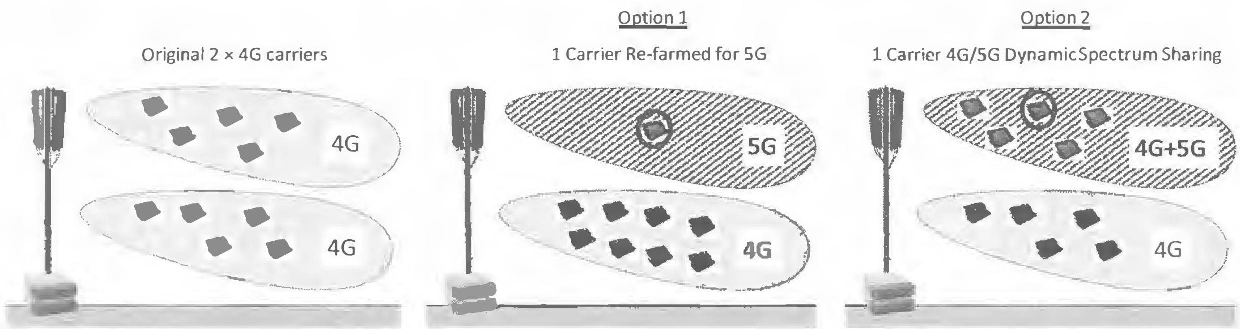


Figure 485 – Re-farming an existing 4G spectrum allocation for 5G

- The re-farming of 4G spectrum is unlikely to provide 5G with the wide channel bandwidths required to achieve very high throughputs but it can be used to provide 5G with spectrum within the lower operating bands which offers improved coverage due to the lower air-interface attenuation
- Dynamic Spectrum Sharing requires the 4G and 5G systems to be synchronised in both the time and frequency domains. In the downlink direction, it is relatively simple to achieve radio frame synchronisation between the two technologies. Both sets of transmissions can share the same downlink timing reference at the Base Station, e.g. derived from GPS or Timing over Packet. In the uplink direction it is necessary to align the Timing Advance applied by the population of 4G and 5G UE
- A UE adds a fixed Timing Advance Offset ($N_{TAoffset}$) to the Timing Advance commands provided by the Base Station. In the case of 4G, the fixed Timing Advance Offset is '0' for FDD and '$624 \times T_s$' for TDD. 5G uses a time unit of T_c rather than T_s, where $T_s = 64 \times T_c$. This means that a 5G UE must be configured to use an offset of 0 when sharing spectrum with 4G FDD, and an offset of $64 \times 624 = 39936 \times T_c$ when sharing spectrum with 4G TDD. This concept is illustrated in Figure 486

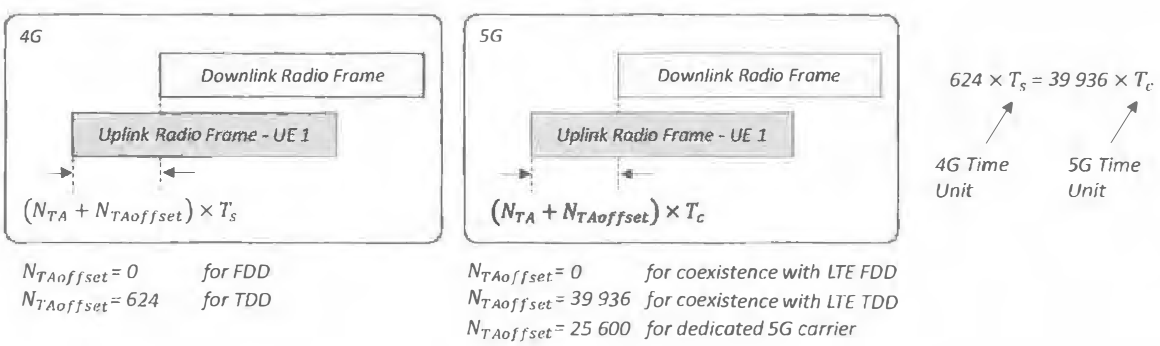


Figure 486 – Alignment of 4G and 5G Timing Advance

- The Base Station instructs the UE to use a specific fixed Timing Advance Offset using the *n-TimingAdvanceOffset* information element shown in Table 364. The value of 25600 is the normal value for 5G when using Frequency Range 1 without Dynamic Spectrum Sharing (applicable to both FDD and TDD). In the case of Frequency Range 2, Dynamic Spectrum Sharing is not applicable and a fixed value of 13792 is used

extract from *ServingCellConfigCommonSIB* or *ServingCellConfigCommon*	
n-TimingAdvanceOffset	n0, n25600, n39936

Table 364 – Information element used to signal $N_{TA\ offset}$

★ Achieving frequency synchronisation between 4G and 5G is relatively simple in the downlink direction. A common frequency reference can be used at the Base Station and both technologies generate a baseband signal which is centered around 0 Hz. However, it should be noted that 4G does not transmit data on the DC subcarrier. When the 4G channel bandwidth includes an odd number of Resource Blocks, this leads to the central Resource Block occupying 13 subcarriers rather than 12 subcarriers. When the 4G channel bandwidth includes an even number of Resource Blocks, this leads to an additional subcarrier between the central pair of Resource Blocks. In both cases, it means that the 4G and 5G Resource Blocks will not be aligned both sides of the central subcarrier. Figure 487 illustrates the case for an odd number of 4G Resource Blocks. The 4G and 5G Packet Schedulers are responsible for ensuring that Resource Block allocations do not overlap

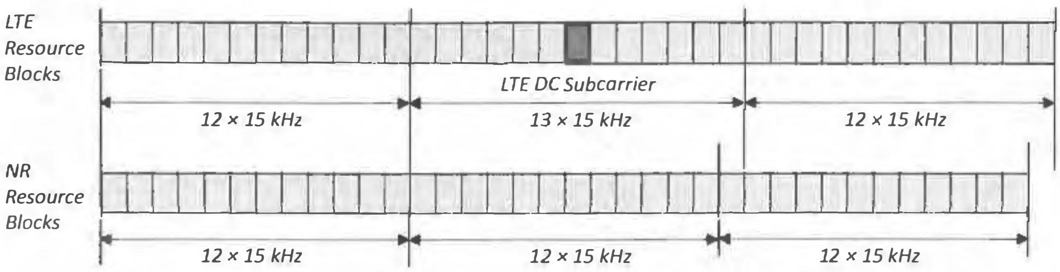


Figure 487 – Impact of unused 4G DC subcarrier upon 4G and 5G Resource Block alignment

★ The 4G transmission will use a 15 kHz subcarrier spacing, while the 5G transmission can use either a 15 kHz or 30 kHz subcarrier spacing. If using the 30 kHz subcarrier spacing, a 5G Resource Element will occupy twice as much bandwidth in the frequency domain but half of the duration in the time domain. Nevertheless, the 4G and 5G transmissions remain orthogonal

