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5G Air Interface

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1.1 5G Phases

1.1.1 NR (New Radio) Phases

The 5G air interface, also known as NR (New Radio), is 3GPP's solution to meet the ITU-R (International Telecommunication Union – Radiocommunication), and in particular the 5D Working Party, defined minimum requirements for a 5G or IMT (International Mobile Telecommunications) 2020 network.

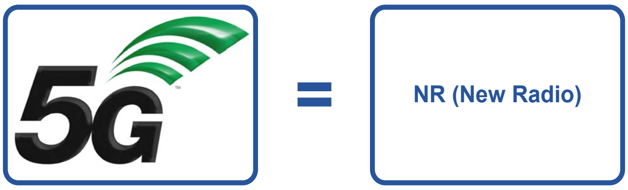


Figure 1-1 5G Air Interface

3GPP have defined a phased approach to 5G, referred to as 5G Phase 1 and 5G Phase 2. These are defined in 3GPP Release 15 and Release 16 respectively. The early focus for 5G Phase 1 is eMBB (Enhanced Mobile Broadband) data services and some URLLC (Ultra Reliable Low Latency Communications) support. 5G Phase 2 is planning to complete the IMT-2020 requirements with various enhancements, as well as support for MIoT (Massive Internet of Things).

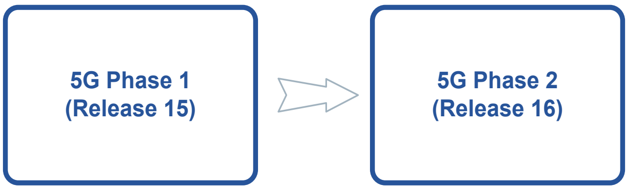


Figure 1-2 5G Phase 1 and Phase 2

1.1.2 5G NR Roadmap

Figure 1-3 illustrates the timescales for 5G Release 15 and Release 16. It is worth nothing that an "Early Drop" of the specification was defined for NSA (Non-Standalone) operation. Whereby, the 5G RAN (Radio Access Network) connects to the LTE RAN and utilizes the LTE EPC (Evolved Packet Core). In terms of NSA operation, this early freeze to the specifications enabled service providers to push forward with early 5G deployments.

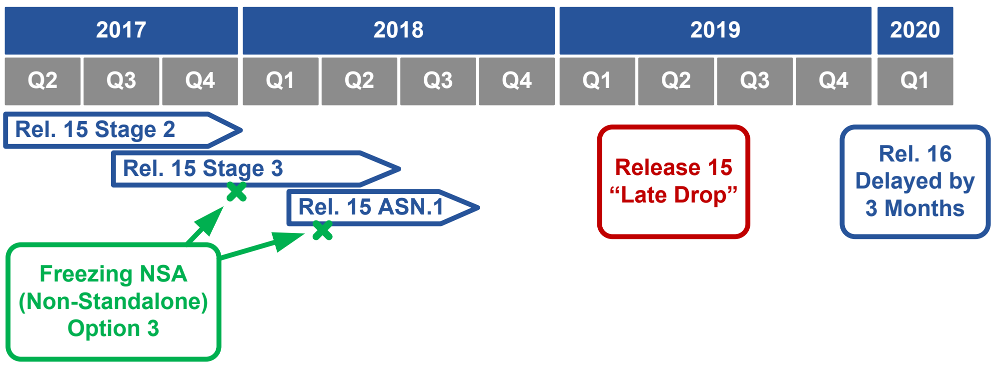


Figure 1-3 5G 3GPP Releases

The "main drop" Release 15 specification includes support for SA (Standalone) operation - whereby the 5G RAN communicates to a 5GC (5G

Core). It is worth noting that there is also a “late drop” which finalizes Release 15.

Release 16 is already underway; however, the associated Stage 2 specifications, specifically for the RAN (Radio Access Network) won’t be frozen till 2020. With Stage 3 and ASN.1 related specifications being frozen later in 2020.

1.2 5G RAN Architecture

Figure 1-4 illustrates the 5G RAN[1]. The key network element is the gNB (New Radio Node B), which connects to the 5GC (5G Core) via various reference points (N2 and N3). It is worth noting that the gNBs can also be connected to each other using the Xn reference point. This provides similar functionality to the LTE X2 interface, i.e. support for inter gNB mobility, interference mitigation, dual connectivity etc.

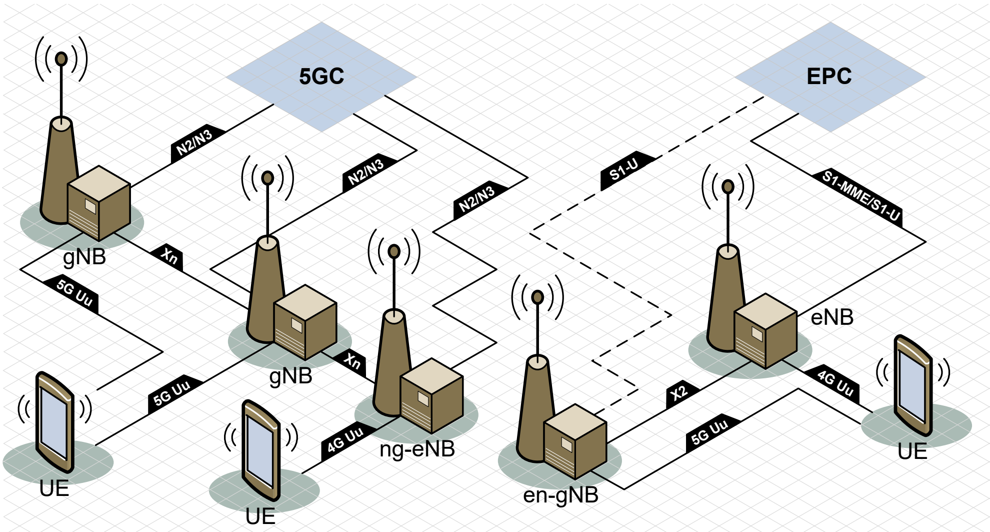


Figure 1-4 5G RAN Architecture

The existing LTE RAN has also been enhanced in order to support 5G. Initially, this included the 5G “bolt on” in the for of a en-gNB (E-UTRA NR gNB) to support NSA operation. However, LTE eNB’s also have been modified to facilitate access to the 5G core network, as well as to support eNB to gNB communication. This new format of LTE eNB is termed the ng-eNB (next generation eNB).

Note that Figure 1-4 shows the basic 5G RAN architecture; in reality, this architecture will undoubtedly follow a distributed model known as C-RAN (Centralized RAN).

1.2.1 Dual-Connectivity

DC (Dual Connectivity) is used when a device consumes radio resources provided by at least two different network access points (such as an gNB or eNB for example). In addition, each network access point involved in providing dual connectivity for a device may assume different roles. This feature is an important step since it enables one of the early 5G options.

[1] TS 38.300 – NR and NG-RAN Overall Description

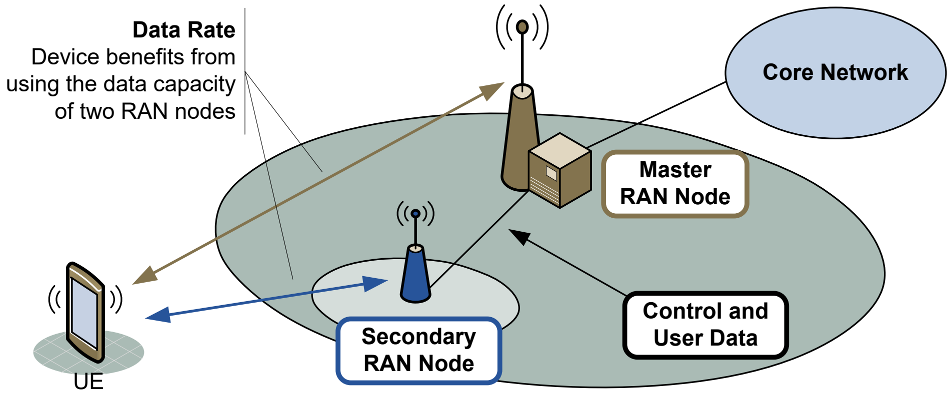


Figure 1-5 Dual Connectivity

Terminology for Dual Connectivity includes:

- Bearer Split - in dual connectivity, this term refers to the ability to split a bearer over multiple RAN Nodes. Note that not every bearer for the device has to be a split bearer.
- Dual Connectivity - is the operation where a device consumes radio resources provided by at least two different network points (Master and Secondary) connected while in the RRC (Radio Resource Control) Connected state.
- MCG (Master Cell Group) - is the group of the serving cells associated with the Master RAN Node.
- Master RAN Node - in dual connectivity mode, this is the gNB/ng-eNB/eNB which terminates the core network connectivity and therefore acts as the mobility anchor towards the core network.
- SCG (Secondary Cell Group) - is the group of serving cells associated with the Secondary RAN Node.
- Secondary RAN Node - in dual connectivity mode, this is an gNB, ng-eNB or eNB providing additional radio resources to the device, which is not the Master RAN Node.

New Radio Dual Connectivity

Figure 1-6 illustrates an example of Dual Connectivity between two gNBs, namely NR-DC (New Radio Dual Connectivity).

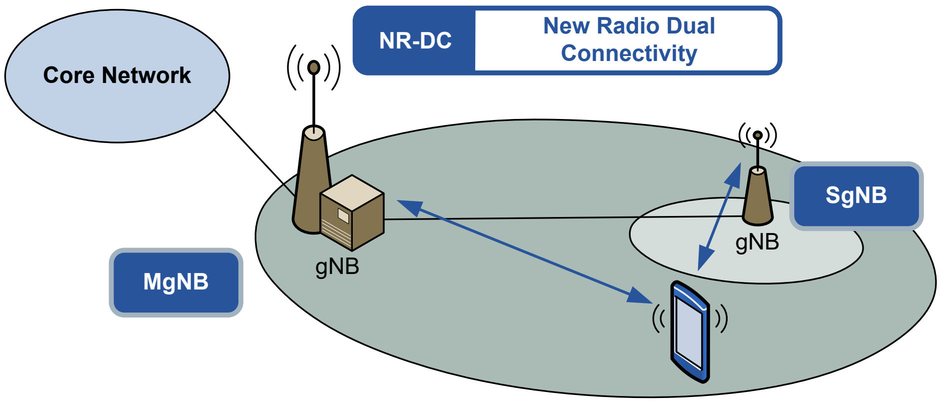


Figure 1-6 NR Dual Connectivity Options

In this case, one of the cells is a small cell, however it could equally be a second capacity layer.

1.2.2 5G RAN Deployment Options

The architecture of a 5G New Radio access network is based on two high level options; namely, SA (Standalone) or NSA (Non-Standalone) deployment. Generally, Standalone connectivity is based on the gNB connecting directly to the 5G Core. In contrast, the Non-Standalone term is applied when multiple RAN technologies are utilized. For example, the gNB connects via an LTE eNB, which in turn utilizes the EPC (Evolved Packet Core) or 5G Core. This is illustrated is Figure 1-7, which shows the different "options" that were introduced within the 5G radio network feasibility study.

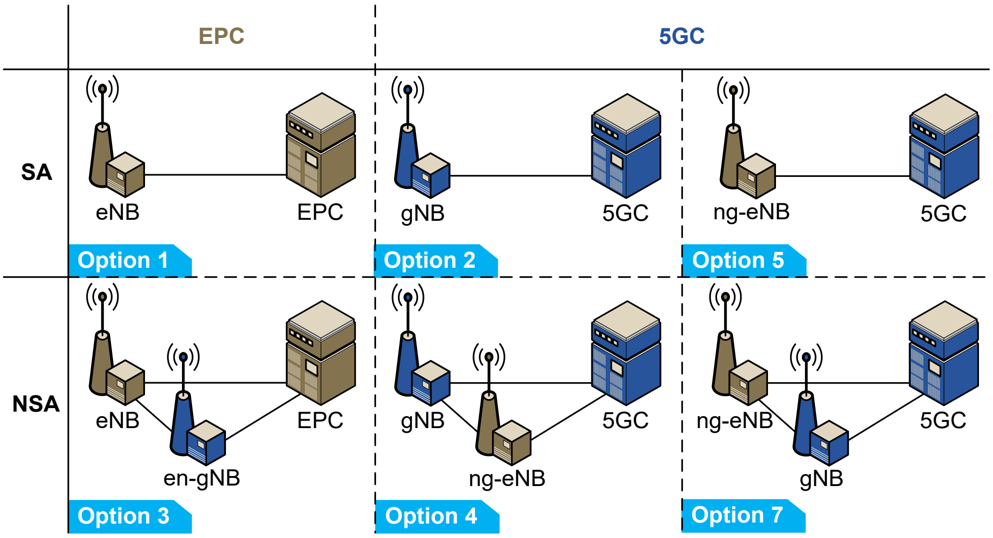


Figure 1-7 Standalone vs Non-Standalone Deployment

The options identified in Figure 1-7 are summarized below:

- Option 1 - this is considered to be the pure legacy LTE option, which does not include any 5G technology.
- Option 2 - this standalone configuration sees the device connecting to the 5G Core via a gNB.
- Option 3 - this option uses the EPC (Evolved Packet Core) as the core network, with a Dual Connectivity option whereby the eNB is the master RAN node and a gNB is the secondary RAN Node. Both RAN nodes can have user plane connectivity to the EPC.
- Option 4 - this is a Dual Connectivity scenario in which a gNB serves as the master RAN node and an ng-eNB serves as secondary RAN node. The 5G Core network is used for control and user plane.
- Option 5 - this is an LTE RAN solution which integrates into the 5G Core. As such, the eNB will be an ng-eNB (next generation eNB).
- Option 7 - this dual connectivity option introduces the ng-eNB acting as the master RAN node, with a gNB as secondary RAN Node. The control and user plane connections are terminated in the 5G Core.

Currently the main Non-Standalone configuration is identified as "Option 3x". This has been chosen for initial 5G Phase 1 support, with the "x" relating to a specific bearer splitting option. Following this, the next stage of Phase 1 enables the gNB to connect to the 5GC via an ng-eNB, identified as "Option 7". Note, that as soon as a service provider has a 5GC the gNB's can directly connect to the 5G Core, thus facilitating options 2 and option 4.

1.2.3 Multi RAT Dual Connectivity

When one incorporates LTE as a potential option for Dual Connectivity alongside 5G, a number of different connectivity options exist between the device and the core network. Termed MR-DC (Multi-RAT Dual Connectivity), the following figures outline the different deployment options which exist for service providers (a summary is provided in Figure 1-8).

Name	Abbr.	Option	Master	Secondary	Core
New Radio Dual Connectivity	NR-DC	2 (5G-5G DC)	gNB	gNB	5GC
E-UTRA – NR Dual Connectivity	EN-DC	3	eNB	en-gNB	EPC
NG-RAN – E-UTRA-NR Dual Connectivity	NGEN-DC	7	ng-eNB	gNB	5GC
NR – E-UTRA Dual Connectivity	NE-DC	4	gNB	ng-eNB	5GC

Figure 1-8 Dual Connectivity Options

E-UTRA – NR Dual Connectivity

Figure 1-9 outlines EN-DC (E-UTRA – NR Dual Connectivity), in which the device connects to a MeNB (Master eNB) and a SgNB (Secondary gNB). With this configuration, the master node will be connected to the EPC (Evolved Packet Core), with SgNB connecting to the MeNB via the X2 interface.

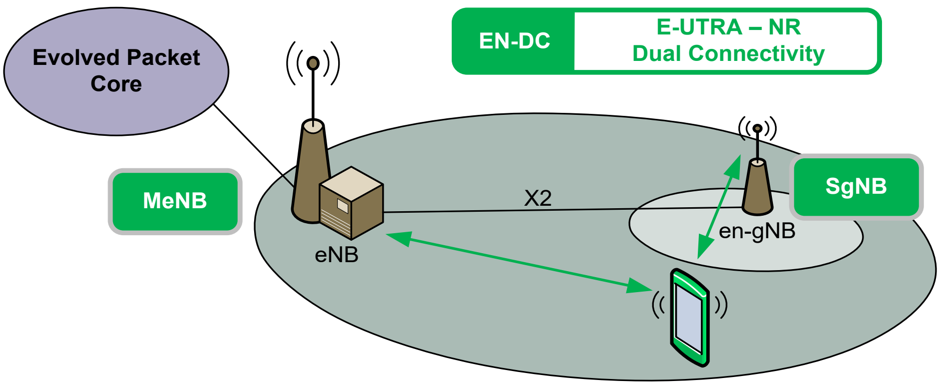


Figure 1-9 E-UTRA – NR Dual Connectivity

NG-RAN – E-UTRA-NR Dual Connectivity

Figure 1-10 introduces the use of the ng-eNB (next generation eNB) as the master RAN node within a NGEN-DC (NG-RAN - E-UTRA-NR Dual Connectivity) scenario. In this example, the ng-eNB connects in to the 5G Core, with a gNB acting as the secondary node. Connectivity between the Mng-eNB (Master ng-eNB) and the SgNB is based on the Xn interface.

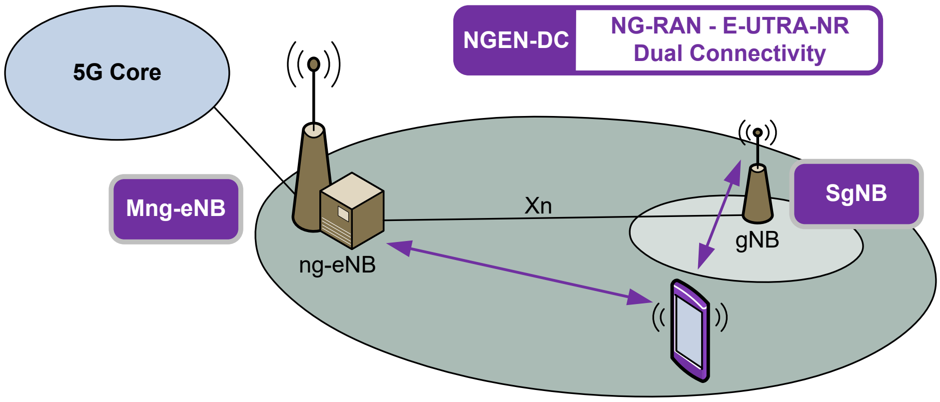


Figure 1-10 NG-RAN – E-UTRA-NR Dual Connectivity

NR – E-UTRA Dual Connectivity

Similar in concept to NGEN-DC, Figure 1-11 outlines the architecture for NE-DC (NR - E-UTRA Dual Connectivity). With this approach, a gNB serves as the master RAN node, connecting in to the 5G Core. The secondary RAN node is an ng-eNB, which connects to the MgNB via the Xn interface.

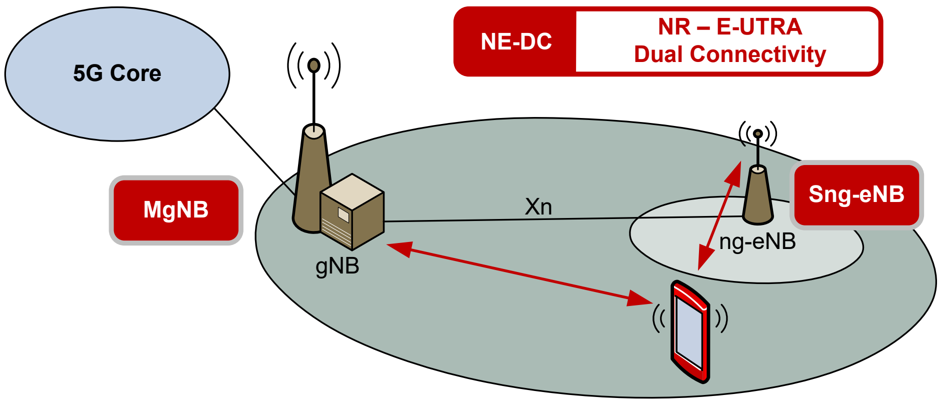


Figure 1-11 NR – E-UTRA Dual Connectivity

1.2.4 NR Protocol Stack

The protocols utilized by a 5G device will vary depending on whether air interface Control Plane signalling is being transferred or User Plane is being transferred. In addition, various options for splitting both the User Plane and the SRB (Signalling Radio Bearer) also exist, which can influence where the protocols reside.