★ Achieving frequency synchronisation in the uplink direction requires an adjustment to the default 5G waveform. The SC-FDMA waveform used by 4G has a 7.5 kHz offset applied to avoid having a DC subcarrier. By default, the CP-OFDM and DFT-S-OFDM waveforms used by 5G do not include this 7.5 kHz offset and the DC subcarrier can be used to transfer data. These 4G and 5G frequency domain positions are illustrated in Figure 488

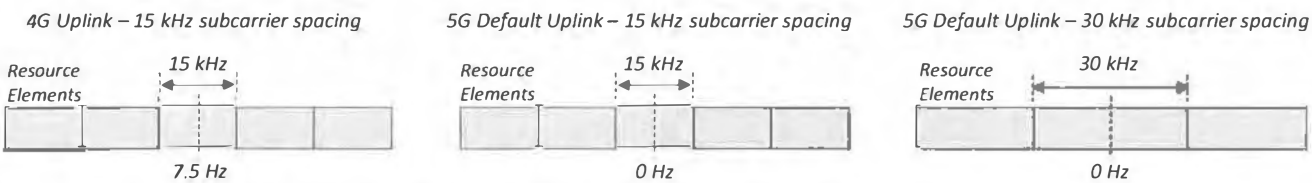


Figure 488 – Alignment of 4G and 5G uplink center frequencies

★ In the case of Dynamic Spectrum Sharing, the Base Station can instruct the 5G UE to apply a 7.5 kHz offset using the *frequencyShift7p5khz* information element presented in Table 365. This aligns the 4G and 5G uplink transmissions and allows them to coexist within the same Resource Element grid

extract from *ServingCellConfigCommonSIB* or *ServingCellConfigCommon*	
frequencyShift7p5khz	true

Table 365 – Information element used to apply 7.5 kHz shift to the uplink

★ 5G transmissions must operate around the 4G Cell specific Reference Signal (CRS). Figure 489 illustrates an example of the 4G CRS when using 2 antenna ports. One antenna port transmits the CRS using the Resource Elements labelled as 'CRS', while the other antenna port transmits the CRS using the Resource Elements labelled as 'DTX', i.e. each antenna port applies DTX to the Resource Elements used by the other antenna port

★ This 4G transmission pattern creates a challenge for the 5G SS/PBCH Blocks. An SS/PBCH Block occupies 4 symbols, whereas Figure 489 illustrates that there is a maximum of 3 empty symbols between the CRS transmissions. (this reduces to a maximum of 2 empty symbols when 4G uses 4 antenna ports for CRS transmission). Thus, it is not possible to time multiplex an SS/PBCH Block with the 4G CRS when the SS/PBCH Block uses a 15 kHz subcarrier spacing. Table 48 in section 2.5.2 indicates that a large proportion of the operating bands within Frequency Range 1 use a 15 kHz subcarrier spacing for the SS/PBCH. Thus, an alternative solution is required

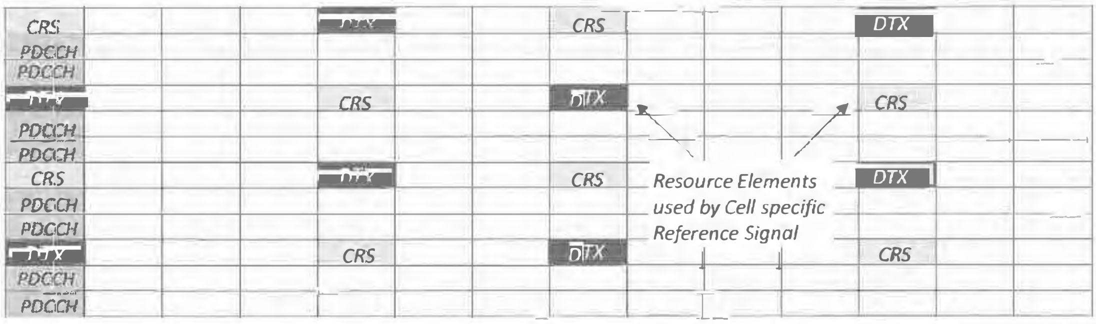


Figure 489 – 4G Cell specific Reference Signal (assuming 4G transmission on 2 CRS antenna ports)

★ The 4G Base Station can use MBSFN subframes to reduce the quantity of symbols used by the CRS. An MBSFN subframe restricts the CRS to the first symbol. The remaining 13 symbols are then available for the 5G Base Station to transmit either one or two SS/PBCH Blocks. In the case of FDD, MBSFN subframes can be configured during subframes 1, 2, 3, 6, 7 and 8, whereas in the case of TDD, MBSFN subframes can be configured for use during subframes 3, 4, 7, 8 and 9. A slot offset can be applied to delay the timing of 5G radio frames relative to 4G radio frames. When using FDD, this offset can be used to allow 5G slot 0 to coincide with 4G slot 1, i.e. 5G slot 0 coincides with an MBSFN subframe and the SS/PBCH Block transmissions can then start from 5G slot 0

★ A drawback associated with using MBSFN subframes as a solution for time multiplexing the 5G SS/PBCH Blocks is that they can create an overhead towards the transfer of 4G data. Older 4G devices will not be able to receive downlink data during MBSFN subframes. 3GPP release 10, and newer devices are able to receive downlink data when using Transmission Modes 9 or 10

★ When 5G uses the 30 kHz subcarrier spacing, the SS/PBCH Blocks occupy only 2 LTE symbols. In this case, the SS/PBCH Blocks can be time multiplexed between the CRS transmissions. Figure 490 illustrates an SS/PBCH Block which is time multiplexed between CRS transmissions when assuming 4 CRS antenna ports. The SS/PBCH Block starts during symbol 4 when using the 30 kHz symbol numbering. This corresponds to an SS/PBCH Block transmission belonging to the first 30 kHz option within Table 56 (section 3.4)

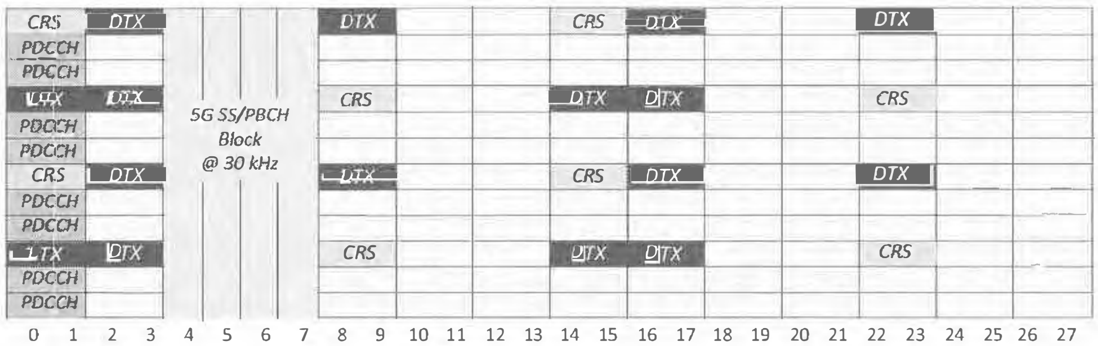


Figure 490 – Time multiplexing of 4G CRS and 5G SS/PBCH Block (assuming 4G transmission on 4 CRS antenna ports)

★ In terms of 5G PDSCH transmission, there are two general options which depend upon the subcarrier spacing:

- o when using the 15 kHz subcarrier spacing, the 5G PDSCH can be time and frequency multiplexed around the 4G CRS, i.e. the 4G CRS punctures the 5G PDSCH transmission, reducing the number of Resource Elements available for PDSCH transmission. In this case, 5G PDSCH resource allocations can occupy a relatively large number of symbols
- o when using the 30 kHz subcarrier spacing, it is not possible to frequency multiplex the 4G CRS and the 5G PDSCH (due to the wider bandwidth of each 5G subcarrier). In this case, only time multiplexing is permitted. When using 4 antenna ports to transmit the CRS, the 5G PDSCH resource allocation duration is limited to a maximum of 4 symbols

★ Table 366 presents the parameter structure which can be provided to the UE when 5G is using the 15 kHz subcarrier spacing and the 5G PDSCH is frequency multiplexed with the CRS. This parameter structure is described in section 3.6.7.1. It is used to provide the UE with information regarding the location of the CRS, so the UE can then ignore the CRS Resource Elements when decoding the 5G PDSCH

RateMatchPatternLTE-CRS	
carrierFreqDL	0 to 16383
carrierBandwidthDL	n6, n15, n25, n50, n75, n100
mbsfn-SubframeConfigList	1 to 8 instances of *EUTRA-MBSFN-SubframeConfig*
nrofCRS-Ports	n1, n2, n4
v-Shift	n0, n1, n2, n3, n4, n5

Table 366 – *RateMatchPatternLTE-CRS* parameter structure

- 5G transmissions must also account for the 4G Synchronisation Signals and the 4G PBCH. The Base Station can use the *RateMatchPattern* parameter structure shown in Table 107 (section 3.6.7.2) to configure Reserved Resources which occupy specific combinations of Resource Blocks and symbols. A first set of Reserved Resources can be configured for the Synchronisation Signals using a period of 5 ms, whereas a second set of Reserved Resources can be configured for the PBCH using a period of 10 ms. An example of these reservations is illustrated in Figure 177. The Reserved Resources indicate Resource Block / symbol combinations within which the UE should not attempt to receive the 5G PDSCH
- The 5G Demodulation Reference Signal (DMRS) for the PDSCH can be impacted by Dynamic Spectrum Sharing with LTE. There is an impact if a single additional DMRS position is configured for a PDSCH resource allocation duration of 13 or 14 symbols. The additional DMRS transmission usually occupies symbol 11, but this symbol coincides with a CRS symbol when using Dynamic Spectrum Sharing with a 15 kHz subcarrier spacing. In this case, the additional DMRS symbol is moved from symbol 11 to symbol 12. The additional DMRS positions are presented in Table 114 within section 3.7.3
- In addition to the above, the 5G Packet Scheduler must co-ordinate its resource allocations with the 4G Packet Scheduler. Co-ordination ensures that the two Packet Schedulers do not allocate the same resources. The rate at which the co-ordination function operates will determine the responsiveness of the system. A rapid co-ordination rate allows the Packet Schedulers to frequently change the resources they are permitted to allocate
- UE declare their support for some aspects of Dynamic Spectrum Sharing within their UE capability information. The *rateMatchingLTE-CRS* information element is used to indicate within which bands the UE supports rate matching around the LTE Cell specific Reference Signal (CRS). The *additionalDMRS-DL-Alt* information element is used to indicate within which bands the UE supports the use of symbol 12 rather than symbol 11 for the additional DMRS symbol described above

18 UE IDENTITIES

18.1 IMSI

★ The International Mobile Subscriber Identity (IMSI) is a globally unique permanent subscriber identity associated within the USIM. An IMSI can be moved between UE by moving the USIM. The ITU-T specifies the structure of an IMSI within recommendation E.212

★ An IMSI is stored on the USIM and by the User Data Management (UDM) Network Function within the 5G Core Network

★ The structure of an IMSI is illustrated in Figure 491

- o the 'home' Public Land Mobile Network (PLMN) is identified using a combination of the Mobile Country Code (MCC) and Mobile Network Code (MNC). The ITU is responsible for allocating the MCC, whereas the national administrator is responsible for allocating the MNC. A UE uses the 'home' PLMN Identity when searching for a network, e.g. when completing a band scan, a UE will search for a cell which is broadcasting the 'home' PLMN Identity within SIB1
- o the subscriber is identified within the home PLMN using the Mobile Subscriber Identification Number (MSIN). The MSIN is allocated by the service provider

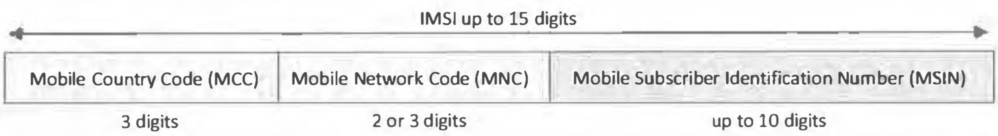


Figure 491 – Structure of IMSI

★ The IMSI can be used as the '5GS Mobile Identity' within NAS signalling procedures. For security reasons, the IMSI is included within NAS messages using a 'concealed' format which can hide the actual value. The 'Protection Scheme' indicated as part of the '5GS Mobile Identity' field can be set to 'null' in which case the IMSI is visible within the message. Alternatively, the 'Protection Scheme' can be set to 'ECIES Scheme Profile A', 'ECIES Scheme Profile B' or an operator specific scheme. These protection schemes are used to encrypt the IMSI prior to including within the message

★ In the case of 5G, the IMSI is not used for paging procedures

18.2 IMEI

★ The International Mobile Equipment Identity (IMEI) is a permanent identity belonging to a device. It is stored within the device hardware and by the User Data Management (UDM) Network Function within the 5G Core Network

★ The structure of an IMEI is illustrated in Figure 492

- o the Type Allocation Code (TAC) is an 8 digit number which identifies the UE model. It can also identify a specific version of a UE model, i.e. different versions of the same UE model can be allocated different TAC. The TAC is allocated by the GSM Association (GSMA)
- o the Serial Number (SNR) uniquely identifies a device with a specific TAC. All UE which have the same TAC should be allocated different Serial Numbers. The Serial Number is allocated by the device manufacturer
- o the Check Digit (CD) is calculated from a combination of the TAC and Serial Number. It provides a mechanism for detecting data entry errors, e.g. when the IMEI is manually entered into a system