Figure 1-12 illustrates a high-level view of the protocols supported in a device which is capable of 5G operation.

The NR protocols include:

- 5G NAS (Non Access Stratum)[2] - NAS signalling is sent between the device and the 5GC. It is split into 5GMM (5G Mobility Management) and 5GSM (5G Session Management) signalling.
- NR RRC (Radio Resource Control)[3] - like LTE, this is used to establish and maintain the RRC connection between the gNB and the device.

[2] TS 24.501 – NAS (Non Access Stratum) Protocol for 5G System
[3] TS 38.331 – RRC (Radio Resource Control) Protocol Specification

- NR SDAP (Service Data Adaptation Protocol)[4] - this is a new protocol for 5G. It's main role relates to mapping and marking user plane data for QoS (Quality of Service) purposes.
- NR PDCP (Packet Data Convergence Protocol)[5] - like LTE, this supports User Plane and Control Plane, as well as in band control. PDCP's main role involves sequencing and security such as integrity and encryption.
- NR RLC (Radio Link Control)[6] - very similar to LTE RLC, such that it can provide Layer 2 reliability through re-transmission.
- NR MAC (Medium Access Control)[7] - very similar to LTE MAC, however it is designed to operate with the NR Physical Layer. As such, MAC is the key layer with respect to scheduling.
- NR PHY (Physical)[8] - this is the 5G NR and offers data transport services to the higher layers. It includes many of the LTE radio concepts such as power control, synchronization, random access, HARQ (Hybrid Automatic Repeat Request) etc.

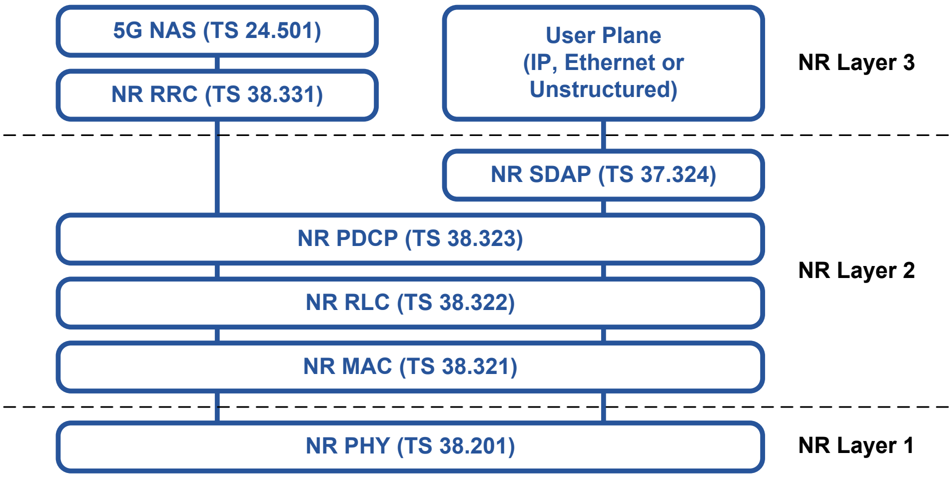


Figure 1-12 5G NR Air Interface Protocol Stack

1.3 C-RAN Concepts

In order to provide acceptable levels of radio coverage, a mobile service provider's RAN infrastructure (whether it's 2G, 3G, 4G or 5G) is extensive. Depending on the scale of the network, RAN node deployments could number in the tens of thousands, to the millions, with each containing dedicated compute resources which tend to be utilized at less than maximum capacity. Consequently, in order to reduce OPEX (Operational Expenditure) and CAPEX (Capital Expenditure), C-RAN (Centralized RAN), also termed Cloud RAN, is being introduced to both 4G and 5G networks.

The 5G NG-RAN can support a number of different deployment configurations. A centralized deployment would be based on C-RAN, which sees a single CU (Central Unit)[9] in control of one or more DU (Distributed Units). A non-centralized deployment would be based on a traditional,

[4] TS 37.324 - SDAP (Service Data Adaptation Protocol) Specification
[5] TS 38.323 - PDCP (Packet Data Convergence Protocol) Specification
[6] TS 38.322 - RLC (Radio Link Control) Protocol Specification
[7] TS 38.321 - MAC (Medium Access Control) Protocol Specification
[8] TS 38.201 - Physical layer; General Description
[9] TS 38.401 – NG-RAN; Architecture Description

monolithic architecture. Key terminology is explained in Figure 1-13, although it should be noted that different standards bodies use different terminology.

CU **Centralized Unit**	Centralized processing, housing higher layer elements of the gNB protocol stack (one CU to multiple DUs)
DU **Distributed Unit**	Houses lower layers of the gNB protocol stack, with reduced processing requirements
RRU **Remote Radio Unit**	Deals with physical layer transmission and reception, supporting technologies such as Carrier Aggregation and Massive MIMO (Multiple Input Multiple Output)

Figure 1-13 C-RAN Terminology

1.3.1 C-RAN Architecture for 5G

Figure 1-14 outlines the 3GPP architecture for the NG-RAN, which includes both Non-Centralized and Centralized deployment methodologies. Note that the ratio of gNB-CU to gNB-DU is one to many; however, a single gNB-DU should only be connected to one gNB-CU (although there can be exceptions to this rule for redundancy purposes). Note also that the RRU is considered part of the gNB-DU functionality. The F1 reference point supports both signalling exchange (both UE and non UE associated) and user plane data transmission.

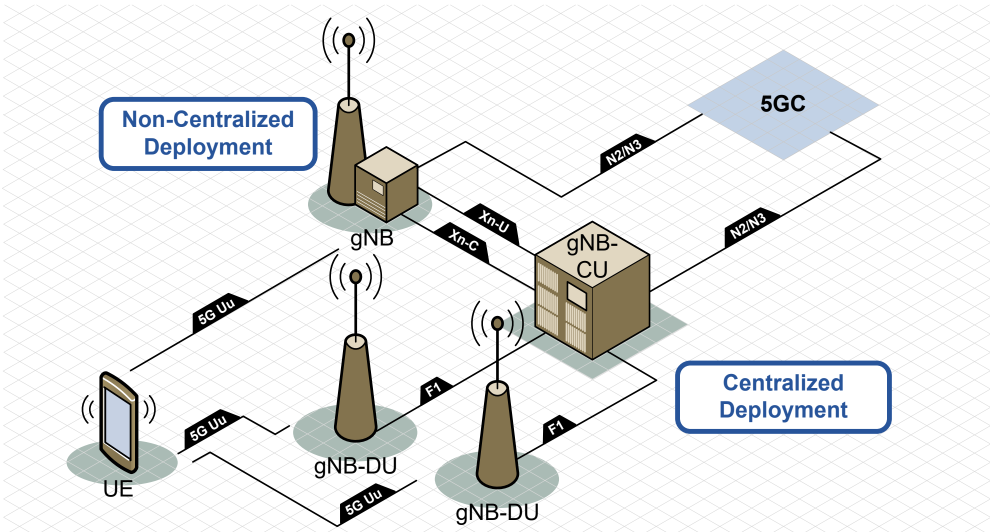


Figure 1-14 5G C-RAN Architecture

1.3.2 Separation of gNB-CU

To further optimize the C-RAN architecture, it is possible to split the Control Plane and User Plane capabilities of the Central Unit. As such, the F1 reference point is divided into F1-C (F1 – Control) and F1-U (F1 – User) elements. F1-C is based on F1AP (F1 Application Protocol)[10] and F1-U is based on GTPv1-U (GPRS Tunnelling Protocol version 1 – User plane). The architecture to achieve this is outlined in Figure 1-15, which also introduces

[10] TS 38.473 – NG-RAN; F1 Application Protocol (F1AP)

the E1 reference point between the gNB-CU-CP and gNB-CU-UP functions. E1 is based on E1AP (E1 Application Protocol)[11].

Note that the gNB-CU-CP can potentially be in control of multiple gNB-CU-UPs. Overall, a single gNB deployment based on a Non Centralized approach can contain a gNB-CU-CP, multiple gNB-CU-UPs and multiple gNB-DUs.

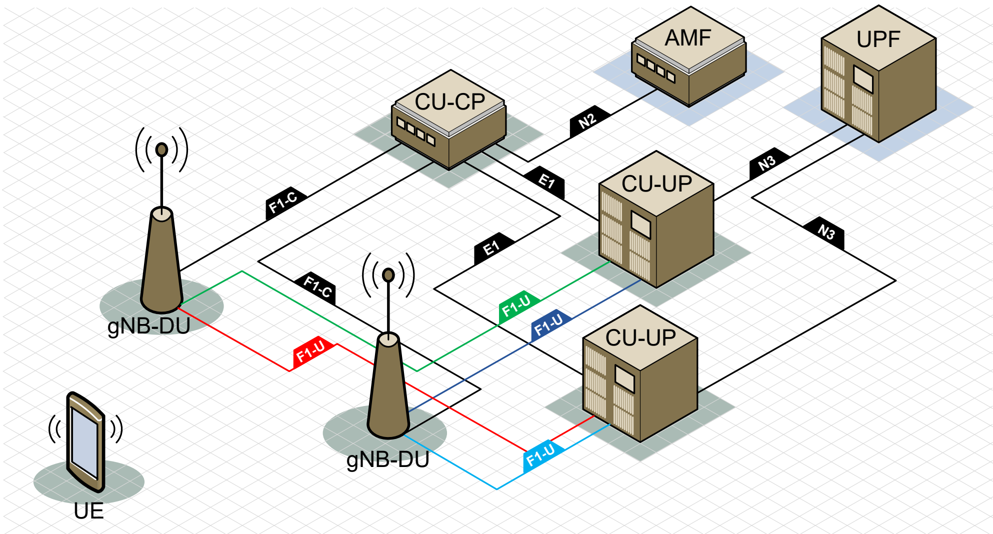


Figure 1-15 Separation of gNB-CU-CP and gNB-CU-UP

1.3.3 F1 Protocol Stack Split

Figure 1-16 outlines the protocol stack split for the 3GPP's Centralized RAN deployment. RRC (Radio Resource Control) supports the control plane between the gNB and the device, whereas SDAP (Service Data Adaptation Protocol) supports the user plane. Both higher layer protocols use the services of PDCP (Packet Data Convergence Protocol).

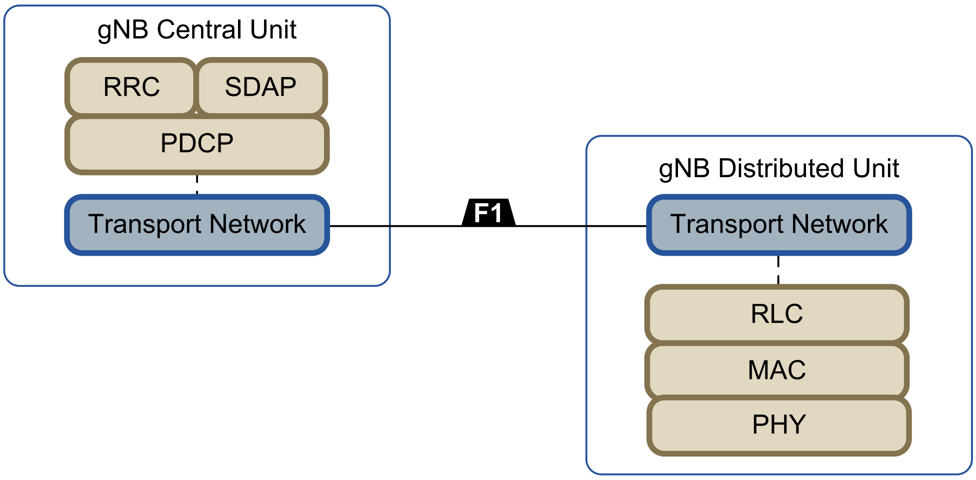


Figure 1-16 C-RAN – 3GPP Approach

Note that a number of options were considered with respect to where the protocol stack should be split, but PDCP (Packet Data Convergence Protocol) was the final choice. This was mainly attributed to the fact that PDCP is also the splitting point for split bearers within Dual Connectivity scenarios.

PDCP fundamentally provides a compression service to higher layer data, which as mentioned may be control plane or user plane traffic. PDCP is also

[11] 3GPP TS 38.463 – NG-RAN; E1 Application Protocol (E1AP)

responsible for implementing ciphering and integrity checking, as well as packet sequencing. All PDCP PDU (Protocol Data Units) will be allocated either a Downlink or Uplink Sequence Number, depending on the direction of traffic transfer. In the case of F1, PDCP PDUs for the user plane are transported using GTPv1-U. PDCP PDUs carrying RRC are transported using F1AP.

1.3.4 EN-DC Configuration for 5G C-RAN

Figure 1-17 outlines the architecture that would be involved if a Non-Centralized RAN node interworks with a C-RAN solution which uses a gNB-CU-CP and gNB-CU-UP. The example given is a 4G eNB interworking with a 5G C-RAN architecture, which you would find in an EN-DC scenario.

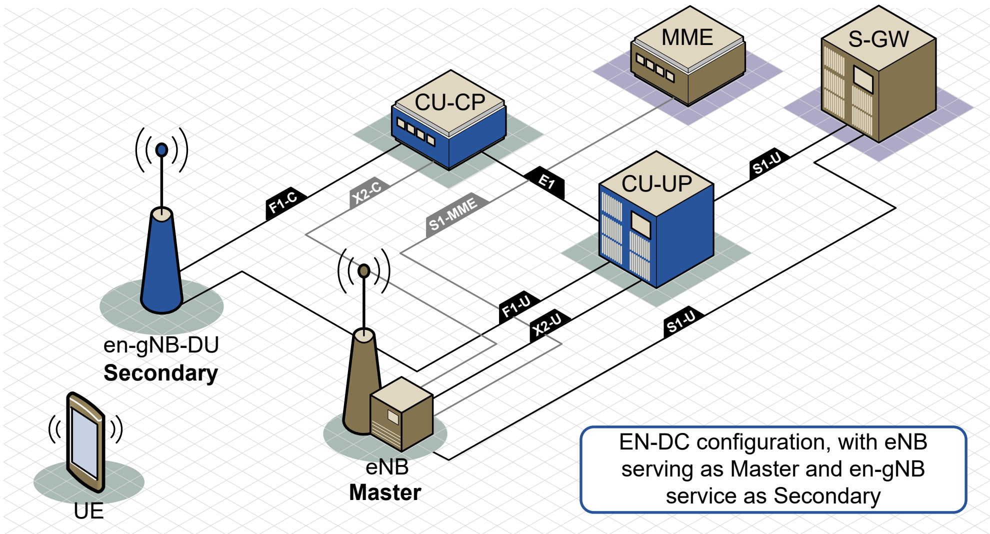


Figure 1-17 Dual Connectivity with Non C-RAN Node (EN-DC Configuration)

1.4 Managing 5G QoS

QoS within the 5G System is applied to a packet of data based on the QoS Flow that it has assigned to it as it traverses the end to end PDU Session. In a given PDU Session, several QoS Flows, each with different QoS characteristics, can potentially be configured.

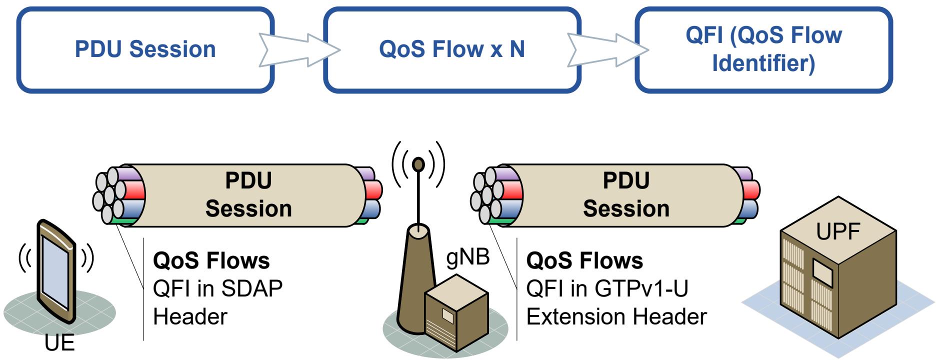


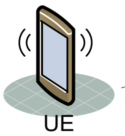
Figure 1-18 PDU Sessions and QoS Flows

A unique QFI (QoS Flow Identifier) is used to differentiate one flow from another within a PDU Session and as such, user plane traffic placed on a specific QoS Flow will be tagged accordingly with the QFI of that flow.

Note that there is not a 1:1 mapping between QoS flows and Access Network resources; it is the responsibility of the device/gNB to map a QoS Flow to a DRB (Data Radio Bearer) which will provide the correct QoS profile.

In the 5G System, the SMF determines which QFI a particular SDF (Service Data Flow) must use. At the device, classification is based on QoS rules which must be configured on the device, either as part of the PDU Session Establishment / Modification process (supplied by the SMF) or as part of a preconfigured rule set. At the UPF, classification is based on a PDR (Packet Detection Rule), which essentially serves the same function as the QoS rule.

Figure 1-19 shows the basic composition of a QoS rule. Note that for a given QFI, several rules may be configured and applicable.



QoS Rule
- QoS Rule Identifier
  Unique within the PDU Session
- QFI of the associated QoS Flow
- Packet Filter Set
  IP address and port information for traffic which must use this QoS flow
- Precedence Value
  The order by which this QoS Rule must be applied, in relation to all other configured rules
- QoS Parameters
  Applicable to the UE

Figure 1-19 QoS Rule Composition

Note that the Packet Filters within the Packet Filter Set can incorporate a variety of different information, depending on the PDU Session type. Figure 1-20 provides more information as to the type of components which can be used.

IP Packet Filter Set
- Source/Destination IP address or IPv6 Prefix
- Source/Destination Port Number
- Protocol ID
- Traffic Class (QoS)
- IPv6 Flow Label
- SPI
- Packet filter direction

Ethernet Packet Filter Set
- Source/Destination MAC Address
- Ethertype
- C-Tag or S-Tag
- IP Packet Filter Set (if Ethertype is IP)
- Packet Filter Direction

Figure 1-20 Packet Filter Information

Default QoS Rule

Every PDU Session must have a Default QoS Rule. This Default QoS Rule can be configured with no packet filters, which means that it will have the highest precedence (lowest priority) value of all the QoS rules. If a particular packet does not fit any other QoS rules, the lack of packet filter ensures it will always fit the Default QoS Rule, which will then determine the QFI the traffic must use.

One Default QoS Rule per PDN Session | **No Packet Filter** | **Lowest Priority Filter**

Figure 1-21 Default QoS Rule Characteristics

1.4.1 QoS Flow Parameters

The QoS characteristics of each QoS flow are defined utilizing a series of QoS parameters, outlined in Figure 1-22. The 5G System supports Delay Critical GBR (Guaranteed Bit Rate), GBR and Non-GBR for PDU Sessions. These parameters identified in Figure 1-22 must be established when the PDU Session or QoS Flow is initially established.

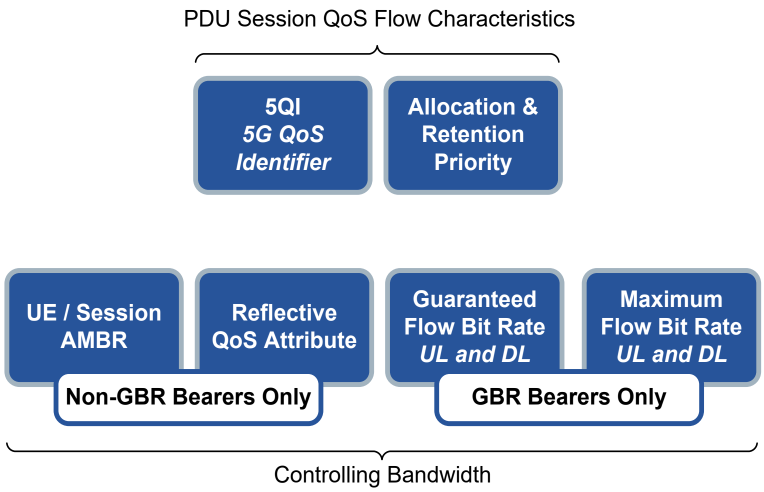


Figure 1-22 QoS Flow Parameters

1.4.2 5G QoS Identifier

The key QoS characteristics attributed to a QoS Flow are determined by its 5QI (5G QoS Identifier) allocation. The 5QI value and its associated traffic handling parameters are applicable on an edge to edge basis, from the UE to the UPF. Figure 1-23 and Figure 1-24 outline the main characteristics that the designated 5QI value will determine.

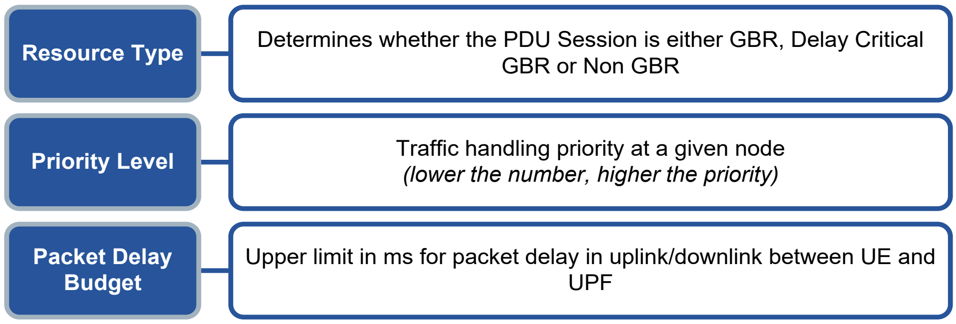


Figure 1-23 5QI QoS Characteristics – Part 1

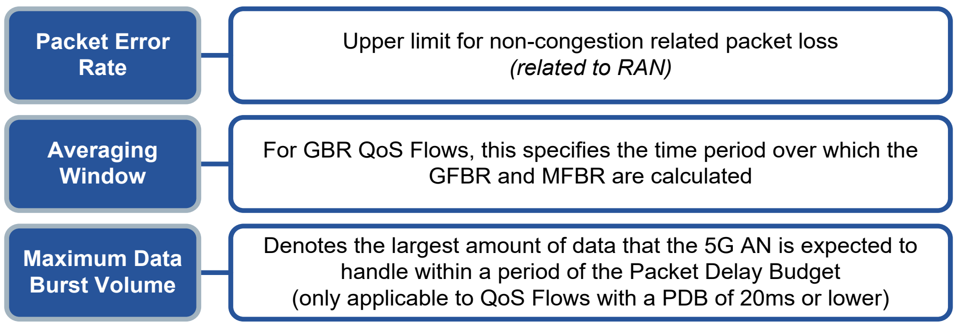


Figure 1-24 5QI QoS Characteristics – Part 2

The 5G System architecture specification[12] provides a standardized set of 5QI values, along with their associated characteristics. Figure 1-25 shows the Delay Critical GBR and GBR mappings, whereas Figure 1-26 shows the Non GBR mappings.

If a service provider chooses to use these standardized mappings, it is not necessary to send the details of the QoS characteristics in signalling; simply sending the 5QI value will suffice. However, if non-standard values are used by the service provider for its 5QI mappings, the associated characteristics must be signalled at the time of PDU Session Establishment / Modification and any time thereafter when the user plane is activated (specifically on N2 between the AMF and the gNB).

As new technologies are introduced, the tables in Figure 1-25, Figure 1-26 and Figure 1-27 are often added to, for example with the introduction of mission critical services and V2X (Vehicle to Everything). For 5G, 5QI values for ULL (Ultra Low Latency) will feature. Note that averaging windows are still to be defined in the 3GPP specifications. In addition, a number of QCI values are yet to be allocated.

5QI	Resource Type	Priority Level	Packet Delay Budget	Packet Error Rate	Default Max Data Burst Volume	Averaging Window	Example Services
1	GBR	20	100ms	10^{-2}	N/A	2000ms	Conversational Voice
2	GBR	40	150ms	10^{-3}	N/A	2000ms	Conversational Video (Live Streaming)
3	GBR	30	50ms	10^{-3}	N/A	2000ms	Real Time Gaming, V2X, Utilities
4	GBR	50	300ms	10^{-6}	N/A	2000ms	Non Conversational Video (Buffered)
65	GBR	7	75ms	10^{-2}	N/A	2000ms	Mission Critical User Plane PTT Voice
66	GBR	20	100ms	10^{-2}	N/A	2000ms	Non-Mission Critical User Plane PTT Voice
67	GBR	15	100ms	10^{-3}	N/A	2000ms	Mission Critical Video user plane
75	GBR	25	50ms	10^{-2}	N/A	2000ms	V2X messages

Figure 1-25 Standardized 5QI to QoS Characteristics Mapping (GBR)

5QI	Resource Type	Priority Level	Packet Delay Budget	Packet Error Rate	Service Example
5	Non GBR	10	100ms	10^{-6}	IMS Signalling
6	Non GBR	60	300ms	10^{-6}	Video (Buffered Streaming)
7	Non GBR	70	100ms	10^{-3}	Voice, Video and Interactive Gaming
8	Non GBR	80	300ms	10^{-6}	Video, TCP (WWW, email, FTP, etc)
9	Non GBR	90	300ms	10^{-6}	Video, TCP (WWW, email, FTP, etc)
69	Non GBR	5	60ms	10^{-6}	Mission critical delay sensitive signalling
70	Non GBR	55	200ms	10^{-6}	Mission critical data
79	Non GBR	65	50ms	10^{-2}	V2X messages
80	Non GBR	68	10ms	10^{-6}	Low latency eMBB Applications eg Augmented Reality

Figure 1-26 Standardized 5QI to QoS Characteristics Mapping (Non GBR)

[12] TS 23.501 – System Architecture for the 5G System

5QI	Resource Type	Priority Level	Packet Delay Budget	Packet Error Rate	Default Max Data Burst Volume	Averaging Window	Example Services
82	Delay Critical	19	10ms	10^{-4}	255 B	2000ms	Discrete Automation
83	Delay Critical	22	10ms	10^{-4}	1358 B	2000ms	Discrete Automation
84	Delay Critical	24	30ms	10^{-5}	1354 B	2000ms	Intelligent Transport Systems
85	Delay Critical	21	5ms	10^{-5}	255 B	2000ms	Electricity Distribution (High Voltage)

Figure 1-27 Standardized 5QI to QoS Characteristics Mapping (Delay Critical GBR)

1.5 5G Bearers

1.5.1 MCG and SCG Cell Terminology

The terms MCG (Master Cell Group) and SCG (Secondary Cell Group) are specific to dual connectivity:

- Master Cell Group - this is a group of serving cells associated with the Master RAN Node, comprising of the SpCell (Special Cell) which is known as the PCell (Primary Cell) and optionally one or more SCell (Secondary Cell).
- Secondary Cell Group - this is a group of serving cells associated with the Secondary RAN Node, comprising of the SpCell which is known as the PSCell (Primary SCell) and optionally one or more SCells.

A SpCell (Special Cell) supports PUCCH (Physical Uplink Control Channel) transmission and contention based Random Access. In addition, it is always activated.

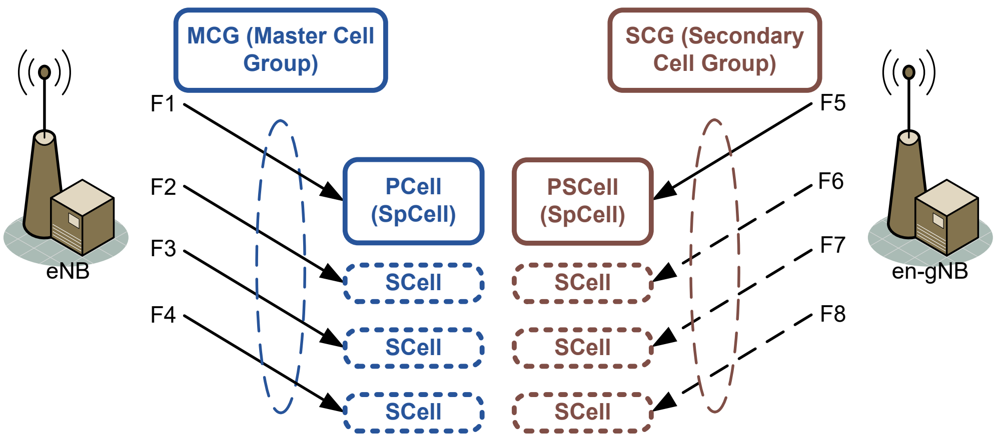


Figure 1-28 MCG and SCG

1.5.2 RRC Considerations

When MR-DC is in operation, both the master and secondary RAN node can exchange RRC signalling with the device. However, the device will maintain a single RRC state which is based on the master RAN node. Moreover, RRC connectivity to the secondary RAN node is optional.

Initially, the device will have RRC connectivity to the master RAN node through SRB1 (Signalling Radio Bearer 1). When a secondary node is added, initial RRC messages from the secondary node, such as the RRC Connection Configuration, are sent to the device via the master RAN node. The master

RAN node will encapsulate RRC from the secondary RAN node within its own RRC messages that it sends to the device.

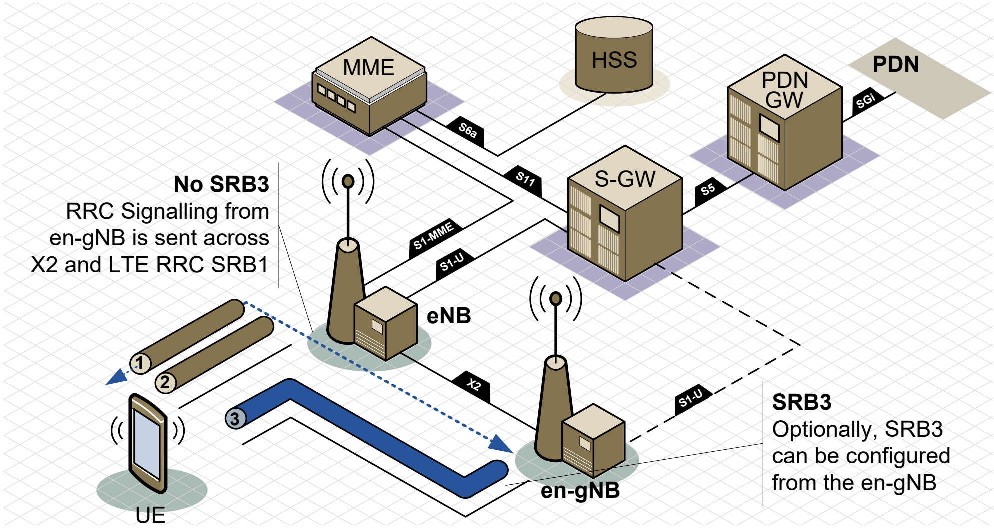


Figure 1-29 RRC Considerations

If the secondary RAN node is a gNB, a separate RRC connection (SRB3) can be established between the device and the gNB. SRB3 will carry a subset of RRC messages that are only relative to the secondary RAN node, such as mobility between cells belonging to the secondary RAN node. If there is any reconfiguration taking place which requires coordination by the master RAN node, SRB3 will not be used for this. If SRB3 is not utilized, all RRC messages associated with the secondary RAN node must be transported via the master RAN node.

1.5.3 MCG Split SRB

MCG Split SRB is a mechanism which provides RRC diversity and is ultimately designed to decrease the chance of connection failures and increase the reliability of RRC packet transmission from the Master RAN node. This is achieved by implementing multi-connectivity on the control plane, allowing RRC messages to take two different paths to get to the device. Figure 1-30 outlines this concept, whereby the RRC controlling entity residing in the master RAN node will also use the secondary RAN node for RRC PDU (Protocol Data Unit) delivery.

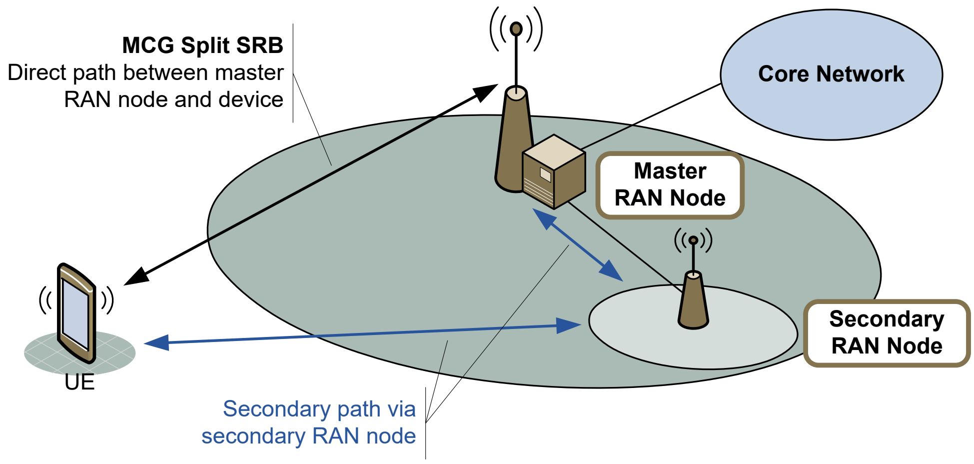


Figure 1-30 MCG Split SRB

Note that MCG Split SRB also applies to uplink RRC messages, whereby the device can be instructed to duplicate its RRC messages and then also use the secondary RAN node for uplink transmission.

1.5.4 User Plane Splitting

Figure 1-31 outlines the user plane bearer core network connectivity options for when Dual Connectivity is in operation. As can be seen in Figure 1-31, it is possible for the secondary RAN node to have its own user plane connection to the core network, as well as various RAN bearer splitting options.

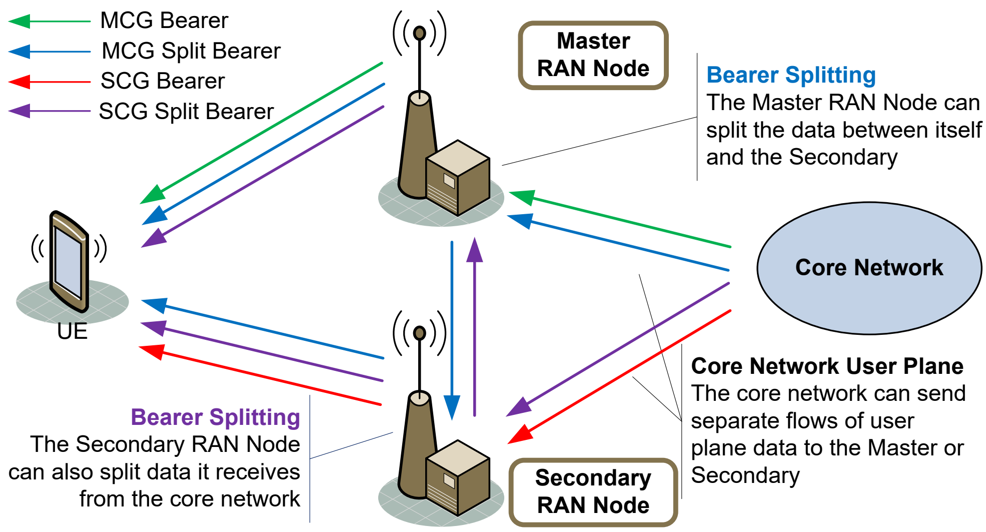


Figure 1-31 User Plane Connectivity

- MCG (Master Cell Group) bearers - core network connections will be terminated at the master RAN node. The secondary RAN node will not be involved in data transfer to the Uu.
- SCG (Secondary Cell Group) bearers - core network connections will be terminated at the secondary RAN node. The master RAN node will not be involved in data transfer to the Uu.

In terms of the granularity of the user plane splitting, within 5G the user plane can be split at the UPF to the granularity of an individual QoS Flow.

Split Bearer

Figure 1-32 outlines the protocol stack which is used to support bearer splitting at the master and secondary nodes. Any transfer of data between the nodes is based on a user plane connection across Xn.

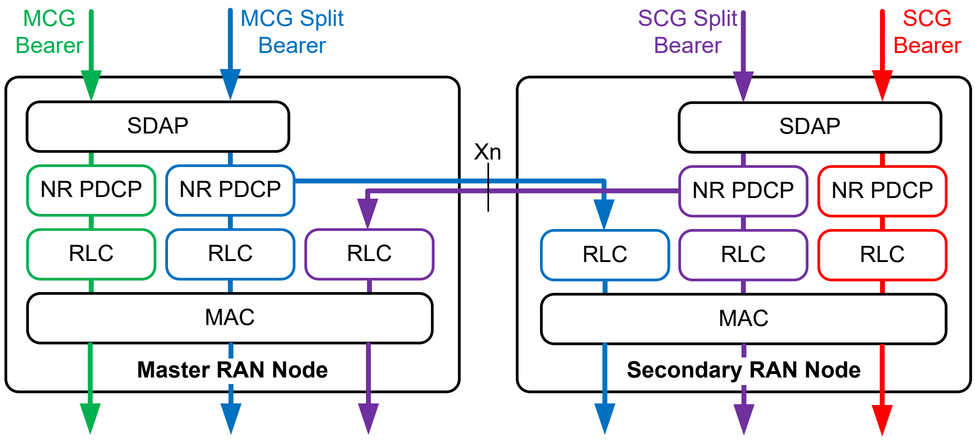


Figure 1-32 Split Bearer

Figure 1-33 shows the protocol stack required at the device to support EN-DC. Since EN-DC utilizes the EPC there is no SDAP protocol present.

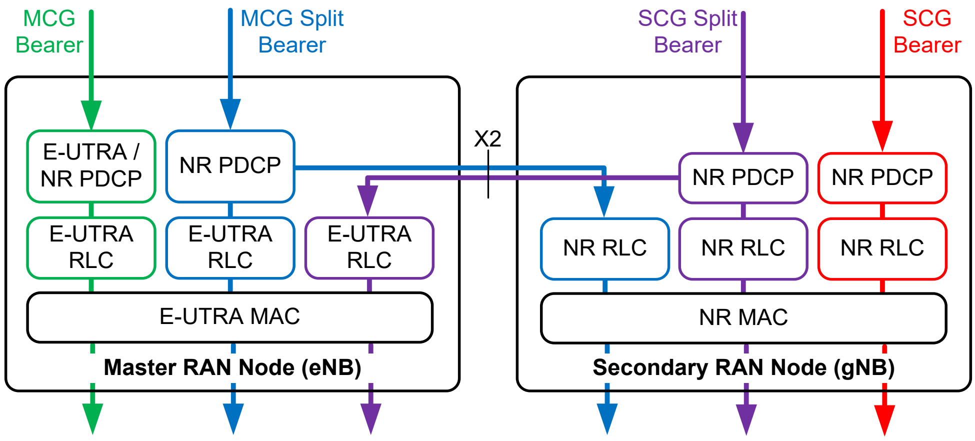


Figure 1-33 MR-DC Split Bearer (EN-DC) – UE Perspective

2 5G Physical Layer

2.1 5G Waveform: CP-OFDM and DFT-s-OFDM

The 5G NR radio “carrier” is based on an OFDM (Orthogonal Frequency Division Multiplexing) waveform. Specifically, the downlink and uplink transmission waveforms are conventional OFDM using a CP (Cyclic Prefix). In addition, the uplink can include an additional transform precoding stage. The optional use of transform precoding is typically related to devices with limited uplink link budgets e.g. IoT devices. Figure 2-1 indicates the two waveforms available for 5G.

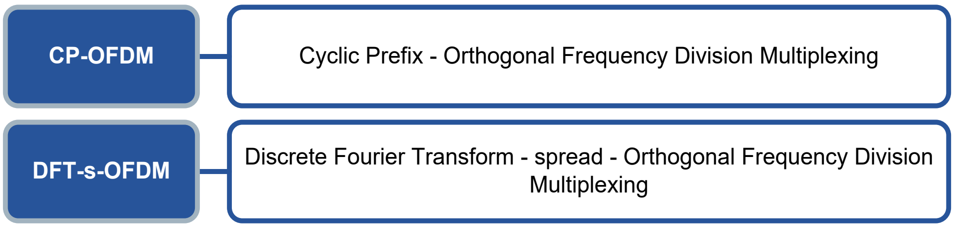


Figure 2-1 5G Waveforms

2.1.1 OFDM Subcarriers

OFDM in 5G NR, like LTE, utilizes multiple subcarriers, as illustrated in Figure 2-2. The big change for 5G NR is that there are various SCS (Subcarrier Spacing) options defined. These are identified as μ (Numerology).