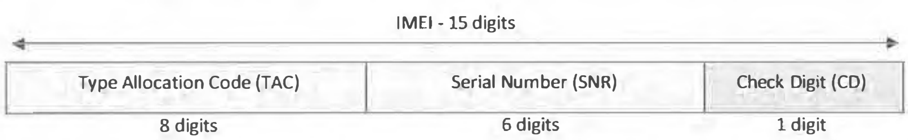


Figure 492 – Structure of IMEI

★ The IMEI can be used within NAS signalling procedures as the '5GS Mobile Identity'. In contrast to the IMSI, the IMEI does not use a 'Protection Scheme' to provide encryption. Instead, the IMEI can be included directly within NAS signalling messages

18.3 SUPI & SUCI

- ★ A 5G Subscription Permanent Identifier (SUPI) can be either:
  - o an International Mobile Subscriber Identity (IMSI)
  - o a Network Access Identifier (NAI)
- ★ An NAI has the following structure: username@realm. It represents a network specific identity for a private network and is specified by IETF RFC 7542
- ★ A Subscription Concealed Identifier (SUCI) allows the SUPI to be signalled without exposing the identity of the user. Signalling procedures use the SUCI rather than the SUPI to provide privacy. For example, the '5GS Mobile Identity' within NAS signalling procedures can be based upon a SUCI (alternatively, the '5GS Mobile Identity' can be an IMEI, IMEISV, 5G-GUTI or 5G-S-TMSI)
- ★ The SUCI uses a 'Protection Scheme' which can be set to 'null' in which case the SUPI is visible within the message. Alternatively, the 'Protection Scheme' can be set to 'ECIES Scheme Profile A', 'ECIES Scheme Profile B' or an operator specific scheme. These protection schemes are used to encrypt the SUPI prior to including within the message

18.4 5G-GUTI

- ★ The 5G Globally Unique Temporary Identifier (5G-GUTI) is allocated by the AMF. It is a temporary identity so it does not have a fixed association with a specific subscriber nor device. The use of a temporary identity helps to improve privacy. The AMF can change the allocated 5G-GUTI at any time
- ★ The structure of the 5G-GUTI is illustrated in Figure 493. It is a concatenation of the Globally Unique AMF Identifier (GUAMI) and 5G-TMSI. The GUAMI is a concatenation of the PLMN Identity and the AMF Identifier. Inclusion of the GUAMI allows identification of the AMF which allocated the 5G-GUTI. The 5G-TMSI identifies the UE within that AMF

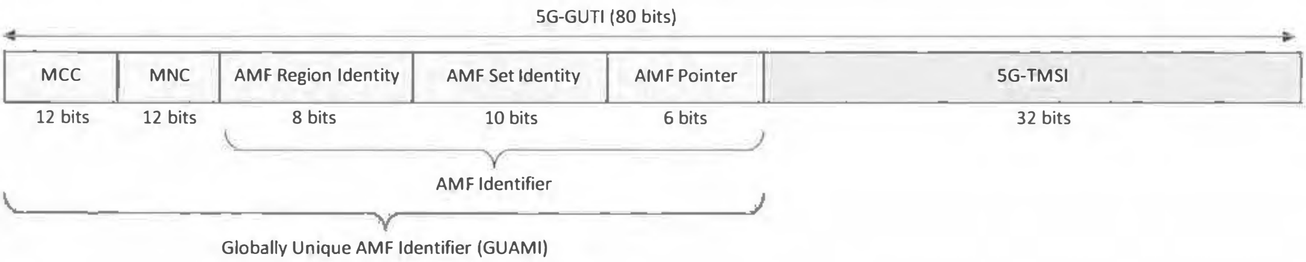


Figure 493 – Structure of 5G-GUTI

- ★ 3GPP has specified a mapping between the 5G-GUTI and the 4G GUTI. This mapping is used when a UE moves between technologies. For example, when a UE moves from 5G to 4G and is required to send a GUTI to the MME, then the UE maps the 5G-GUTI onto the 4G GUTI and forwards it to the MME. The MME can then complete the reverse mapping to identify the AMF that it needs to contact in order to retrieve the UE context. Similarly, when a UE moves from 4G to 5G then the 4G GUTI can be mapped onto the 5G-GUTI and sent to the AMF. The AMF can then extract the MME Identity and subsequently request the UE context

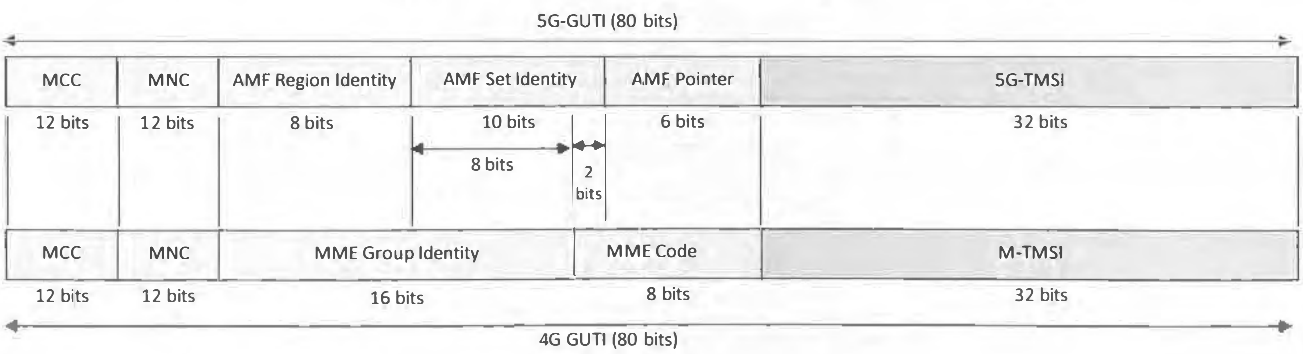


Figure 494 – Mapping between 5G-GUTI and GUTI

18.5 5G-S-TMSI

★ The 5G-S-TMSI is a shortened version of the 5G-GUTI, i.e. it excludes the PLMN Identity and the AMF Region Identity. This means that it can be used to identify a UE within a specific AMF Region but it cannot be used to identify a UE across a set of AMF Regions.

★ It is more efficient to use the 5G-S-TMSI rather than the 5G-GUTI when completing signalling procedures because the smaller size helps to reduce the signalling overhead

★ The structure of the 5G-S-TMSI is illustrated in Figure 495. It is a concatenation of the AMF Set Identity, the AMF Pointer and the 5G-TMSI

Figure 495 – Structure of 5G-S-TMSI

★ The 5G-S-TMSI is used within RRC signalling procedures. For example, the first 39 bits of the 5G-S-TMSI can be included within an *RRCSetupRequest* message, while the last 9 bits can be included within an *RRCSetupComplete* message. The 5G-S-TMSI can also be included within a *Paging* message

18.6 RNTI

★ Radio Network Temporary Identifiers (RNTI) are applicable within the Radio Access Network. They are allocated by the Base Station and are subsequently stored by both the Base Station and UE. They are used to address either an individual UE, a group of UE or all UE. For example, the C-RNTI can be used to address an individual UE, whereas an INT-RNTI can be used to address a group of UE and the SI-RNTI can be used to address all UE

★ A UE is addressed by using the RNTI to scramble the CRC bits which are attached to the PDCCH DCI payload, i.e. an RNTI is used to address the UE on the PDCCH. The PDCCH can then be used to provide uplink and downlink resource allocations, power control commands, pre-emption indications, Slot Format changes and System Information update indications

★ The set of RNTI is presented in Table 367. All RNTI have a length of 16 bits

★ The SI-RNTI is used to scramble the CRC bits belonging to DCI Format 1_0 when allocating PDSCH resources for the transmission of System Information. 3GPP has standardised a single SI-RNTI value which is used by all UE

★ The P-RNTI is used to scramble the CRC bits belonging to DCI Format 1_0 when allocating PDSCH resources for the transmission of Paging messages, or when using the PDCCH to encapsulate a 'Short Message'. A 'Short Message' can be used to indicate that System Information content has changed and needs to be re-acquired. It can also be used to indicate an Earthquake and Tsunami Warning System (ETWS) primary notification on SIB6, or an ETWS secondary notification on SIB7, or a Commercial Mobile Alert System (CMAS) notification on SIB8. 3GPP has standardised a single P-RNTI value which is used by all UE

RNTI	DCI Format	Application	Value
SI-RNTI	1_0	PDSCH resources for System Information	FFFF
P-RNTI	1_0	PDSCH resources for Paging messages	FFFE
RA-RNTI	1_0	PDSCH resources for Random Access Response (RAR)	0001 - FFEF
TC-RNTI	0_0, 1_0	PUSCH resources for MSG3 re-transmissions, PDSCH resources for MSG4	
C-RNTI	0_0, 0_1, 1_0, 1_1	PUSCH and PDSCH resources for application data and control plane signalling	
MCS-C-RNTI	0_0, 0_1, 1_0, 1_1	Dynamic selection of low Spectral Efficiency MCS Table for PDSCH and PUSCH	
CS-RNTI	0_0, 0_1, 1_0, 1_1	Configured Grant Scheduling for PUSCH, Semi-Persistent Scheduling for PDSCH	
TPC-PUSCH-RNTI	2_2	Closed loop uplink power control commands for the PUSCH	
TPC-PUCCH-RNTI	2_2	Closed loop uplink power control commands for the PUCCH	
TPC-SRS-RNTI	2_3	Closed loop uplink power control commands for the SRS	
INT-RNTI	2_1	Interruption signalled using Pre-emption Indications	
SFI-RNTI	2_0	Dynamic changes to the slot format signalled using Slot Format Indicators (SFI)	
SP-CSI-RNTI	0_1	Trigger to activate/deactivate Semi-Persistent CSI reporting from the UE	

Table 367 – Types of Radio Network Temporary Identifiers (RNTI)

- ★ The RA-RNTI is used during the Random Access procedure when allocating PDSCH resources for the Random Access Response (MSG2). There is a one-to-one mapping between the RA-RNTI and the time-frequency resource used by the UE when transmitting the Random Access Preamble. This means that all UE using the same Random Access occasion will share the same RA-RNTI and the same PDCCH transmission. The content of the PDSCH differentiates between the set of UE using the Random Access Preamble Identity (RAPID) within the MAC sub-header
- ★ The Temporary C-RNTI (TC-RNTI) is allocated during the Random Access procedure within the Random Access Response (MSG2). It is subsequently used to address the UE when allocating PUSCH resources for MSG3 re-transmissions. It is not necessary to use the TC-RNTI when allocating resources for the initial MSG3 transmission because that resource allocation is included within MSG2 (rather than within a PDCCH transmission). The TC-RNTI is also used when allocating PDSCH resources for MSG4
- ★ The Cell RNTI (C-RNTI) is set equal to the TC-RNTI after successful Random Access contention resolution. The C-RNTI is changed whenever a UE completes a handover towards a new cell. The C-RNTI is used to address the UE when allocating PDSCH or PUSCH resources to that UE. It can also be used to initiate a PDCCH Order with DCI Format 1_0
- ★ The MCS-C-RNTI, CS-RNTI, TPC-PUSCH-RNTI, TPC-PUCCH-RNTI, TPC-SRS-RNTI, SP-CSI-RNTI can be allocated to a UE using the *PhysicalCellGroupConfig* parameter structure, e.g. within an *RRCSetup*, *RRCReconfiguration* or *RRCResume* message
- ★ The MCS-C-RNTI can be used to dynamically switch between the MCS tables applied to the PUSCH or PDSCH. In the case of dynamic scheduling, a UE applies the low spectral efficiency MCS table if it receives a resource allocation using the MCS-C-RNTI
- ★ The Configured Scheduling RNTI (CS-RNTI) can be used to activate and deactivate 'Configured Grant' transmissions in the uplink and 'Semi-Persistent Scheduling' (SPS) in the downlink. It is also used when allocating dynamic resources for re-transmissions
- ★ The TPC-PUSCH-RNTI, TPC-PUCCH-RNTI and TPC-SRS-RNTI are used to provide Transmit Power Control (TPC) commands for the PUSCH, PUCCH and SRS respectively. DCI Formats 2_2 and 2_3 are able to provide TPC commands for a group of UE rather than only a single UE. This means that multiple UE can be allocated the same RNTI and all those UE decode the same PDCCH payload. Each UE is able to extract its TPC commands from the appropriate position within the payload
- ★ The Interruption RNTI (INT-RNTI) is used to provide a Pre-emption Indication within DCI Format 2_1. A UE can be configured with an INT-RNTI using the *DownlinkPreemption* parameter structure that belongs to the *PDCCH-Config*. DCI Format 2_1 is able to provide Pre-emption Indications to a group of UE rather than only a single UE. This means that multiple UE can be allocated the same RNTI and all those UE decode the same PDCCH payload. Each UE is able to extract its Pre-emption Indication from the appropriate position within the payload. The use of Pre-emption Indications is described in section 3.6.6
- ★ The Slot Format Indicator RNTI (SFI-RNTI) can be used to dynamically change the Slot Format using DCI Format 2_0. The Slot Format can be changed by reconfiguring 'flexible' symbols to either uplink or downlink symbols. A UE can be allocated an SFI-RNTI within the *SlotFormatIndicator* parameter structure. DCI Format 2_0 is able to provide Slot Format Indicators to a group of UE rather than only a single UE. This means that multiple UE can be allocated the same RNTI and all those UE decode the same PDCCH payload. Each UE is able to extract its Slot Format Indicator from the appropriate position within the payload
- ★ The Semi-Persistent CSI RNTI (SP-CSI-RNTI) can be used to trigger the activation or deactivation of semi-persistent CSI reporting on the PUSCH. This is done using the 'CSI Request' field within DCI Format 0_1 when the CRC bits have been scrambled using the SP-CSI-RNTI