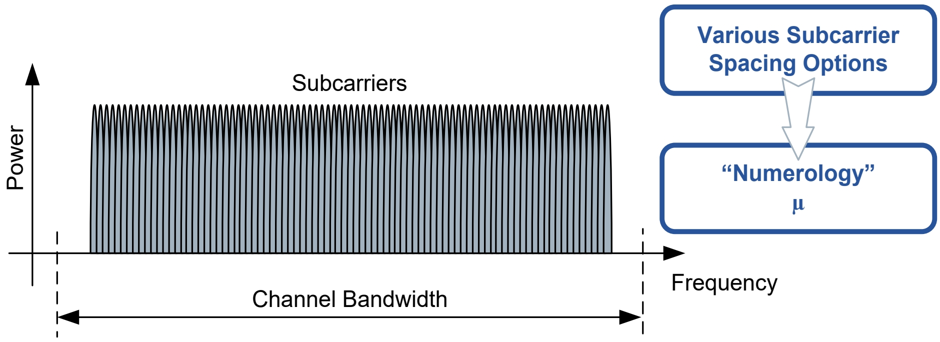


Figure 2-2 5G NR Subcarriers

Figure 2-3 illustrates how each subcarrier carries the modulated symbol, noting that the frequency, phase and amplitude do not change during that symbol. Depending on the frequency of the individual subcarrier, as well as the duration of the symbol (which changes based on the numerology), the number of cycles for a symbol will change.

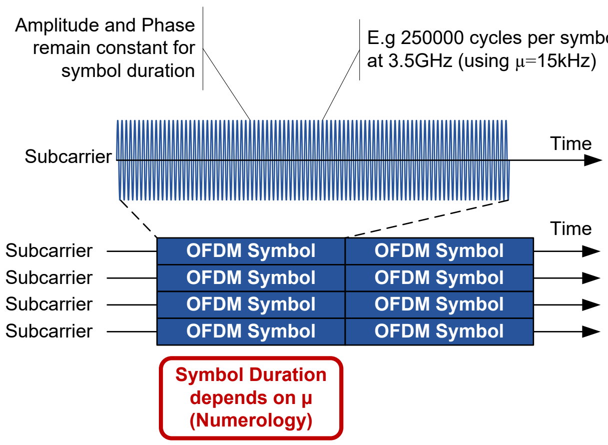


Figure 2-3 OFDM Symbol

2.1.2 Orthogonal Frequency Division Multiplexing

OFDM has already been widely used in LTE. OFDM has a number of advantages and disadvantages.

OFDM Advantages:

- Wide channels are more resistant to fading and OFDM equalizers are much simpler to implement than those in CDMA.
- OFDM is almost completely resistant to multi-path interference due to very long symbols. Note that at higher numerologies the symbol durations will be reduced. However, beam forming at these higher frequencies will minimize potential multipath issues.
- OFDM is ideally suited to MIMO due to the easy matching of transmit signals to the uncorrelated RF channel.

OFDM Disadvantages:

- Sensitive to frequency errors and phase noise due to close subcarrier spacing.
- Sensitive to Doppler shift which creates interference between subcarriers. The frequency is a key part of Doppler shift, i.e. higher frequencies suffer more. As such, NR forces higher frequencies to utilize a larger numerology.
- Pure OFDM creates high PAPR (Peak-to-Average Power Ratio). However, various techniques and codes are used to minimize this.

2.1.2.1 Transmitted Signal

OFDM waveforms typically create a high PAPR. The peaks are created when the symbols to be transmitted are the same and nulls are created when the symbols are different. In reality, since there are a number of subcarriers involved the signal over time is no longer sinusoidal but instead Gaussian.

Depending on the symbol sequence, the resultant combined signal may be constructive or destructive. This is illustrated in Figure 2-4.

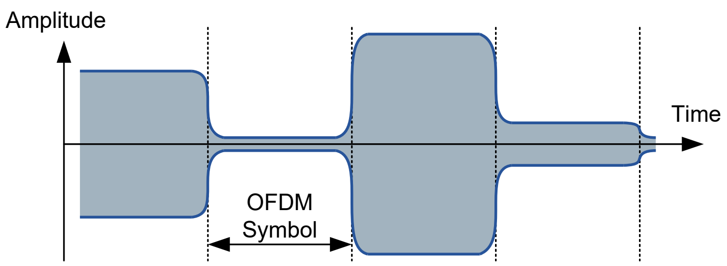


Figure 2-4 Transmitted Signal

It is worth nothing that 5G NR, like LTE, uses various mechanisms to reduce the PAPR.

2.1.2.2 Combating Interference in the Time Domain

While the OFDM process overcomes interference in the frequency domain, issues still exist in the time domain. One of the major problems effecting radio transmission systems is that of ISI (Inter Symbol Interference). This is caused by multipath effects and it manifests itself in terms of a delayed and attenuated copy of the original signal.

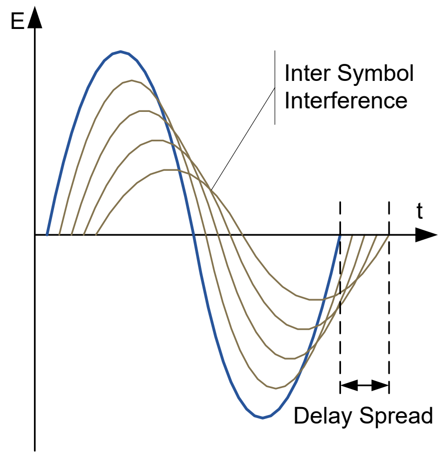


Figure 2-5 Inter Symbol Interference

One method of combating this effect is the use of equalizers. However, these require a known bit pattern such as a training sequence which in turn reduces the overall capacity of the channel to carry user data. Further, the need for an equalizer also adds costs in terms of both money and processing power.

2.1.3 Cyclic Prefix

In most OFDM systems, a CP (Cyclic Prefix) can be used to counter the effects of multipath propagation. This can be represented as a “guard period” which is located just in front of the user data portion and as such, is able to mitigate Delay Spread. The CP is in fact the final part of the OFDM Symbol copied and placed in front of the same OFDM symbol. This is represented in Figure 2-6.

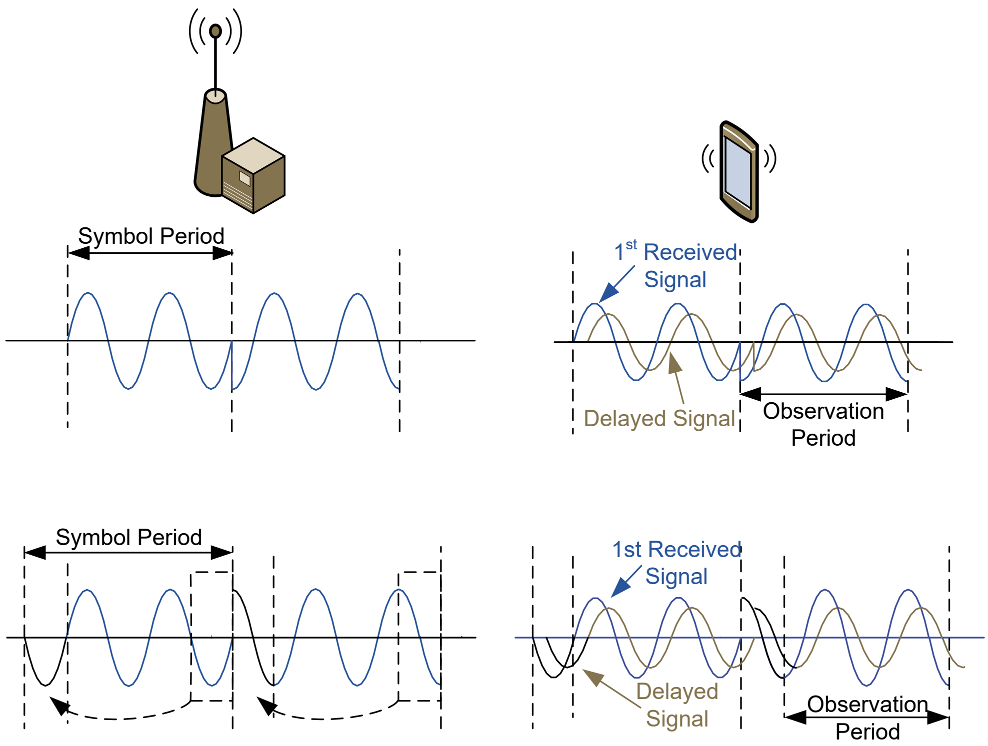


Figure 2-6 Cyclic Prefix

In this example the CP represents 20% of the symbol and since the Delay Spread in this case was only about 10% the symbol can be received. For 5G NR there is a normal CP and an extended CP. The extended CP provides a greater period for multipath protection and hence is linked to large cell sizes. Unfortunately, extended CP also reduces the number of symbols per slot/subframe and as such the data rate is reduced.

Figure 2-7 illustrates an example of the CP being added to the front, i.e. the symbol duration is increased which would provide a lower data rate with the benefit of being resistant to multipath delay spread.

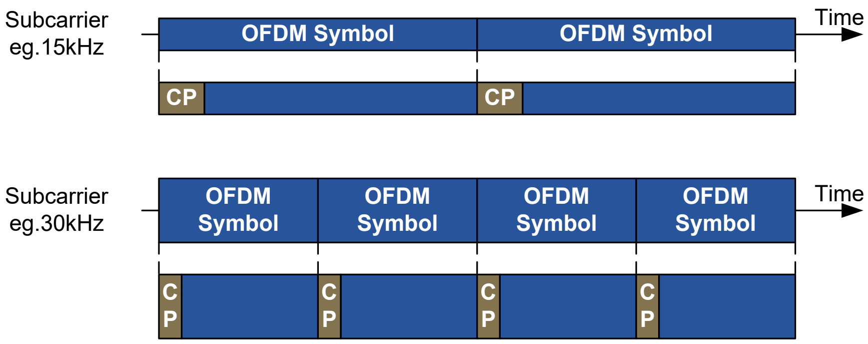


Figure 2-7 Symbol Period

2.2 5G NR Duplexing

5G NR (New Radio) utilizes a lot of existing transmission and reception techniques. However, there are many new or enhanced aspects relating to the 5G NR waveform, frame structure and numerology, as well as channel bandwidth.

2.2.1 FDD and TDD Duplexing Modes

Like LTE, 5G NR has the requirement to operate in different frequency bands, with a combination of duplexing modes. The main duplexing modes are FDD (Frequency Division Duplexing) and TDD (Time Division Duplexing).

Figure 2-8 illustrates a basic comparison of FDD and TDD operation. FDD utilizes a separate frequency for the DL (Downlink) and UL (Uplink). In comparison, TDD utilizes a single frequency and alternates downlink and uplink transmission in time. For 5G, the choice of FDD or TDD is mainly based on the service provider’s spectrum allocation and the frequency band chosen.

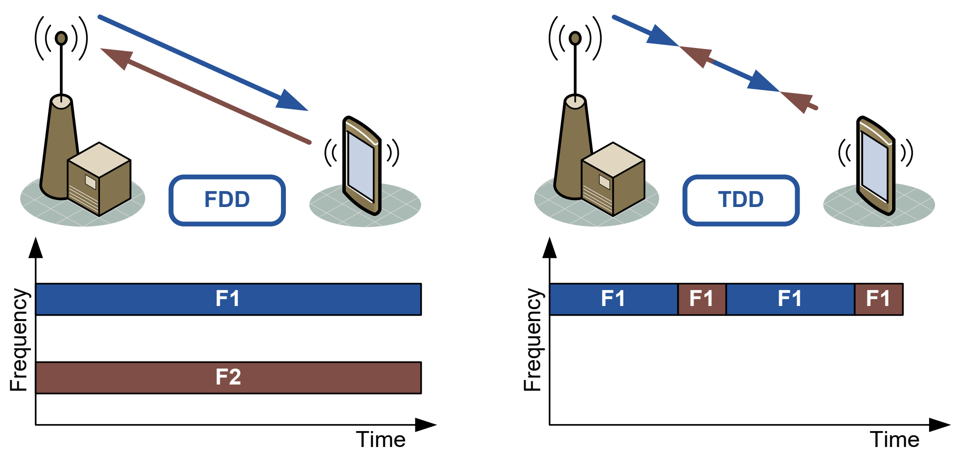


Figure 2-8 FDD and TDD

2.2.2 Supplementary Downlink

The use of SDL (Supplementary Downlink) is typically related to providing a capacity boost in the downlink. In WRC-15 (World Radio Conference 15), the frequency range 1427MHz to 1518MHz was made available for SDL operation. As such, both LTE and 5G NR 3GPP specifications include SDL bands which reside between these frequencies.

If the SDL frequency is lower than the primary band the coverage footprint is larger, however this extra coverage cannot be used. This is due to the device still needing an uplink to provide UCI (Uplink Control Information).

Figure 2-9 illustrates an example whereby the SDL band is lower than the main operating band and provides greater coverage. Devices inside the blue ring are able to benefit from the SDL operation with greater resource allocation, as well as better indoor penetration (if a lower frequency is in use).

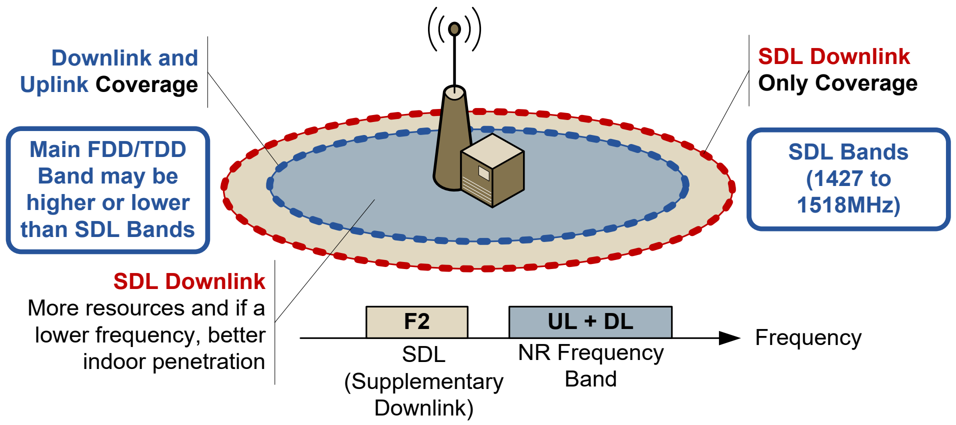


Figure 2-9 Supplementary Downlink

2.2.3 Supplementary Uplink

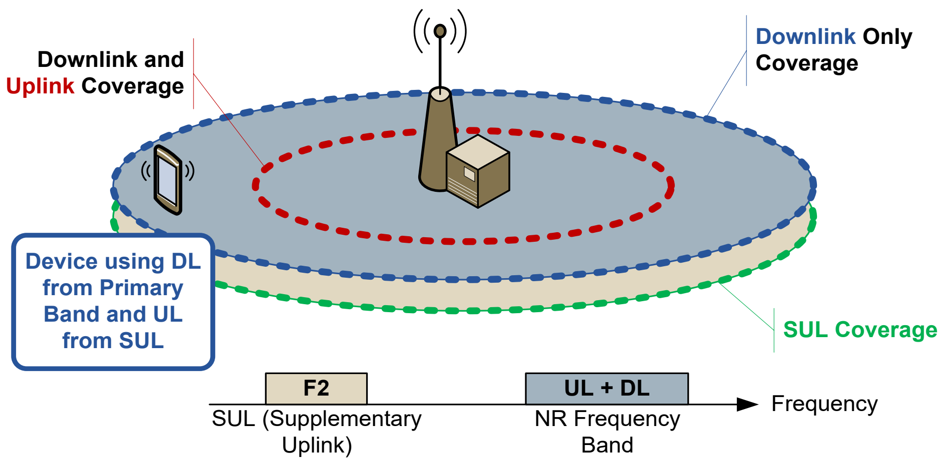


Figure 2-10 Supplementary Uplink

5G NR also supports SUL (Supplementary Uplink). Figure 2-10 illustrates an example of SUL operation. The primary band (shaded blue) provides good downlink and uplink coverage, however as a result of device power limitations the uplink coverage is actually reduced (red area). The SUL is typically implemented at a lower frequency band and thus the uplink footprint is much greater (green area). In so doing, devices on the edge of the blue shaded area can utilize the downlink from the primary band and the uplink from the SUL.

Note: a device operating simultaneous transmission of more than one UL in different bands may lead to in-device interference.

2.3 5G Frequency Bands

5G NR includes the concept of FR (Frequency Range), as well as adding new frequency bands and carrier numbering. Figure 2-11 identifies key areas related to the use of 5G frequency bands, including when operating with EN-DC (E-UTRA - NR Dual Connectivity).

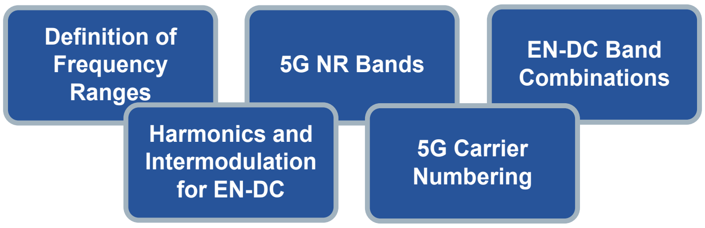
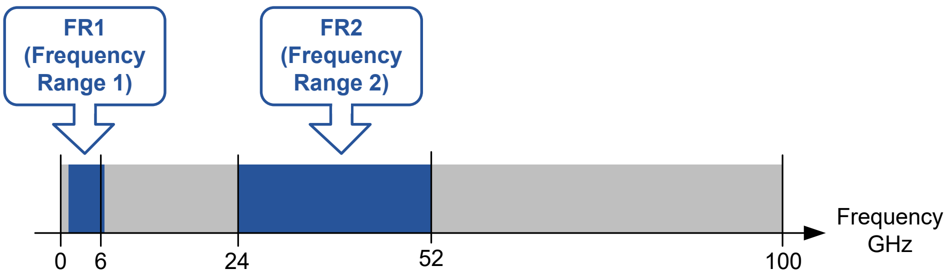


Figure 2-11 5G Frequency Bands

2.3.1 Definition of Frequency Ranges

3GPP specifications define various requirements which are sometimes defined separately for different FR (Frequency Range). Figure 2-12 illustrates the two frequency range designations, namely FR1 (Frequency Range 1) and FR2 (Frequency Range 2), as well as their corresponding frequency range. Note that FR1 is the sub 6GHz band, whereas FR2 covers approximately 24GHz to 53GHz.



Frequency Range Designation	Corresponding Frequency Range
FR1	410MHz – 7125MHz
FR2	24250MHz – 52600MHz

Figure 2-12 5G Frequency Bands

Existing WCDMA and LTE bands are retained for 5G NR. Figure 2-13 illustrates the change in identification of a band, which for 5G NR is prefixed by an “n”. It is worth noting that there is not always a corresponding band, for example LTE Band 4 does not currently exist as a NR band. In addition, there are new NR bands that have been introduced.

Figure 2-13 Band Identification

2.3.2 5G NR Bands

In terms of the 3GPP specifications, there are three variants for transmission and reception, as illustrated in Figure 2-14. These are Range 1 and Range 2, as well as Interworking operation with other radios. The latter includes the EN-DC operating bands.

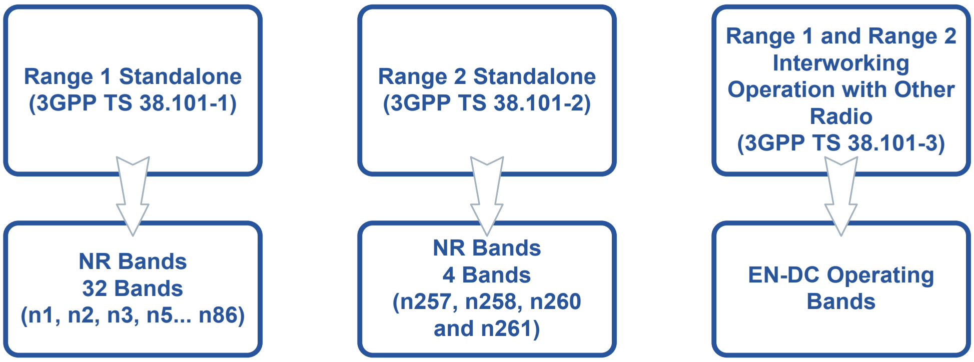


Figure 2-14 3GPP Band Specifications

A list of FR1 and FR2 bands, as well as EN-DC band combinations is also available via the “5G Air Interface Resources” on the Mpirical LearningZone.