18.7 I-RNTI

- ★ The Inactive RNTI (I-RNTI) is applicable to the RRC Inactive State. In contrast to other RNTI, the I-RNTI is not used to scramble the CRC bits belonging to the PDCCH payload. Instead, the I-RNTI is used to address the UE within RRC signalling messages
- ★ An I-RNTI can be allocated to a UE within an *RRCRelease* message when moving the UE from RRC Connected to RRC Inactive. The I-RNTI is used to identify both the UE and the Base Station which hosts the UE context. This allows the UE context to be moved from one Base Station to another Base Station if the UE is mobile while RRC Inactive
- ★ There are two variants of the I-RNTI:
  - o a full I-RNTI which has a length of 40 bits. This variant can be included within an *RRCResumeRequest1* message which has a size of 64 bits. This is relatively large for a MSG3 transmission so there is a risk that uplink coverage may be compromised
  - o a short I-RNTI which has a length of 24 bits. This variant can be included within an *RRCResumeRequest* message which has a size of 48 bits. This is the normal size for MSG3 when transferring a CCCH message
- ★ The *useFullResumeID* flag within SIB1 instructs the UE to use either the full or short I-RNTI when resuming a connection, i.e. this flag instructs the UE to send either an *RRCResumeRequest* message or an *RRCResumeRequest1* message
- ★ 3GPP does not specify the number of bits within the I-RNTI which should be used to identify the Base Station, and the number of bits which should be used to identify the UE. The division of the total number of bits is left to the network implementation
- ★ The I-RNTI can be used to address a UE within an RRC *Paging* message when the UE is RRC Inactive. The RRC Inactive state is described in section 1.8.3, while the RAN Notification Areas which are applicable to RRC Inactive are described in section 16.13

19 ABBREVIATIONS

16QAM	16 Quadrature Amplitude Modulation
64QAM	64 Quadrature Amplitude Modulation
256QAM	256 Quadrature Amplitude Modulation
3GPP	3rd Generation Partnership Project
5G-GUTI	5G Globally Unique Temporary Identifier
5GMM	5G Mobility Management
5QI	5G Quality of Service Identifier
5GS	5G System
5GSM	5G Session Management
5G-TMSI	5G Temporary Mobile Subscription Identifier
AAS	Active Antenna System
AC	Access Class
AC	Admission Control
ACLR	Adjacent Channel Leakage Ratio
ACS	Adjacent Channel Selectivity
AF	Application Function
AGC	Automatic Gain Control
AM	Acknowledged Mode
AMBR	Aggregate Maximum Bit Rate
AMC	Adaptive Modulation and Coding
AMF	Access and Mobility Management Function
AMR	Adaptive Multi-Rate
ANR	Automatic Neighbour Relations
AoA	Angle of Arrival
APN	Access Point Name
ARFCN	Absolute Radio Frequency Channel Number
ARP	Allocation and Retention Priority
ARQ	Automatic Repeat Request
AS	Access Stratum
AUSF	Authentication Server Function
BCCH	Broadcast Control Channel
BCH	Broadcast Channel
BER	Bit Error Rate
BI	Back-off Indicator
BLER	Block Error Rate
BPRE	Bits Per Resource Element
BSR	Buffer Status Report
BTS	Base Transceiver Station
CA	Carrier Aggregation
CAZAC	Constant Amplitude Zero Auto-Correlation
CB	Coordinated Beamforming
CBC	Cell Broadcast Center
CBG	Code Block Group
CBGFI	CBG Flushing Out Information
CBGTI	CBG Transmission Information
CBRA	Contention Based Random Access
CC	Component Carrier
CCCH	Common Control Channel
CCE	Control Channel Element
CCO	Cell Change Order
CD	Collision Detection
CDD	Cyclic Delay Diversity
CDM	Code Division Multiplexing
CFI	Control Format Indicator
CFRA	Contention Free Random Access
CGI	Cell Global Identity
CIF	Carrier Indicator Field
CM	Channel Measurement
CM	Connection Management
CMAS	Commercial Mobile Alert Service
CN	Core Network
CoMP	Co-ordinated Multi-Point transmission
CORESET	Control Resource Set
CP	Control Plane
CP-OFDM	Cyclic Prefix OFDM
CQI	Channel Quality Indicator
CRC	Cyclic Redundancy Check
CRI	Contention Resolution Identity
C-RNTI	Cell Radio Network Temporary Identifier
CRS	Cell specific Reference Signal
CS	Circuit Switched
CS	Coordinated Scheduling
CSFB	CS Fallback
CSG	Closed Subscriber Group
CRB	Common Resource Block
CRI	CSI Reference Signal Resource Indicator
CSI	Channel State Information
CS-RNTI	Configured Scheduling RNTI
CSI RS	CSI Reference Signal
CSI-RSRP	CSI Reference Signal Received Power
CSI-RSRQ	CSI Reference Signal Received Quality
CSI-SINR	CSI Reference Signal SINR
CSMA	Carrier Sense Multiple Access
CSS	Common Search Space
CU	Centralised Unit
CW	Code Word
D2D	Device to Device
DAI	Downlink Assignment Index
DC	Direct Current
DC	Dual Connectivity
DCCH	Dedicated Control Channel
DCH	Dedicated Channel
DCI	Downlink Control Information
DFT	Discrete Fourier Transform
DFT-S-OFDM	Discrete Fourier Transform Spread OFDM
DHCP	Dynamic Host Configuration Protocol
DiffServ	Differentiated Services
DL-SCH	Downlink Shared Channel
DMRS	Demodulation Reference Signal
DNN	Data Network Name
DPI	Deep Packet Inspection
DRB	Data Radio Bearer
DRX	Discontinuous Reception
DSCP	Differentiated Services Code Point
DSS	Dynamic Spectrum Sharing
DTCH	Dedicated Traffic Channel
DTX	Discontinuous Transmit
DU	Distributed Unit
E1AP	E1 Application Protocol
EARFCN	E-UTRA Absolute RF Channel Number
EBB	Eigen based Beamforming
ECP	Extended Cyclic Prefix
EHPLMN	Equivalent HPLMN
EIR	Equipment Identity Register
EIRP	Effective Isotropic Radiated Power
eMBB	Enhanced Mobile Broadband
EMM	EPS Mobility Management

EN-DC	E-UTRA New Radio Dual Connectivity
EPC	Evolved Packet Core
EPRE	Energy Per Resource Element
E-RAB	E-UTRAN Radio Access Bearer
ESM	EPS Session Management
ETWS	Earthquake and Tsunami Warning System
E-UTRAN	Evolved UMTS Radio Access Network
E-UTRA	Evolved UMTS Radio Access
EVS	Enhanced Voice Services
F1AP	F1 Application Protocol
FCC	Federal Communications Commission
FDD	Frequency Division Duplex
FDM	Frequency Division Multiplexing
FFT	Fast Fourier Transform
FGI	Feature Group Indicator
FI	Framing Information
FMS	First Missing SDU
FQDN	Fully Qualified Domain Name
FT	Fourier Transform
FTP	File Transfer Protocol
FWA	Fixed Wireless Access
GBR	Guaranteed Bit Rate
GFBR	Guaranteed Flow Bit Rate
GNSS	Global Navigation Satellite System
GoB	Grid of Beams
GP	Guard Period
GPS	Global Positioning System
GMLC	Gateway Mobile Location Centre
GSCN	Global Synchronisation Channel Number
GSMA	GSM Association
GTP-U	GPRS Tunnelling Protocol User Plane
GTPv2-C	GPRS Tunnelling Protocol Control Plane
GUAMI	Globally Unique AMF Identifier
GUMMEI	Globally Unique MME Identity
GUTI	Globally Unique Temporary UE Identity
HARQ	Hybrid Automatic Repeat Request
HPLMN	Home Public Land Mobile Network
HRPD	High Rate Packet Data
HSS	Home Subscriber Server
HTTP	Hypertext Transfer Protocol
IC	Interference Cancellation
ICI	Inter Carrier Interference
ICIC	Inter Cell Interference Coordination
I-CSCF	Interrogating Call Session Control Function
IDFT	Inverse Discrete Fourier Transform
IFFT	Inverse Fast Fourier Transform
IFT	Inverse Fourier Transform
IM	Interference Measurement
IMEI	International Mobile Equipment Identity
IMS	IP Multimedia Subsystem
IMSI	International Mobile Subscriber Identity
INT-RNTI	Interruption RNTI
IoT	Interference over Thermal
IoT	Internet of Things
IP	Internet Protocol
IR	Incremental Redundancy
I-RNTI	Inactive RNTI
ISI	Inter Symbol Interference
ITU	International Telecommunication Union
JR	Joint Reception
JT	Joint Transmission

LADN	Local Area Data Network
LAI	Location Area Identity
LBRM	Limited Buffer Rate Matching
LCG	Logical Channel Group
LCID	Logical Channel Identity
LDPC	Low Density Parity Check
LI	Layer Indicator
LI	Length Indicators
LNA	Low Noise Amplifier
LSB	Least Significant Bit
LSM	Limited Service Mode
LTE	Long Term Evolution
MAC	Medium Access Control
MAC-I	Message Authentication Code for Integrity
MBMS	Multimedia Broadcast Multicast Service
MBR	Maximum Bit Rate
MBSFN	MBMS Single Frequency Network
MCC	Mobile Country Code
MCG	Master Cell Group
MCL	Minimum Coupling Loss
MCS	Mission Critical Service
MCS	Modulation and Coding Scheme
MDT	Minimisation of Drive Tests
MEC	Multi-Access Edge Computing
MFBR	Maximum Flow Bit Rate
MGL	Measurement Gap Length
MGRP	Measurement Gap Repetition Period
MGTA	Measurement Gap Timing Advance
MHA	Mast Head Amplifiers
MIB	Master Information Block
MICO	Mobile Initiated Connection Only
MIMO	Multiple Input Multiple Output
MISO	Multiple Input Single Output
MME	Mobility Management Entity
MMEC	MME Code
MMEGI	MME Group Identity
MMEI	MME Identity
mMIMO	massive MIMO
mMTC	massive Machine Type Communications
MMTEL	Multimedia Telephony
MN	Master Node
MNC	Mobile Network Code
MO	Mobile Originating
MPR	Maximum Power Reduction
MPS	Multimedia Priority Service
MR-DC	Multi-RAT Dual Connectivity
MSB	Most Significant Bit
MSI	Minimum System Information
MSIN	Mobile Subscriber Identification Number
MT	Mobile Terminating
M-TMSI	MME Temporary Mobile Subscriber Identity
MU-MIMO	Multi-User MIMO
N3IWF	Non-3GPP Interworking Function
NACC	Network Assisted Cell Change
NAI	Network Access Identifier
NAS	Non-Access Stratum
NAT	Network Address Translation
NCC	Network Colour Code
NCI	NR Cell Identifier
NCGI	New Radio Cell Global Identity
NCP	Normal Cyclic Prefix
NDI	New Data Indicator
NE	Network Element

NE-DC	New Radio - E-UTRA Dual Connectivity
NEF	Network Exposure Function
NF	Network Function
NFV	Network Function Virtualisation
NGAP	Next Generation Application Protocol
ng-eNode B	next generation eNode B
NGRAN	Next Generation RAN
NNSF	NAS Node Selection Function
NR	New Radio
NR-ARFCN	New Radio ARFCN
NRF	Network Function Repository Function
NSA	Non-Standalone
NSSAI	Network Slice Selection Assistance Info.
NSSF	Network Slice Selection Function
NUL	Normal Uplink
NWDAF	Network Data Analytics Function
NZP	Non-Zero Power
OCC	Orthogonal Cover Code
OCS	Online Charging System
OFCS	Offline Charging System
OFDM	Orthogonal Frequency Division Multiplexing
OSI	Other System Information
OSS	Operations Support System
OTA	Over The Air
OTDOA	Observed Time Difference of Arrival
OTT	Over The Top
PA	Power Amplifier
PAPR	Peak to Average Power Ratio
PBCH	Physical Broadcast Channel
PCEF	Policy and Charging Enforcement Function
PCFICH	Physical Control Format Indicator Channel
PCCH	Paging Control Channel
PCEF	Policy and Charging Enforcement Function
PCell	Primary Cell
PCF	Policy Control Function
PCH	Paging Channel
PCI	Physical Channel Identity
PCI	Physical layer Cell Identity
PCRF	Policy and Charging Rules Function
P-CSCF	Proxy - Call Session Control Function
PDCCH	Physical Downlink Control Channel
PDCP	Packet Data Convergence Protocol
PDN	Packet Data Network
PDSCH	Physical Downlink Shared Channel
PDU	Packet Data Unit
PEI	Permanent Equipment Identifier
PF	Paging Frame
P-GW	Packet Gateway
PHB	Per Hop Behaviour
PHR	Power Headroom Reports
PHICH	Physical Hybrid ARQ Indicator Channel
PL	Path Loss
PLMN	Public Land Mobile Network
PMCH	Physical Multicast Channel
PMI	Precoding Matrix Indicator
P-MPR	Power Management Maximum Power Reduction
PO	Paging Occasion
PRACH	Physical Random Access Channel
PRB	Physical Resource Block
PRG	Precoding Resource Block Group
P-RNTI	Paging RNTI
PRS	Positioning Reference Signal
PS	Packet Switched
PSCell	Primary SCG Cell
PSD	Power Spectral Density
PSS	Primary Synchronisation Signal
PTAG	Primary Timing Advance Group
PTI	Precoding Type Indicator
PTRS	Phase Tracking Reference Signal
PUCCH	Physical Uplink Control Channel
PUSCH	Physical Uplink Shared Channel
PWS	Public Warning System
QCI	QoS Class Identifier
QCL	Quasi Co-Location
QFI	QoS Flow Identity
QoS	Quality of Service
QPSK	Quadrature Phase Shift Keying
RA	Random Access
RACH	Random Access Channel
RAN	Radio Access Network
RANAC	RAN Area Code
RAPID	Random Access Preamble Identity
RA-RNTI	Random Access RNTI
RAR	Random Access Response
RAT	Radio Access Technology
RAU	Radio Access Unit
RB	Resource Block
RBB	Resource Block Bundle
RBG	Resource Block Group
REG	Resource Element Group
RF	Radio Frequency
RI	Rank Indicator
RIB	Radiated Interface Boundary
RIM	RAN Information Management
RIP	Received Interference Power
RIV	Resource Indication Value
RLC	Radio Link Control
RLF	Radio Link Failure
RLM	Radio Link Monitoring
RM	Registration Management
RMSI	Remaining Minimum System Information
RNA	RAN Notification Area
RNAC	RAN Notification Area Code
RNC	Radio Network Controller
RNTI	Radio Network Temporary Identifier
RNTP	Relative Narrowband Transmit Power
ROHC	Robust Header Compression
RQA	Reflective QoS Attribute
RQI	Reflective QoS Indication
RRC	Radio Resource Control
RRH	Remote Radio Head
RRM	Radio Resource Management
RSRP	Reference Signal Received Power
RSRQ	Reference Signal Received Quality
RSCP	Received Signal Code Power
RSSI	Received Signal Strength Indicator
RSTD	Reference Signal Time Difference
RSU	Road Side Unit
RTCP	Real time Transport Control Protocol
RTP	Real-time Transport Protocol
RTT	Round Trip Time
RU	Radio Unit
RV	Redundancy Version
S1-AP	S1 Application Protocol
S1-CP	S1 Control Plane
S1-UP	S1 User Plane
SA	Standalone