2.3.3 EN-DC Band Combinations

In terms of EN-DC operation, Release 15 supports various band combinations ranging from “1 LTE + 1 NR” up to “4 LTE + 2 NR” (with the 2 NR bands being FR1 or FR2). The full list of combinations can be found in the “5G Air Interface Resources” on the Mpirical LearningZone.

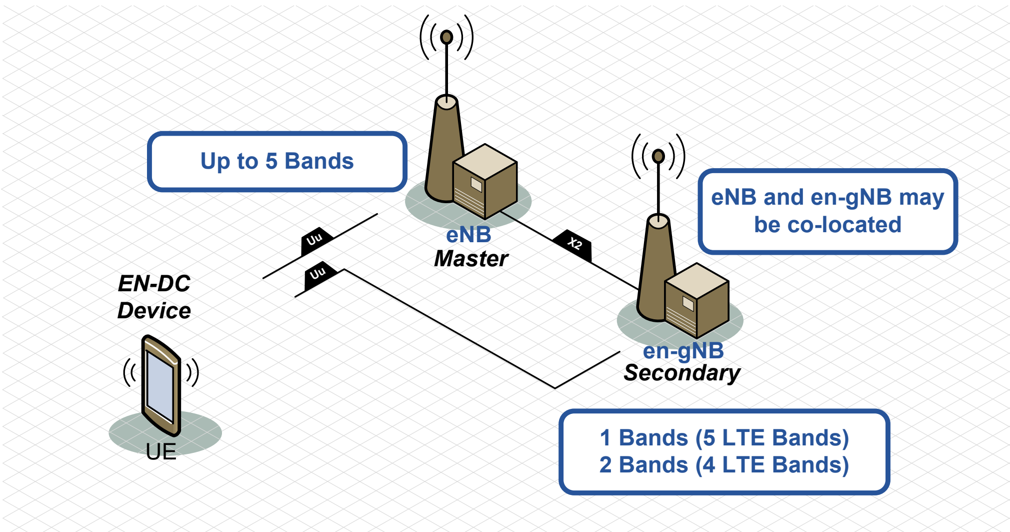


Figure 2-15 EN-DC Band Combination

2.3.4 Baseband Processing Combination

The capabilities of a device supporting both NR and E-UTRA are provided to the NG-RAN. This also includes MR-DC (Multi-RAT Dual Connectivity) band combinations, listing the supported E-UTRA and NR band combinations.

Figure 2-16 illustrates the key parameters related to supported band combinations, as well as supported BPC (Baseband Processing Combination). The BPC includes key information about CA (Carrier Aggregation), for example, the maximum bandwidth supported per CC (Component Carrier).

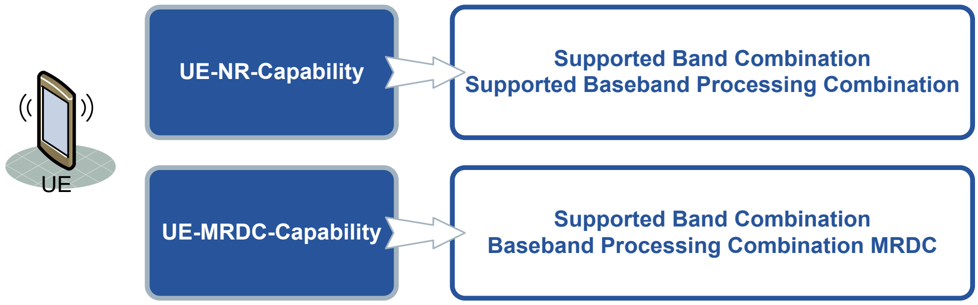


Figure 2-16 Band and Baseband Processing Combination

2.3.5 Harmonics and Intermodulation

Utilizing multiple frequencies, as well dual connectivity deployments, may lead to various interference issues. Broadly, there are three different types of in-device interference due to simultaneous UL transmission over different bands:

Figure 2-17 Harmonics and Intermodulation

In some cases, this will impact NR, LTE or other systems such as Wi-Fi, Bluetooth and GNSS (Global Navigation Satellite System).

2.3.5.1 Interference from Harmonic

One example of Interference from harmonic can be seen when in EN-DC operation, whereby the harmonics from the LTE UL (Uplink) cause interference in the NR DL (Downlink), as illustrated in Figure 2-18.

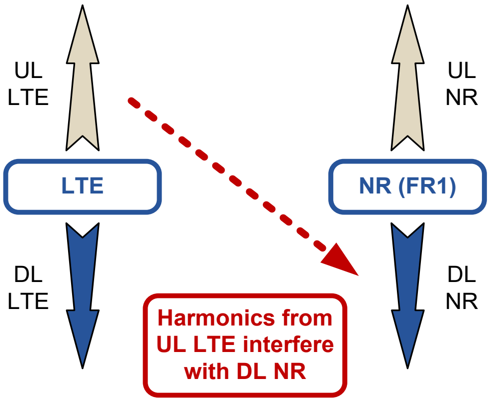


Figure 2-18 Interference from Harmonic

This situation only occurs on specific LTE bands, when the harmonics orders (2^{nd}, 3^{rd}, 4^{th} etc) are impacting the NR DL band. The higher the order of harmonic, the lower the interference/impact. In some cases, the specifications make allowances for this type of interference, known as "receiver sensitivity degradation".

2.3.5.2 Interference from Harmonic Mixing

In addition to the harmonics themselves, harmonic mixing will also cause interference. This typically causes issues with the DL LTE signals, as illustrated in Figure 2-19. As such the device sensitivity for LTE will be impacted.

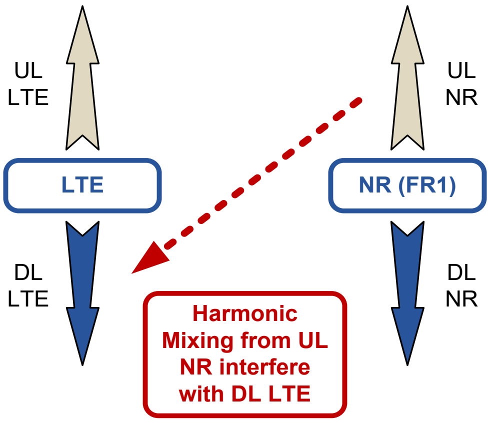


Figure 2-19 Interference from Harmonic Mixing

2.3.5.3 Interference from IMD (Intermodulation)

IMD (Intermodulation) is a significant issue in any radio system. Figure 2-20 illustrates how a combination of 2 or more uplink frequencies (or their harmonics) can cause interference to the downlink radio. Thus, reducing the receiver sensitivity.

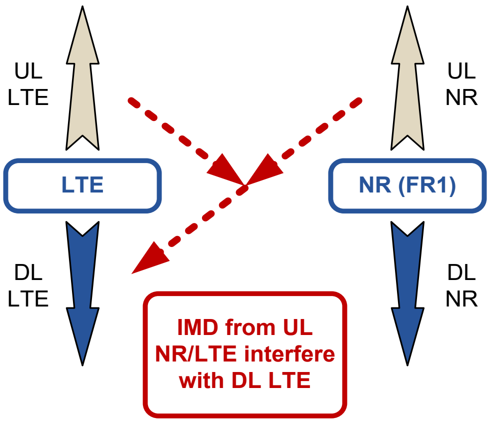


Figure 2-20 Interference from IMD (Intermodulation)

For NR and EN-DC operation, there is a large number of combinations. This number is greatly increased with combinations of harmonics and associated intermodulation results. As such, the 3GPP produced a series of TR (Technical Reports) which highlight the Harmonic, Harmonic Mixer and IMD related products, as well as the bands/systems they effect. Figure 2-21 illustrates the key specifications; note that others exist.

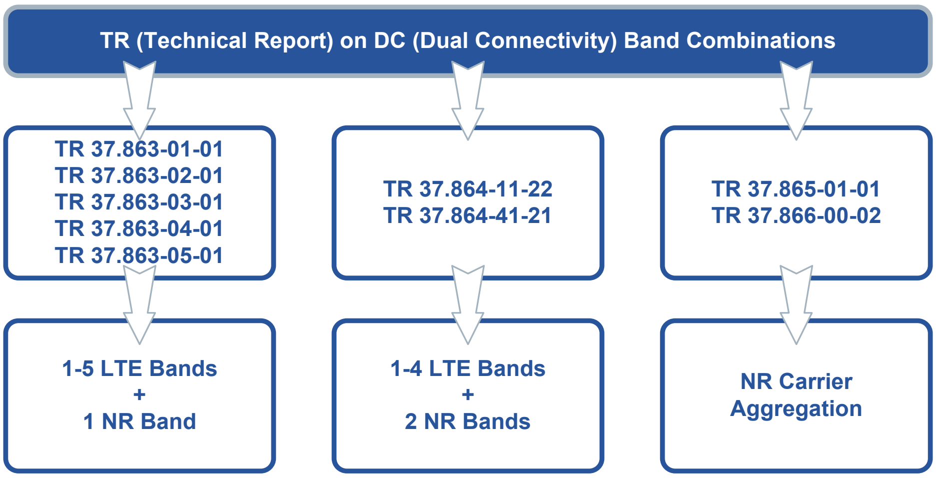


Figure 2-21 Harmonic and Intermodulation Information

2.3.6 5G Carrier Numbering

The channel raster defines a set of RF (Radio Frequency) reference frequencies that are used to identify the RF channel position. A global frequency raster is defined for all frequencies from 0 to 100 GHz and is used to define the set of allowed RF reference frequencies. The granularity of the global frequency raster is ΔF_{Global}.

The RF reference frequency in the uplink and downlink is designated by the NR-ARFCN (NR Absolute Radio Frequency Channel Number). The relationship between the NR-ARFCN and the RF reference frequency F_{REF} in MHz for the downlink and uplink is given by the equation shown in Figure 2-22.

$$F_{REF} = F_{REF\text{-}Offs} + \Delta F_{Global} (N_{REF} - N_{REF\text{-}Offs})$$

Frequency Range (MHz)	ΔF_{Global} (kHz)	$F_{REF\text{-}Offs}$ (MHz)	$N_{REF\text{-}Offs}$	Range of N_{REF}
0 – 3000	5	0	0	0 – 599999
3000 – 24250	15	3000	600000	600000 – 2016666
24250 – 100000	60	24250.08	2016667	2016667 – 3279165

Figure 2-22 NR-ARFCN Parameters for the Global Frequency Raster

NOTE: For each operating band, a subset of frequencies from the global frequency raster are applicable and this forms a channel raster with a granularity ΔF_{Raster}, which may be equal to or larger than ΔF_{Global}. Figure 2-23 illustrates an example of band n41 which utilizes a ΔF_{Raster} = 15kHz.

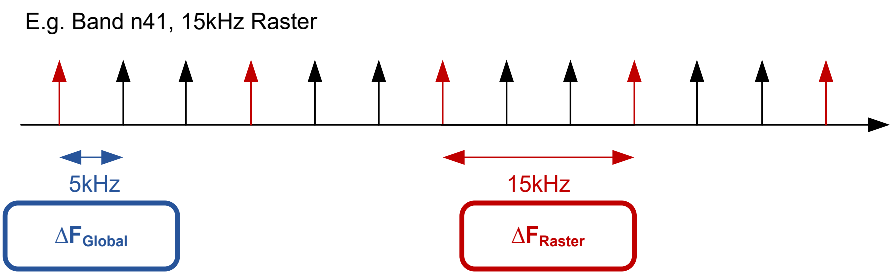


Figure 2-23 Example ΔF_{Raster} Example (n41)

2.4 NR Numerology and Frame Structure

2.4.1 Numerology

A key part of the 5G NR is flexibility. As such, there are various options for subcarrier spacing; these are identified as μ (Numerology). Figure 2-24 illustrates μ=0 to μ=4. In so doing, the subcarrier spacings of 15kHz, 30kHz, 60kHz, 120kHz and 240kHz are defined. It is worth noting that the 3GPP specification also mentions 480kHz subcarrier spacing however this may not be available until 5G Phase 2 (Release 16).

As well as the numerology indicating subcarrier spacing, it also impacts many other physical layer configurations and timings.

Figure 2-24 also illustrates the fact that all numerologies support a normal CP, however μ=2 (60kHz) also supports an extended CP.

μ	$\Delta f = 2^{\mu} \cdot 15$ [kHz]	Cyclic Prefix
0	15	Normal
1	30	Normal
2	60	Normal, Extended
3	120	Normal
4	240	Normal

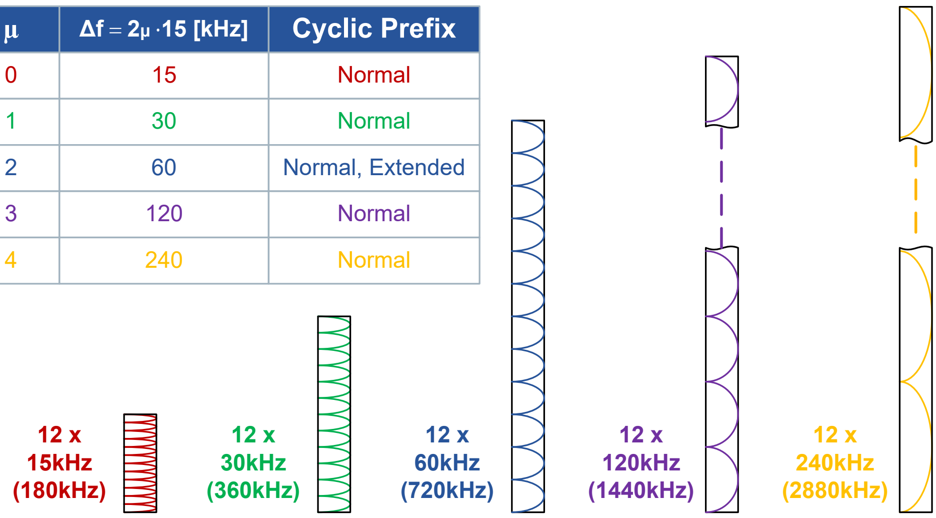


Figure 2-24 Supported Transmission Numerologies (μ=0 to μ=4)

A larger SCS is typically linked to higher frequencies since they experience greater doppler shift. As an example, the doppler shift at 300km/h would be ~528Hz for a 1.9GHz carrier, compared with ~972Hz for a 3.5GHz carrier.

2.4.2 Slot Length

Each 5G NR numerology has a different number of slots per frame/subframe, as illustrated in Figure 2-25. What is important to note is even though the higher numerologies have more slots in a frame, the actual bandwidth is greater, i.e. less subcarriers for a given bandwidth. The trade-off is related to QoS and latency requirements, as well as frequency ranges.

μ	N_{symb}^{slot}	$N_{slot}^{frame,\mu}$	$N_{slot}^{subframe,\mu}$
0	14	10	1
1	14	20	2
2	12/14	40	4
3	14	80	8
4	14	160	16

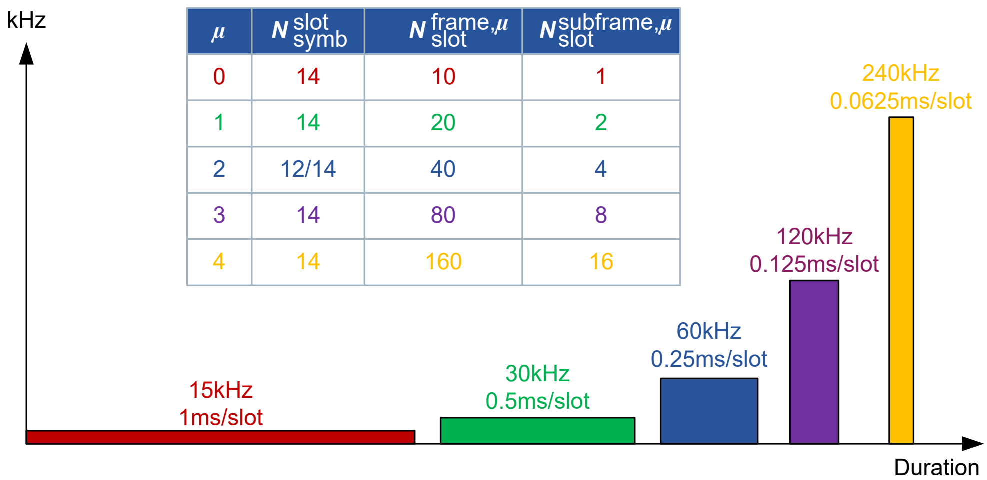
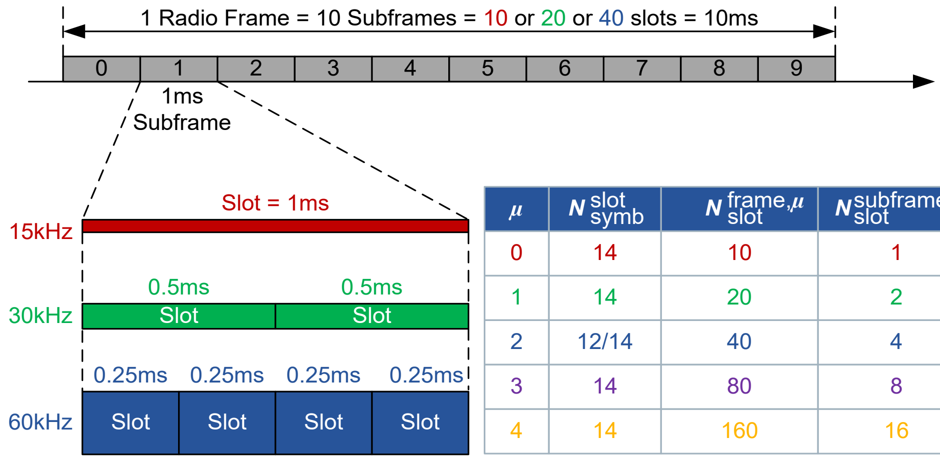


Figure 2-25 NR Slot Length slot (μ=0 to μ=4)

2.4.3 Frame Structure

The 5G NR frame structure follows that of LTE, utilizing a 10ms Frame with ten 1ms subframes. However, since 5G NR supports multiple numerologies the number of slots varies. Figure 2-26 illustrates the frame structure for μ=0, 1 and 2, which respectively include 1, 2 or 4 slots per subframe, i.e. 10, 20 or 40 slots per frame.



μ	N_{symb}^{slot}	$N_{slot}^{frame,\mu}$	$N_{slot}^{subframe,\mu}$
0	14	10	1
1	14	20	2
2	12/14	40	4
3	14	80	8
4	14	160	16

Figure 2-26 μ=0, 1 and 2 Frame Structure

2.4.4 NR Slots

The number of symbols per slot is typically 14, with the exception of μ=2 which supports an extended CP. Figure 2-27 visualizes the symbols per slot for μ=0, 1, 2 and 3.

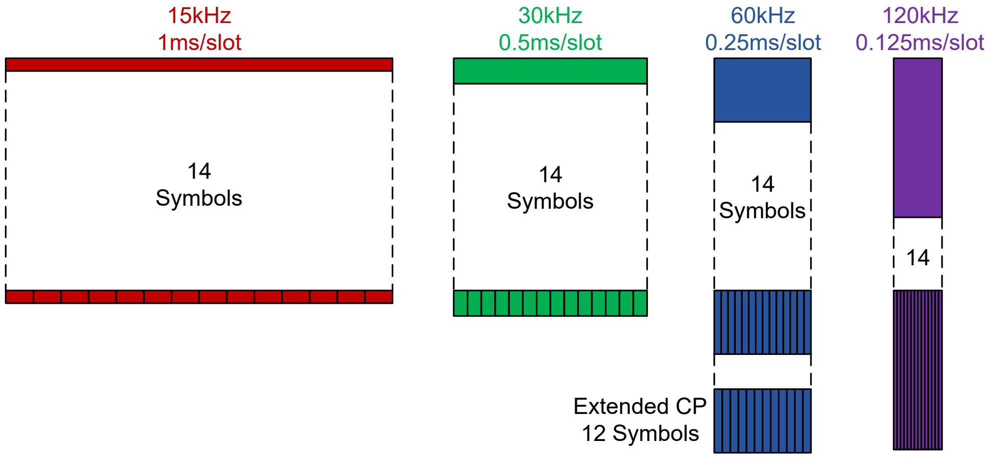
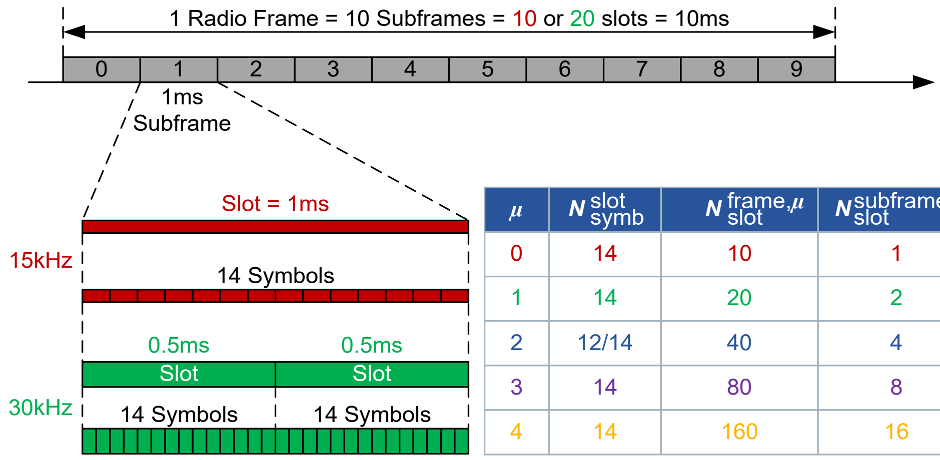


Figure 2-27 Visualization of Symbols/slot (μ=0 to μ=3)

Figure 2-28 illustrates a comparison of μ=0 and μ=1.



μ	N_{symb}^{slot}	$N_{slot}^{frame,\mu}$	$N_{slot}^{subframe,\mu}$
0	14	10	1
1	14	20	2
2	12/14	40	4
3	14	80	8
4	14	160	16

Figure 2-28 Comparing μ=0 and μ=1 Frame Format

Note: For TDD operation, various slot configuration options are allowed which enable dynamic assignment of DL and UL symbols.

2.4.5 5G NR Time Unit

The NR time domain is expressed in T_c (Time Units):

$$Tc = 1/(\Delta f_{max} \cdot N_f)$$

where $\Delta f_{max} = 480 \cdot 10^3$ Hz (sampling time for the maximum subcarrier spacing) and $N_f = 4096$. This equates to ~ 0.509ns.

The constant $\kappa = T_S/T_C = 64$ and relates to the ratio of T_s (LTE Time Unit) to the NR time unit (T_c), where $T_s = 1/(\Delta f_{ref} \cdot N_{f,ref})$, $\Delta f_{ref} = 15 \cdot 10^3 Hz$ and $N_{f,ref} = 2048$.

2.4.6 NR Cyclic Prefix

As defined in Figure 2-29, the size of the cyclic prefix varies with the numerology (subcarrier spacing). If μ=2, an extended CP can also be utilized.

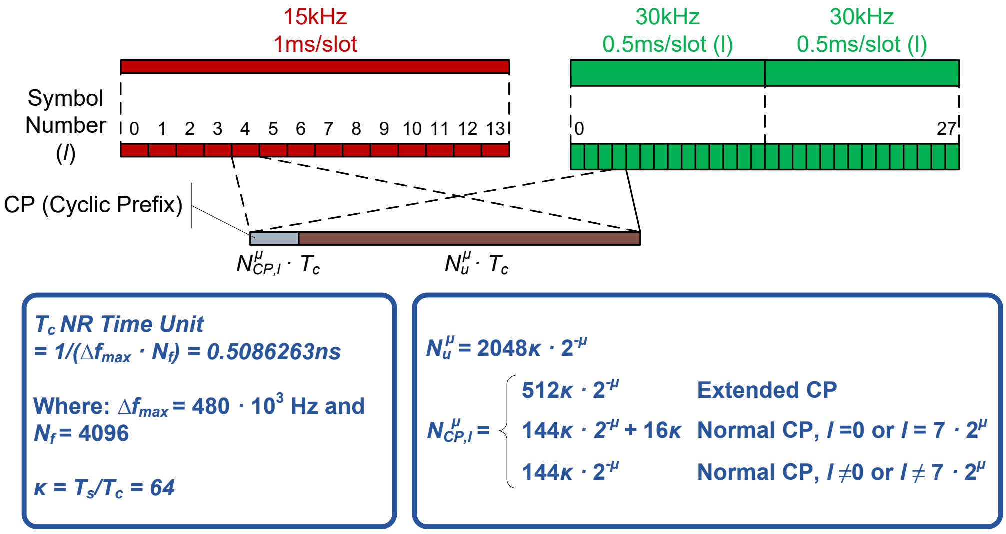


Figure 2-29 5G NR Symbol Timing

When using a normal cyclic prefix, depending on the numerology and the symbol number in the subframe, the size varies. Using the equation in Figure 2-29 it can be seen that the first symbol in the subframe, as well as the symbol after the half way point, has a slightly larger cyclic prefix.

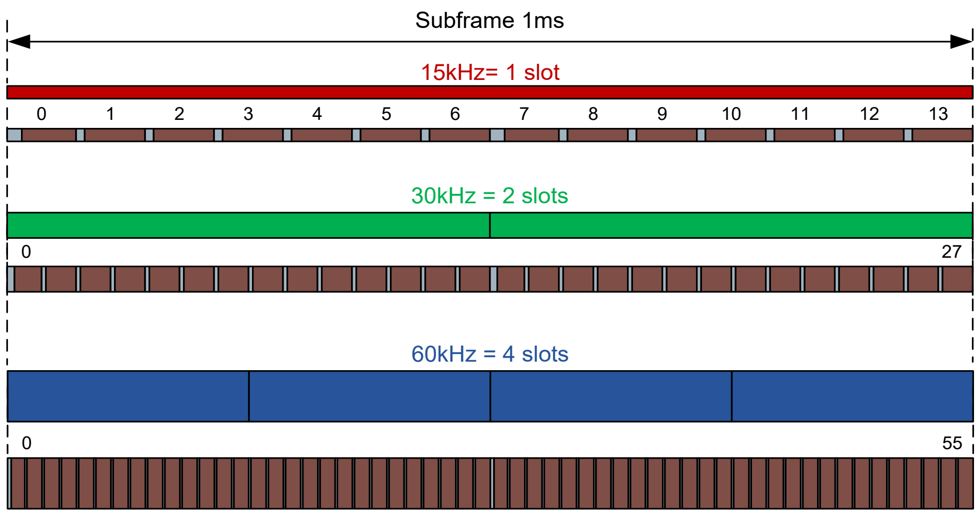


Figure 2-30 Normal Cyclic Prefix (μ=0, 1 and 2)

Figure 2-31 illustrates the relationship the SCS and the CP has on the deployment in terms of Cell Size, Frequency and Achievable Latency.

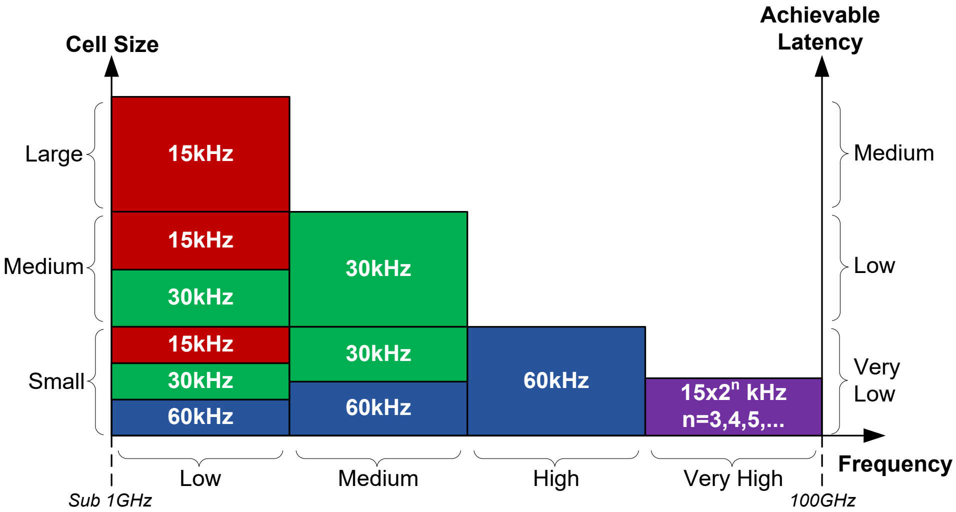
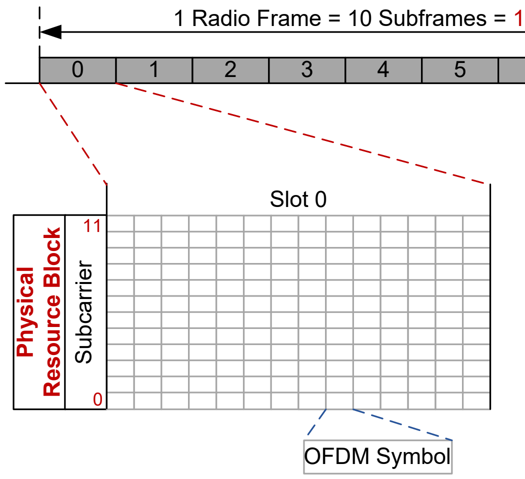


Figure 2-31 Usage of CP and SCS

2.4.7 NR Physical Resource Block

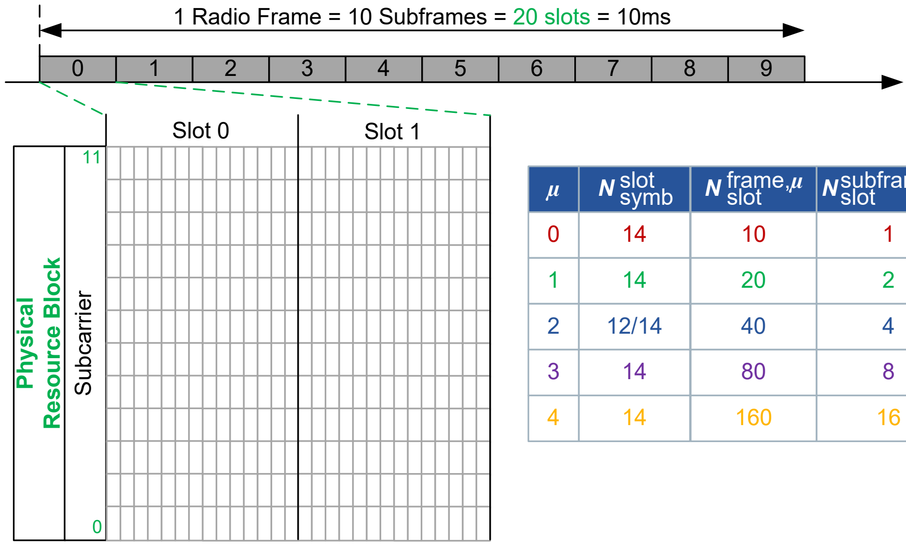
Like LTE, the term PRB (Physical Resource Block) is utilized in 5G NR. PRB specifically relates to the grouping of 12 subcarriers, as illustrated in Figure 2-32 for μ=0.



μ	N^{slot}_{symb}	$N^{frame,\mu}_{slot}$	$N^{subframe,\mu}_{slot}$
0	14	10	1
1	14	20	2
2	12/14	40	4
3	14	80	8
4	14	160	16

Figure 2-32 Physical Resource Block (μ=0)

Figure 2-33 illustrates the PRB for μ=1. The key visual change for μ=1 is the subcarriers are twice as wide, i.e. 30kHz compared to 15kHz and the symbol duration has been halved.



μ	N_{symb}^{slot}	$N_{slot}^{frame,\mu}$	$N_{slot}^{subframe,\mu}$
0	14	10	1
1	14	20	2
2	12/14	40	4
3	14	80	8
4	14	160	16

Figure 2-33 Physical Resource Block (μ=1)

2.4.8 Resource Grid

For each numerology and carrier there is a Resource Grid defined, consisting of $N_{RB}^{Max} \cdot N_{SC}^{RB} - 1$ subcarrier and $N_{symb}^{subframe,\mu}$OFDM symbols. Figure 2-34 also illustrates the concept of a RE (Resource Element) which can be used to carry control, data or one of the various types of reference signals.

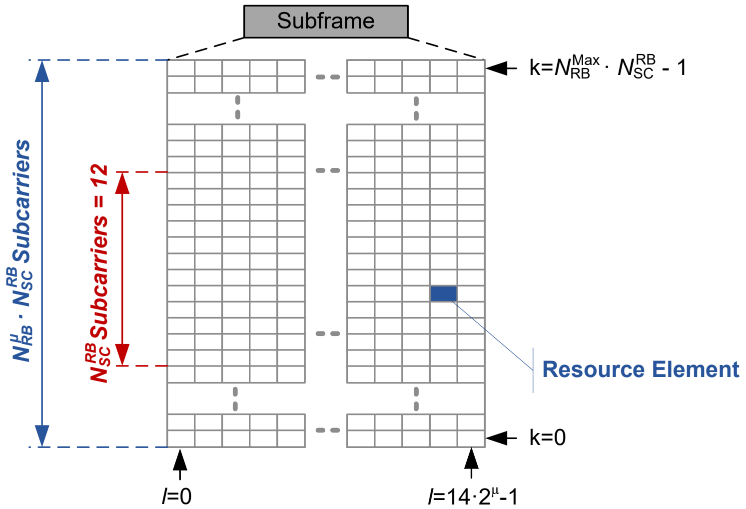


Figure 2-34 Resource Grid and Resource Element

2.4.9 5G NR Transmitted Signal

The complex signal that is transmitted in 5G NR is a time-continuous signal, identified as $s_l^{(p,\mu)}(t)$. This relates to antenna port p and subcarrier spacing configuration μ for OFDM symbol $l \in \{0, 1, \ldots\ldots, N_{slot}^{subframe,\mu} N_{symb}^{Slot} - 1\}$. It is applicable for any subframe, physical channel or signal, except the PRACH (Physical Random Access Channel). It is defined by:

$$s_l^{(p,\mu)}(t) = \sum_{k=0}^{N_{grid}^{size,\mu} N_{SC}^{RB} - 1} a_{k,l}^{(p,\mu)} \cdot e^{j2\pi(k + k_0^{\mu} - N_{grid}^{size,\mu} N_{SC}^{RB}/2)\,\Delta f\,(t - N_{CP,l}^{\mu} T_C - t_{start,l}^{\mu})}$$

Figure 2-35 5G NR Signal Generation

2.4.10 Slot Format Configuration

One of the key flexibilities of 5G NR relates to the DL (Downlink) / UL (Uplink) slot format configurations. Figure 2-36 illustrates basic slot options. A key point to note is that within a slot the symbols can be configured as uplink or downlink, as well as null to accommodate switching.

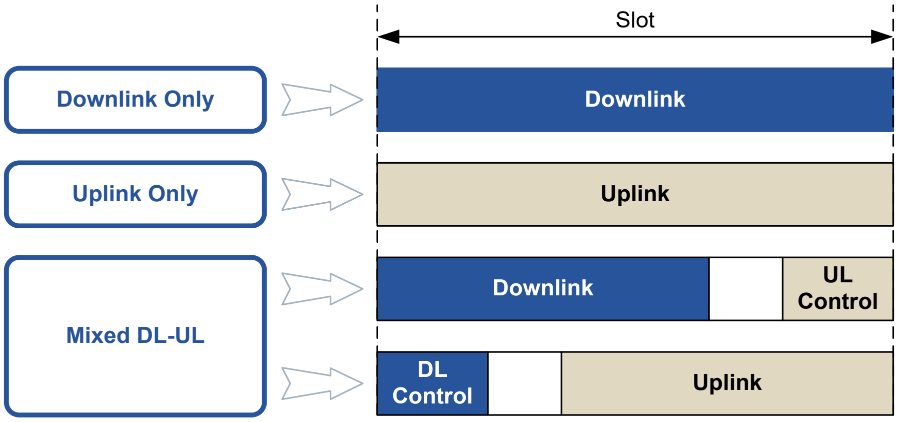


Figure 2-36 NR Slot Options

There are two types of configuration, namely “common” and “dedicated”. The common configuration is illustrated in Figure 2-37 and provides the device with parameters to determine the ratio of DL/UL etc. Note that it is possible for two configurations to be defined - if so they are concatenated.

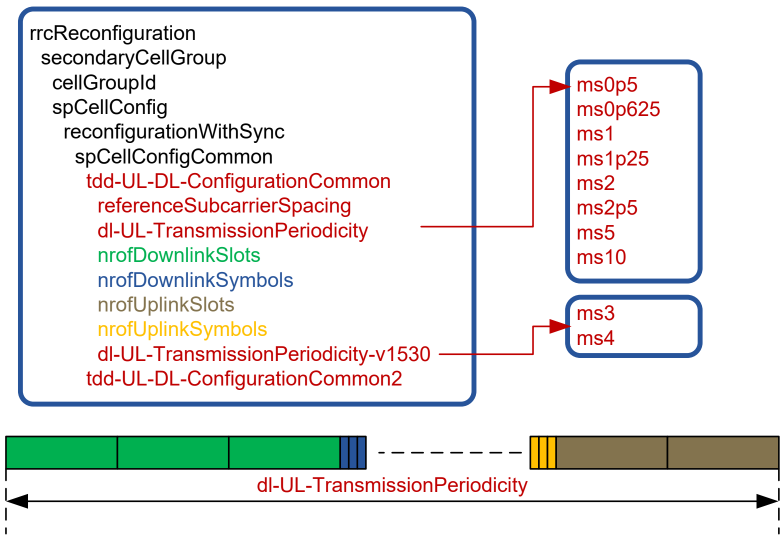


Figure 2-37 TDD DL/UL Common Configuration

In addition, there are dedicated configuration options. This can be visualized via the “5G Air Interface Resources” on the Mpirical LearningZone.

Figure 2-38 illustrates an extract from the slot configuration table[13] for a Normal CP. Slots can be configured for 'downlink' (denoted 'D'), 'flexible' (denoted 'X'), or 'uplink' (denoted 'U'). In addition, a SFI (Slot Format Indication) is used which can be configured dynamically using DCI (Downlink Control Information) or static/semi-static using RRC (Radio Resource Control).

[13] 3GPP TS 38.211 NR; Physical Channels and Modulation

Format	Symbol Number in a Slot													
	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	X	X	X	X	X	X	X	X	X	X	X	X	X	X
3	D	D	D	D	D	D	D	D	D	D	D	D	D	X
4	D	D	D	D	D	D	D	D	D	D	D	D	X	X
⋮														
55	D	D	X	X	X	U	U	U	D	D	D	D	D	D
56-255	Reserved													

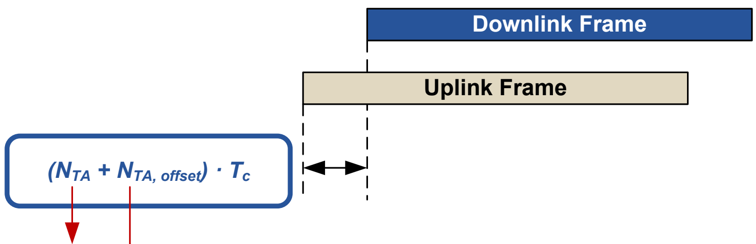
D Downlink
U Uplink
X Flexible

Figure 2-38 Example Slot Formats

The dedicated slot format configuration is very flexible, enabling the system to concatenate and repeat different slot formats. In addition, the system also enables multiple configurations to be set, thus being able to dynamically switch between different slot format combinations. Each combination is identified by a SFI (Slot Format Indication). The parameter TDD-UL-DL-ConfigDedicated is utilized to define slot specific configurations.

2.4.11 Uplink Timing

Like LTE, 5G NR requires a TA (Timing Advance) to ensure the uplink transmissions from devices arrive correctly synchronized. As such, the uplink frame is "advanced" from the device's perspective. This is illustrated in Figure 2-39. Note that for TDD operation an additional offset is also included depending on whether FR1 or FR2 is utilized.