SAE	System Architecture Evolution
SAW	Stop and Wait
SBI	Service based Interface
SC-FDMA	Single Carrier Freq. Division Multiple Access
SCG	Secondary Cell Group
S-CSCF	Serving Call Session Control Function
SCTP	Stream Control Transmission Protocol
SD	Slice Differentiator
SDAP	Service Data Adaptation Protocol
SDF	Service Data Flow
SDL	Supplemental Downlink
SDU	Service Data Unit
SFI	Slot Format Indicator
SFI-RNTI	Slot Format Indicator RNTI
SFN	System Frame Number
SFTD	SFN and Frame Timing Difference
S-GW	Serving Gateway
SI	Segmentation Information
SI	System Information
SIB	System Information Block
SINR	Signal to Interference plus Noise Ratio
SIP	Session Initiation Protocol
SI-RNTI	System Information RNTI
SISO	Single Input Single Output
SLIV	Start and Length Indicator Value
SMF	Session Management Function
SMS	Short Message Service
SMSF	SMS Function
SMTC	SS/PBCH Block Measurement Timing Config.
SMTP	Simple Mail Transfer Protocol
SN	Sequence Number
SN	Secondary Node
SNR	Signal to Noise Ratio
S-NSSAI	Single Network Slice Selection Assistance Information
SO	Segmentation Offset
SON	Self Organising Network
SpCell	Special Cell
SP-CSI-RNTI	Semi-Persistent CSI RNTI
SPS	Semi Persistent Scheduling
SPS-RNTI	Semi Persistent Scheduling RNTI
SR	Scheduling Request
SRB	Signalling Radio Bearer
SRI	SRS Resource Indicator
SRS	Sounding Reference Signal
SRVCC	Single Radio Voice Call Continuity
SS	Synchronisation Signals
SSAC	Service Specific Access Class
SSB	Synchronisation Signal Block
SSBRI	SS/PBCH Block Resource Indicator
SSC	Session and Service Continuity
SSID	Service Set Identifiers
SS/PBCH	Synchronisation Signal / Physical Broadcast Channel
SSS	Secondary Synchronisation Signal
SST	Slice/Service Type
STAG	Secondary TAG
S-TMSI	SAE TMSI
SUCI	Subscription Concealed Identifier
SUL	Supplemental Uplink
SU-MIMO	Single User MIMO
SUPI	Subscription Permanent Identifier
TA	Tracking Area
TAC	Tracking Area Code
TAG	Timing Advance Group
TAI	Tracking Area Identity
TAU	Tracking Area Update
TBS	Transport Block Size
TCI	Transmission Configuration Indicator
TCP	Transmission Control Protocol
TC-RNTI	Temporary C-RNTI
TDD	Time Division Duplex
TDM	Time Division Multiplexed
TEID	Tunnel Endpoint Identifier
TFT	Traffic Flow Template
TM	Transparent Mode
TMA	Tower Mounted Amplifier
TMGI	Temporary Mobile Group Identifier
TMSI	Temporary Mobile Subscriber Identity
TNL	Transport Network Layer
ToC	Table of Contents
ToP	Timing over Packet
TPC	Transmit Power Control
TPMI	Transmitted Precoding Matrix Indicator
TRP	Total Radiated Power
TRP	Transmission / Reception Point
TRS	Tracking Reference Signal
TTI	Transmission Time Interval
TTL	Time To Live
UAC	Unified Access Control
UCI	Uplink Control Information
UCS	Universal Character Set
UDM	Unified Data Management
UDP	User Datagram Protocol
UDSF	Unstructured Data Storage Function
UE	User Equipment
UE-AMBR	UE Aggregate Maximum Bit Rate
URSP	UE Route Selection Policy
ULA	Uniform Linear Array
UL-SCH	Uplink Shared Channel
UM	Unacknowledged Mode
UP	User Plane
UPF	User Plane Function
UpPTS	Uplink Pilot Time Slot
URLLC	Ultra Reliable and Low Latency Communications
V2I	Vehicle to Infrastructure
V2N	Vehicle to Network
V2P	Vehicle to Pedestrian
V2V	Vehicle to Vehicle
V2X	Vehicle to Everything
VoIP	Voice over IP
VoLTE	Voice over LTE
VoNR	Voice over New Radio
VRB	Virtual Resource Block
X2-AP	X2 Application Protocol
X2-CP	X2 Control Plane
X2-UP	X2 User Plane
ZC	Zadoff-Chu
ZP	Zero Power

20 INDEX

5G New Radio in Bullets

Chris Johnson

- Complete text is presented as bullet points
- Can be read with ease and in less time
- More than 480 illustrations and 350 tables
- Content includes both introductory and advanced topics
- Non-Standalone and Standalone Base Station architectures
- Air-interface, Transmission Schemes and Beam Management
- Flow of Data, Signalling Procedures and Spectrum Sharing
- Idle Mode, Physical and MAC Layer procedures
- Practical Radio Network Planning topics
- Voice and data solutions

The author has 25 years of experience working in mobile telecommunications. This started with 6 years within a Research and Development environment, followed by 19 years of providing Technical Consultancy while gaining practical experience of 3G, 4G and 5G within a Radio Design environment. Training courses and technical workshops have been provided on a regular basis

ISBN 9781077484351

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