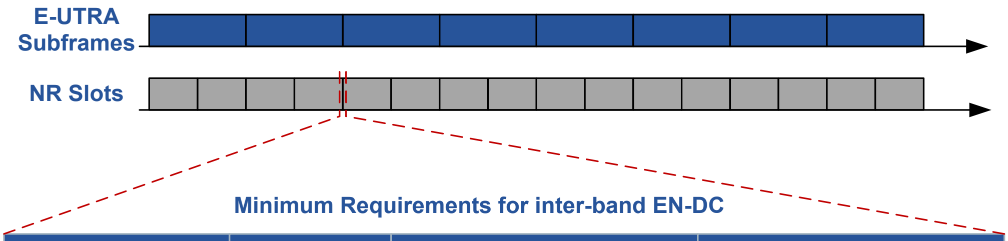


Duplex Mode of cell used for uplink transmission	$N_{TA,\,offset}$
FDD in FR1 or FR2	0 (Note)
TDD in FR1	25560
TDD in FR2	13763
Note: Regardless of whether LTE-NR coexistence is configured or not in FR1	

Figure 2-39 Uplink Timing Relationship

The actual timing advance value is sent to the device by the MAC (Medium Access Control) layer and various procedures are in place to ensure it is correctly maintained.

Figure 2-40 illustrates example values for both asynchronous and synchronous minimum downlink timing for EN-DC. Note that slightly different values also exist for uplink, as well as intra-band combinations.



Minimum Requirements for inter-band EN-DC

E-UTRA SCS Pcell (kHz)	DL in PSCell (kHz)	Asynchronous EN-DC Maximum Receive Timing Difference (µs)	Synchronous EN-DC Maximum Receive Timing Difference (µs)
15	15	500	33
15	30	250	33
15	60	125	33
15	120	62.5	33

Figure 2-40 Minimum Requirements for Inter-Band EN-DC (Downlink)

2.5 Channel Bandwidth

The channel bandwidth supported by a device, for a single NR RF carrier, can vary. From a base station perspective, different device channel bandwidths may be supported within the same spectrum. In addition, multiple carriers, i.e. CA (Carrier Aggregation), to the same device using the base station's channel bandwidth is also allowed.

Figure 2-41 illustrates the concept of Channel bandwidth and N_{RB} (Transmission Bandwidth Configuration). The minimum guardband size also changes depending on the combination of SCS and channel bandwidth.

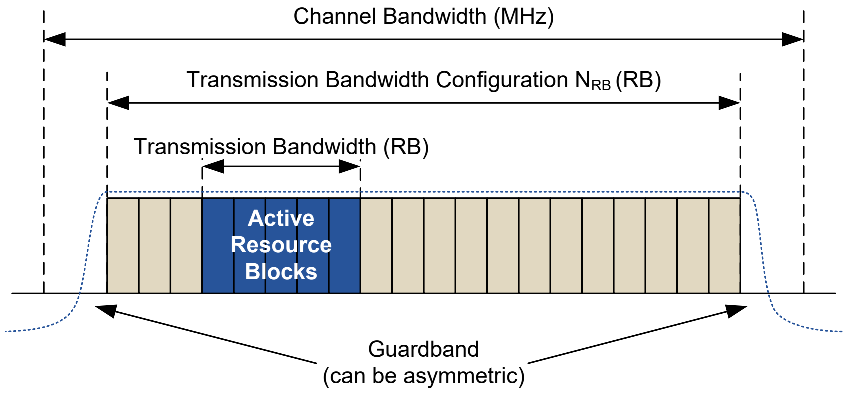


Figure 2-41 Channel and Transmission Bandwidth

2.5.1 Maximum Transmission Bandwidth

The maximum transmission bandwidth also varies depending on the combination of SCS and channel bandwidth. Figure 2-42 and Figure 2-43 illustrates the maximum values in terms of RB (Resource Blocks) for FR1 and FR2 respectfully.

SCS kHz	5 MHz	10 MHz	15 MHz	20 MHz	25 MHz	30 MHz	40 MHz	50 MHz	60 MHz	80 MHz	100 MHz
15	25	52	79	106	133	160	216	270	n/a	n/a	n/a
30	11	24	38	51	65	78	106	133	162	217	273
60	n/a	11	18	24	31	38	51	65	79	107	135

Figure 2-42 FR1 Maximum Transmission Bandwidth Configuration (N_{RB})

SCS kHz	50 MHz	100 MHz	200 MHz	400 MHz
60	66	132	264	n/a
120	32	66	132	264

Figure 2-43 FR2 Maximum Transmission Bandwidth Configuration (N_{RB})

The “5G Air Interface Resources” on the Mpirical LearningZone details additional specific related to guardband sizes.

2.5.2 Carrier BWP (Bandwidth Part)

A BWP (Bandwidth Part) is a subset of contiguous CRB (Common Resource Blocks). It is designed to support low end devices which may support wideband operation. A device can be configured with up to four bandwidth parts in the downlink with a single downlink bandwidth part being active at a given time.

In addition, a device can be configured with up to four bandwidth parts in the uplink with a single uplink bandwidth part being active at a given time. If a device is configured with a supplementary uplink, this too can have up to four bandwidth parts configured with a single uplink bandwidth part being active.

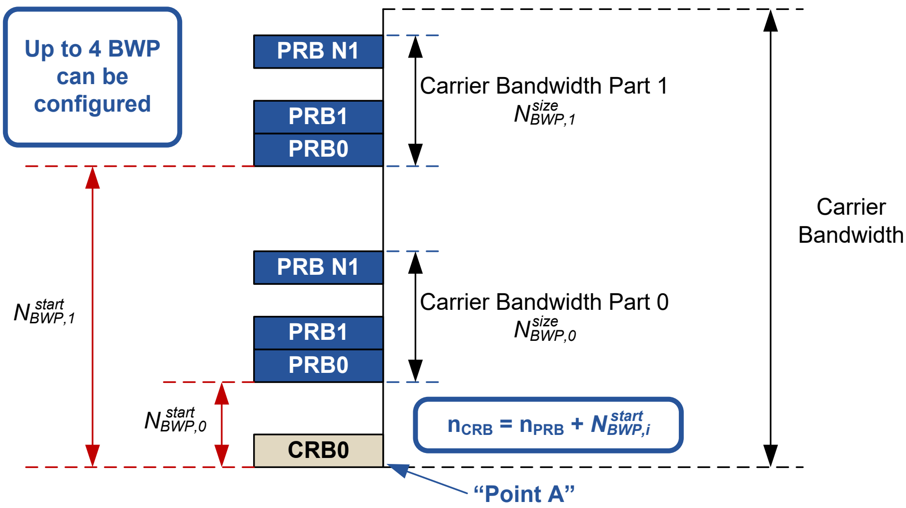


Figure 2-44 Carrier BWP

Figure 2-44 illustrates the concept, as well as the simple calculation for the Common Resource Block number. Common Resource Blocks are numbered from 0 and upwards in the frequency domain for subcarrier spacing configuration μ. The centre of subcarrier 0 of Common Resource Block 0 for subcarrier spacing configuration μ coincides with “Point A”.

In case of TDD, a BWP-pair (UL BWP and DL BWP) will have the same BWP-ID (BWP Identity) and must have the same location.

The system and device can also use different BWP to enable BA (Bandwidth Adaptation). In this case, the receive and transmit bandwidth can be adjusted such that a smaller bandwidth can be used when there is a period of low activity, ultimately, to save power. Note that the location can move in the frequency domain, which would increase scheduling flexibility. In addition, the BWP can have its own SCS, which may be related to different services.

Figure 2-45 illustrates an example of two BWP configurations. It also highlights that switching may be dynamically changed based on the DCI (Downlink Control Information).

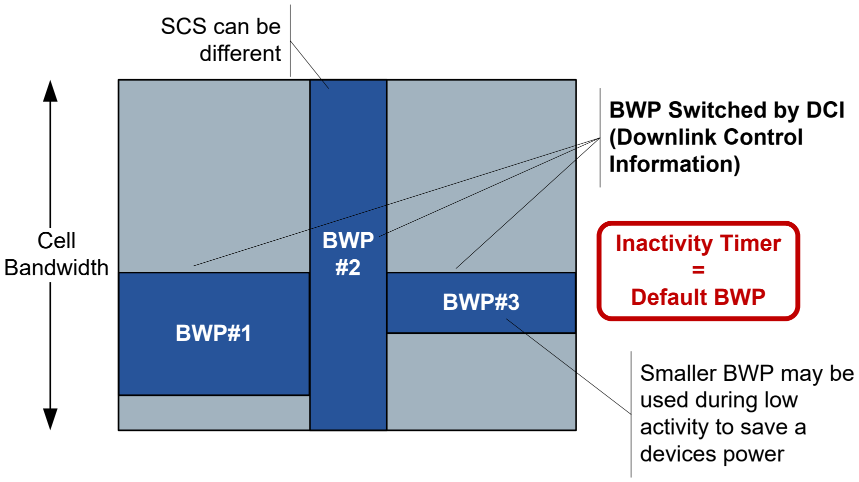


Figure 2-45 Changing BWP

3 5G Massive MIMO and Beamforming

3.1 Why Massive MIMO?

A key part of the 5G NR system relates to the use of Massive MIMO (Multiple Input Multiple Output). The term "Massive MIMO" relates to an antenna array system using a "Massive" amount of antenna elements that can serve multiple users simultaneously. Typically, the number of antenna elements is 128 or 256. This large number of antenna elements relates to the need to use beamforming, especially at the mmWave (Millimeter Wave) frequency bands.

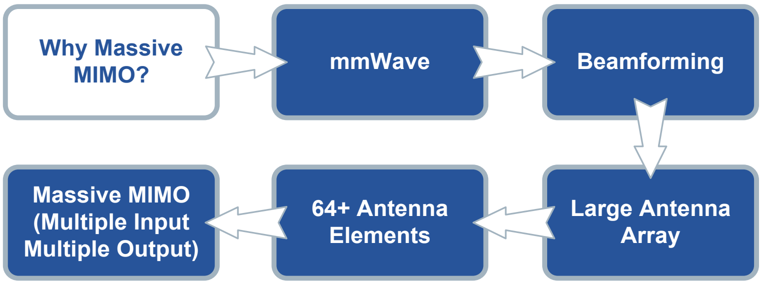


Figure 3-1 - Why Massive MIMO?

3.1.1 Requirement for Massive MIMO

To understand why Massive MIMO is needed it is best to review some key RF (Radio Frequency) basics. Figure 3-2 illustrates the radio path between a transmitter and receiver. P_{TX} represents the power transmitted, R is the distance between and P_{RX} represents the received power.

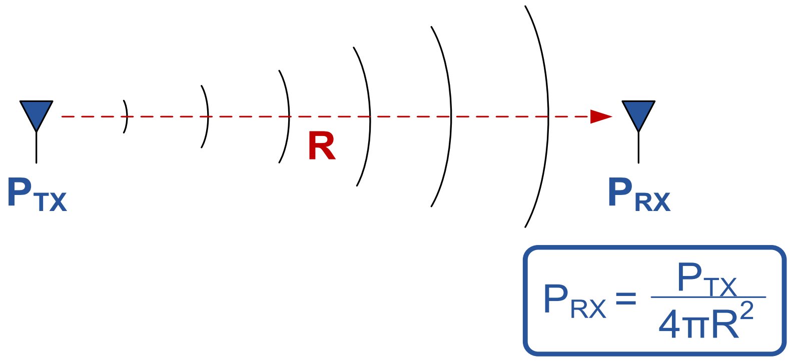


Figure 3-2 Requirement for Massive MIMO

The main issue relates to 5G requiring more bandwidth, which is only available at the higher frequencies, i.e. mmWAVE (Millimetre Wave), which has more spectrum available. Therefore, this needs to be factored into the equation (receiver antenna gain), as illustrated in Figure 3-3. Notice that λ (Wavelength) is now part of the equation and as it gets smaller with higher mmWave frequencies the receiver gain will reduce. The final part of the equation is to add the transmitter antenna gain. Ultimately, Massive MIMO is solving this problem and increasing the transmitter antenna gain. In summary, at higher frequencies Massive MIMO is needed or 5G would not work!

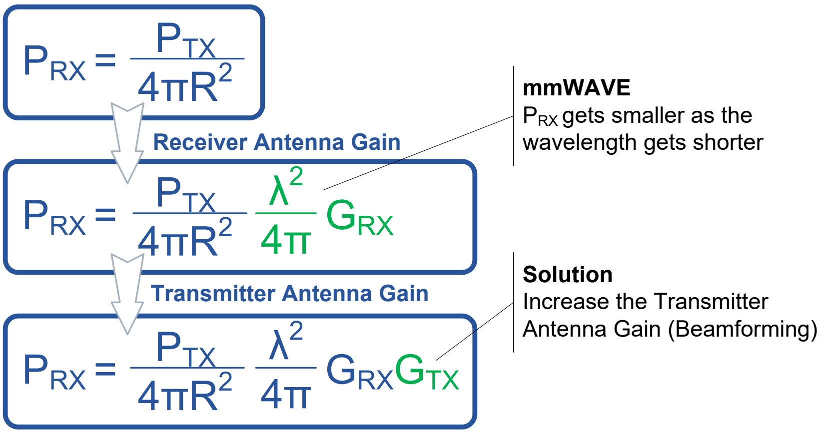


Figure 3-3 Requirement for Massive MIMO

3.1.2 Increasing Capacity

To increase capacity, it is worth recapping the Shannon-Hartley theorem. This identifies the maximum rate at which information can be transmitted over a communications channel of a specified bandwidth in the presence of noise. In terms of increasing capacity, the options include:

- Increase Channels (MIMO) - this utilizes the diverse radio environment to facilitate SM (Spatial Multiplexing) of data streams. It is a proven technique in other systems including LTE.
- Increase Bandwidth (Beamforming) - increasing bandwidth is very difficult, especially since most bands are already saturated. The key point with Massive MIMO is the use of beamforming, whereby the bandwidth can be reused in separate beams.
- Increase S/N (Signal to Noise) - this is part of the equation, however since it is "log2" it has less impact than the previous two options.

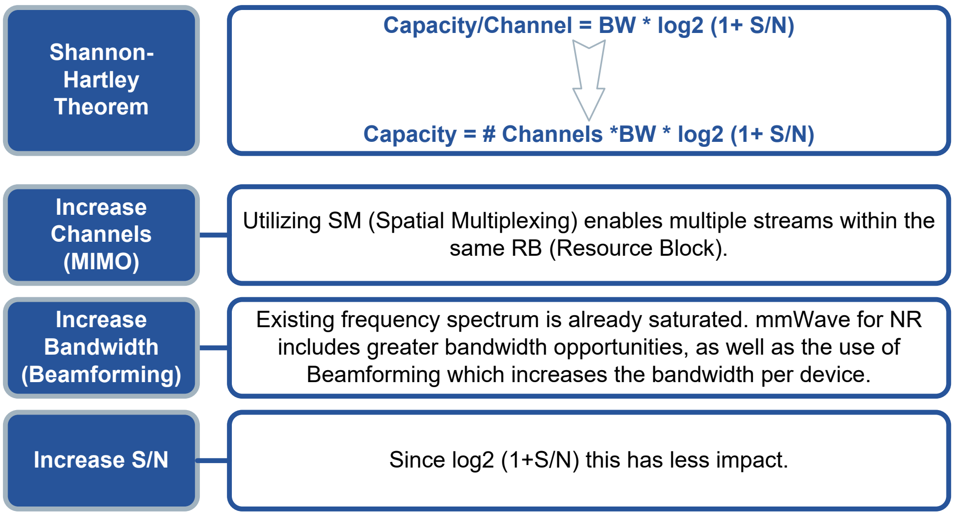


Figure 3-4 Increasing Capacity

3.2 MIMO in 5G

MIMO (Multiple Input Multiple Output) is an antenna technology that utilizes multiple antennas at both the transmitter and the receiver. It has been widely used in wireless systems such as Wi-Fi and LTE.

3.2.1 Summary of Transmission Path in 5G NR

To understand some of the MIMO and also transmission terminology, it is worth identifying the downlink and uplink processing chains for 5G NR, as illustrated in Figure 3-6 and Figure 3-7.

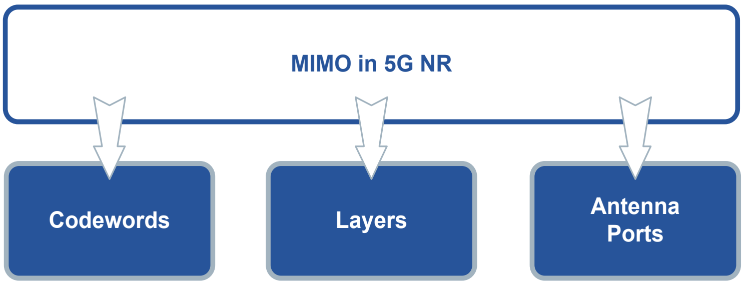


Figure 3-5 MIMO Key Terms

Whilst all the stages are important, a few key terms related to 5G NR Transmission and MIMO are highlighted:

- Codewords - prior to processing the Layer 2 MAC (Medium Access Control) Transport Block, it is first converted into a codeword by performing FEC (Forward Error Correction) and adding a CRC (Cyclic Redundancy Check).
- Layers - one or more codewords are processed by a “Layer Mapper” which creates ν transmission layers, with the number of layers always less than or equal to the number of antenna ports. The term “streams” is commonly used to describe layers carrying information.
- Antenna Ports - this is defined as “a channel over which a symbol on the antenna port is conveyed can be inferred from the channel over which another symbol on the same antenna port is conveyed”. These do not correspond to physical antennas, i.e. a single antenna port can be spread across multiple antennas. In addition, multiple antenna port signals can be transmitted on a single antenna.

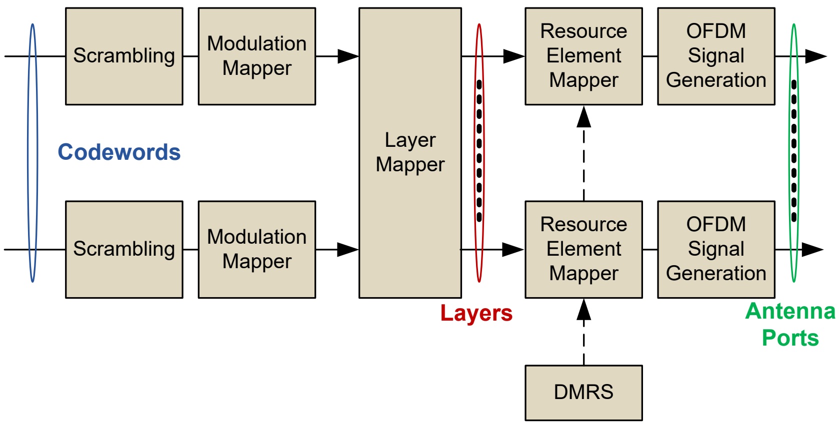


Figure 3-6 5G NR Downlink Processing Chain

Note that the 3GPP Release 15 uplink currently only supports 1 codeword which can map up to 4 layers. In addition, the processing chain for DFT-s-OFDM (Discrete Fourier Transform - spread - Orthogonal Frequency Division Multiplexing) is slightly different, i.e. it includes an additional Transform Precoding stage.

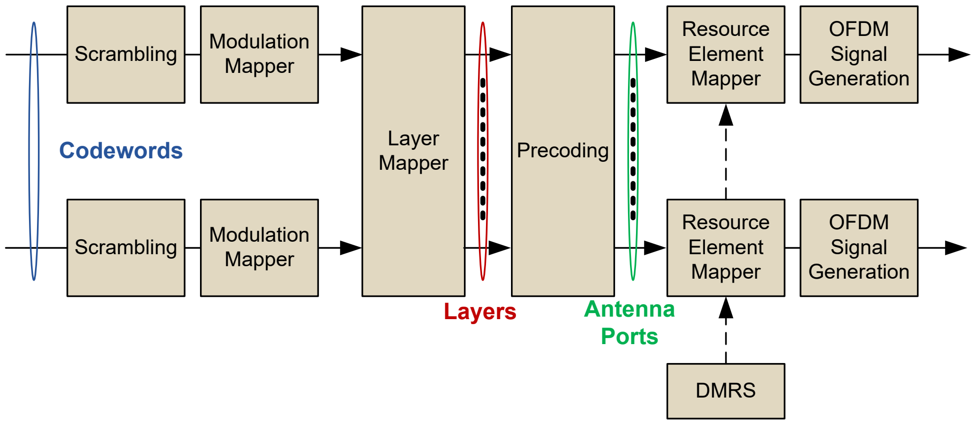


Figure 3-7 5G NR Uplink Processing Chain (CP-OFDM)

MIMO technology utilizes and exploits the spatial dimension of the radio waves as they traverse the air interface between a transmitter and receiver. This spatial dimension is caused by utilizing the natural radio wave phenomenon called multipath. Multipaths are the diverse radio paths that the signals take, i.e. some signals bounce off walls, ceilings, and other objects, reaching the receiving antenna multiple times at different angles and slightly different times.

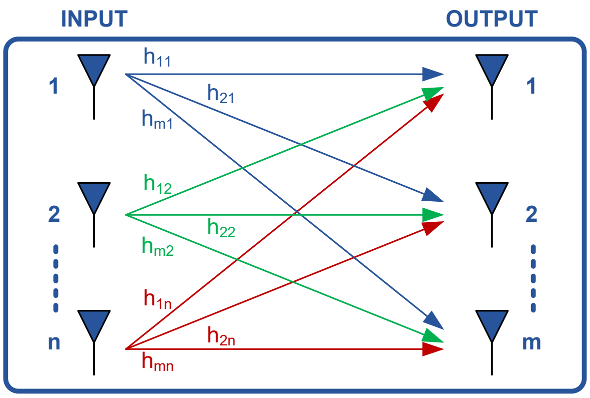


Figure 3-8 MIMO Channel

Figure 3-8 illustrates the basic MIMO channel and the various signals between a transmitter and receiver. Note that each signal e.g. h_{11}, will utilize multiple multipaths to arrive on each receive antenna. The intelligence is in the system design, since it can decode each of these signals independently.

Typically, MIMO designation is used, e.g. 2x2. This refers to the number of “input” and “output” antenna ports, whereby input=transmit and output=receive at an antenna, e.g. the base station antenna.

3.2.2 MIMO Spatial Multiplexing

MIMO systems can identify separate signals, i.e. layers/streams and these can be used to carry the same information, effectively a form of diversity. However, they can also be used to carry different information, which is termed SM (Spatial Multiplexing) and typically requires good radio conditions, i.e. a spatially diverse channel with good signal levels. Spatial Multiplexing implies “different” data on the streams, as illustrated in Figure 3-9.

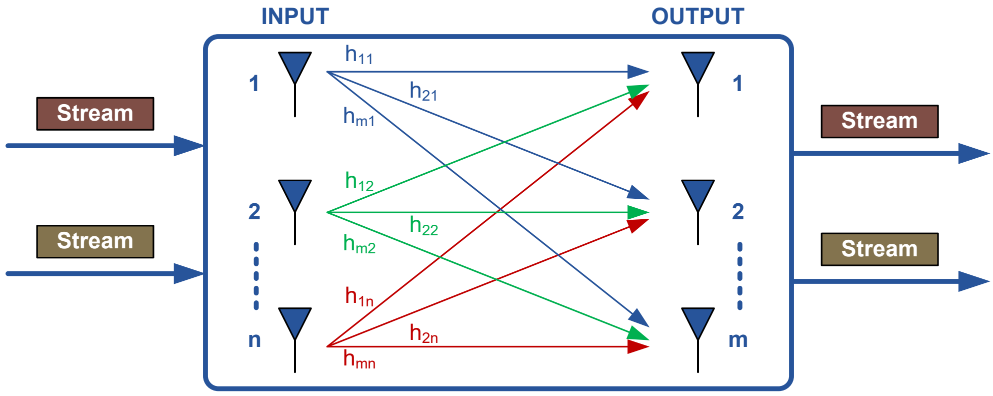


Figure 3-9 MIMO Spatial Multiplexing

3.2.3 SU-MIMO vs MU-MIMO

Like LTE, 5G NR supports both SU-MIMO (Single-User MIMO) and MU-MIMO (Multi-User MIMO). SU-MIMO, as its name suggests is designed to increase the performance for a single user. In contrast, MU-MIMO is designed to serve multiple users simultaneously on the same frequency resource, primarily relying on spatial separation or beam separation.

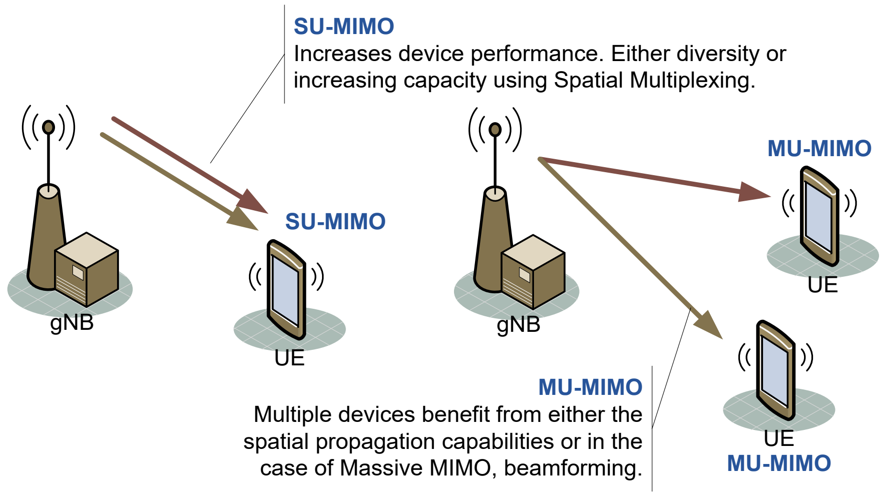


Figure 3-10 MU-MIMO

Using MU-MIMO changes the performance of the channel. In some cases, users on the edge of a cell may require SU-MIMO to increase the performance and reliability.

3.3 Beamforming (Massive MIMO)

Beamforming, as its name suggests, is the “forming” of a “beam” of RF energy. Fundamentally, the electromagnetic wave radiation pattern from a system is focused like a beam from a torch (or laser).

3.3.1 Spatial Multiplexing vs Beamforming

These are not mutually exclusive, however typically in the sub 6GHz band the channel characteristics are rich in multipaths and therefore ideally suited for spatial multiplexing. In contrast, at mmWave the system relies on beamforming (to get the power to the device) which has fewer multipaths.

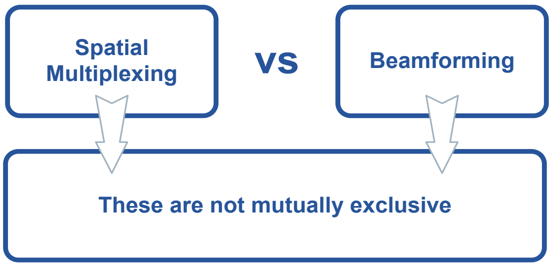


Figure 3-11 Spatial Multiplexing vs Beamforming

Figure 3-12 illustrates the key differences between Sub 6GHz and mmWave with respect to MIMO and channel characteristics.

	Sub 6GHz	mmWave
MIMO Order	Up to 8x8	Less MIMO (usually 2x2)
Main Technique	Spatial Multiplexing	Beamforming to a Single Device
Channel Characteristics	Rich Multipaths ideal for Spatial Multiplexing	Fewer Multipaths due to beamforming

Figure 3-12 Sub 6GHz vs mmWave

In addition, the sub 6GHz band is typically used to cover a larger area with more devices being supported and greater mobility.

3.3.2 Creating a Beam

The easiest method to create a beam is to place multiple antennas in an “array”. Note that there many implementation options when it comes to aligning the antenna elements. The simplest is illustrated in Figure 3-13 whereby the antennas are aligned in a line. Notice that as an additional antenna element is added, the radiation pattern is changed, becoming more directional.

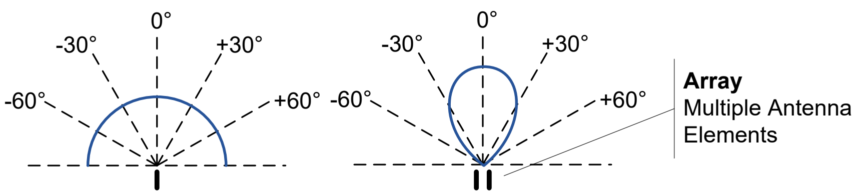


Figure 3-13 Beamforming - Antenna Array

Figure 3-14 illustrates the basic concept of how the electromagnetic waves are reinforced in the main beam direction. This is typically termed the main lobe. It is also worth noting that the spacing between the antenna elements is expressed in wavelengths (λ), with different spacing having a different result.

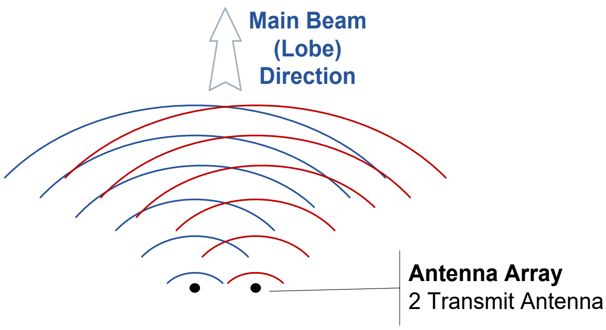


Figure 3-14 Beamforming Basics

3.3.3 Narrow Beams and Beam Steering

Unfortunately, energy is also partially reinforced in unwanted directions, referred to as "side lobes". An example of side lobes is illustrated in Figure 3-15. Notice as the number of antenna elements is increased, the main lobe gain is increased and the beam becomes narrower. In addition, the sidelobes are reduced. The final example in Figure 3-15 illustrates four equally spaced antenna elements, however the phase of each is offset by an equal amount, e.g. 90deg; as a result, the beam is transmitted in a specific direction.

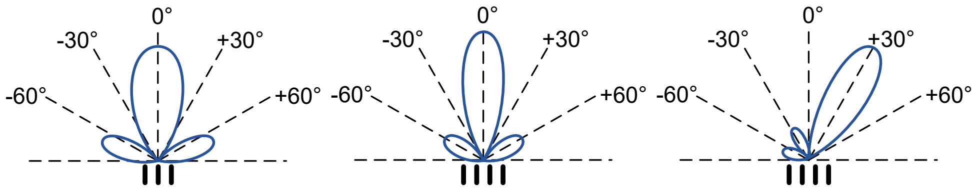


Figure 3-15 Beamforming - Additional Antenna Elements

Therefore, by changing the antenna elements' phase, a beam can effectively be steered.

3.3.4 Beamforming Nulls

Another key aspect of beamforming is the generation of Nulls. As illustrated in Figure 3-16, this is the area in which no or little energy is transmitted.

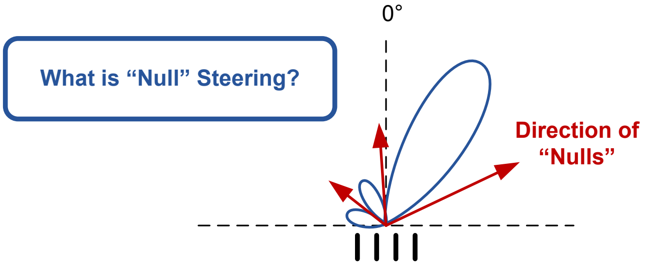
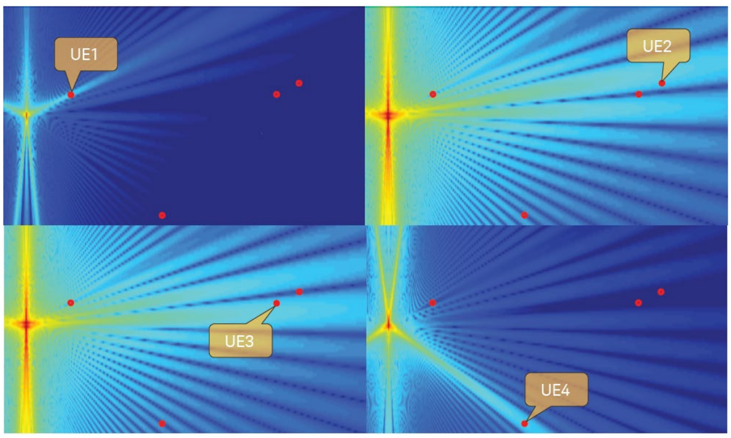


Figure 3-16 Beamforming Nulls

The concept of "Null Steering" is equally as important as beam steering. This can be illustrated by reviewing the radiation patterns which are sent from an antenna at the same time to four spatially separate devices. The key point relates to the fact that whist the main lobe targets the intended device, the nulls are steered to ensure minimal interference towards other devices.



Source: Keysight Technologies

Figure 3-17 Multiple Beams

The actual radiation pattern will be 3D. Figure 3-18 illustrates an example of a main lobe direction being changed, as well as the resultant change to the position of the sidelobes and the nulls.

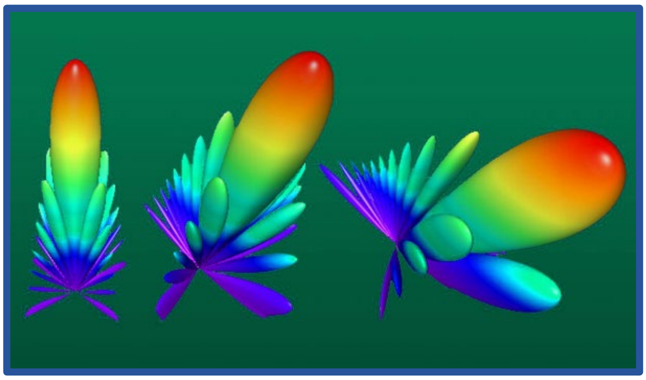


Figure 3-18 Example of Beamforming Lobe

3.3.5 Massive MIMO Antennas

The range of antennas available for MIMO and Massive MIMO is huge. Inside an antenna there will be multiple antenna elements. As illustrated in Figure 3-19 these can be cross-polar (dual slant). In conventional systems a "sub-array" meant that one antenna port would feed multiple elements. However, as techniques such as vertical tilting were required, i.e. FD-MIMO (Fully Dimension MIMO) in LTE, the sub-array size is reduced, thus enabling more control.

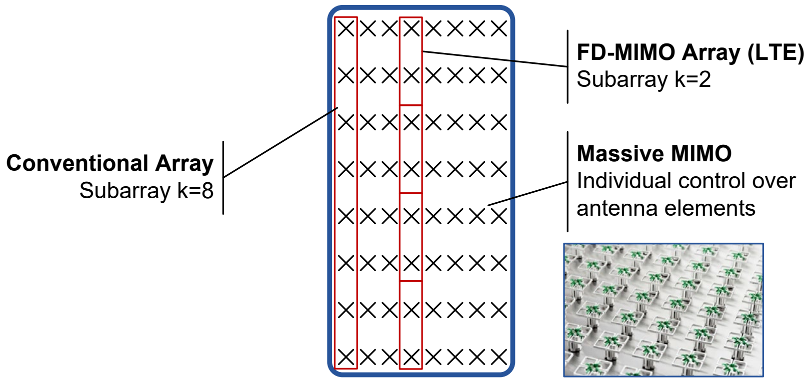


Figure 3-19 Antenna Elements

For Massive MIMO, there is a requirement to have even more control. As such, systems exist which have control over individual antenna elements.

3.3.5.1 Massive MIMO Antenna

Massive MIMO is mostly linked to the requirement to have beamforming at the mmWave frequencies. However, the concept can still be used in the sub-6GHz band. Since antenna element size and spacing is a factor of wavelength, the size of the antenna will increase as the frequency gets lower (assuming the same level of performance and control is required). Figure 3-20 illustrates typical Massive MIMO antenna sizes for sub 6GHz operation. Each antenna has 64T64R, meaning 64 RF Transceiver Channels.

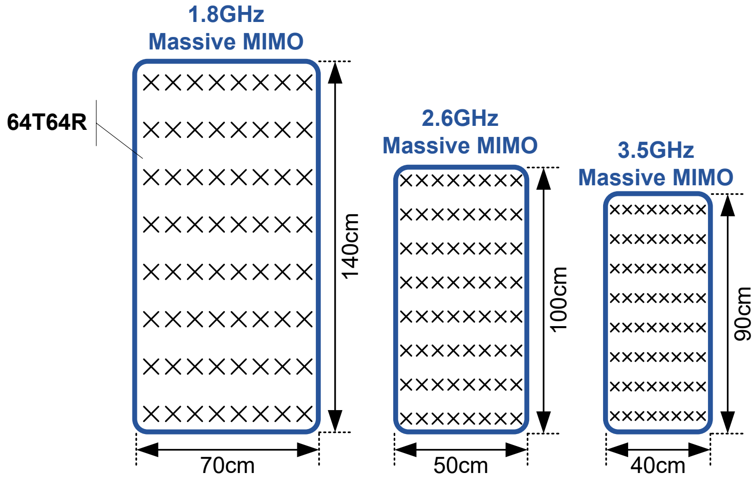


Figure 3-20 Massive MIMO Antenna (Sub 6GHz)

The key benefit of using 64T64R over traditional 8T8R is an increase to the peak per-carrier capacity, an increase in cell-edge capacity and an extension in overall coverage.

3.3.6 MIMO in a Handset

5G devices, such as handheld mobiles are also being targeted for MIMO enhancements, as well as the use of beam manipulation. Figure 3-21 illustrates a scenario with multiple antenna elements on a handheld device. These could then be used to manipulate the radiation pattern around the hand, as well as providing limited steering capability towards the cell.

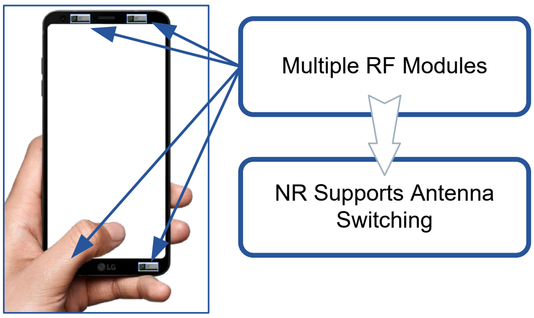


Figure 3-21 MIMO Devices

3.3.7 Multiple Panel Antenna

5G NR supports single panel antennas and multi-panel antennas. An example of multi-panel operation is illustrated in Figure 3-22, which includes four panels each with 8x4x2=64 element.

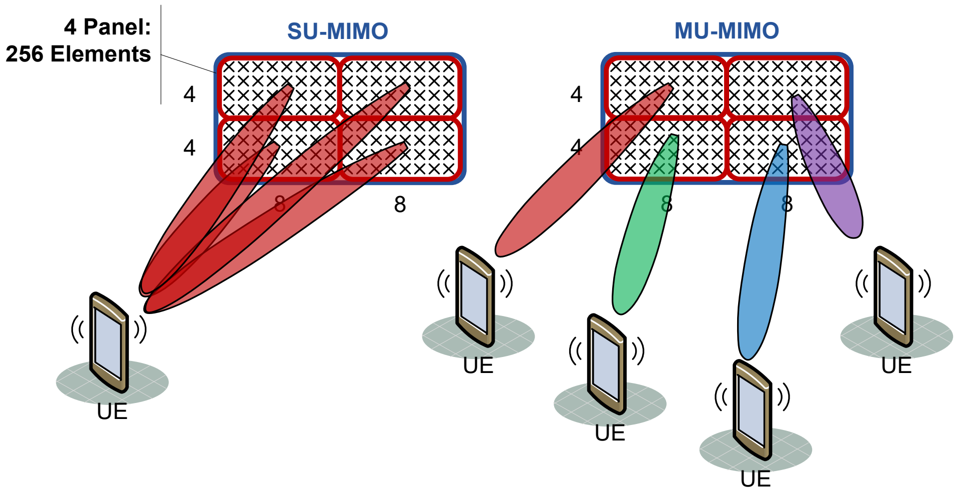


Figure 3-22 Multi-Panel Antennas

The first example illustrates how all panels can be utilized in a SU-MIMO scenario. In contrast, the second scenario focuses on MU-MIMO operation, with each panel serving a separate user.

3.4 NR Beam Management

Utilizing Massive MIMO is not without its challenges. One key issue relates to the fact that a beam is used to communicate to a user. However, since the user could be anywhere in the cell - where does the system point the beam?

The answer relates to the use of a technique called “beam sweeping”. Effectively moving the beam over time so that eventually a beam is pointed at the device. Note for 3GPP Release 15 the device is not required to support two simultaneous beams.

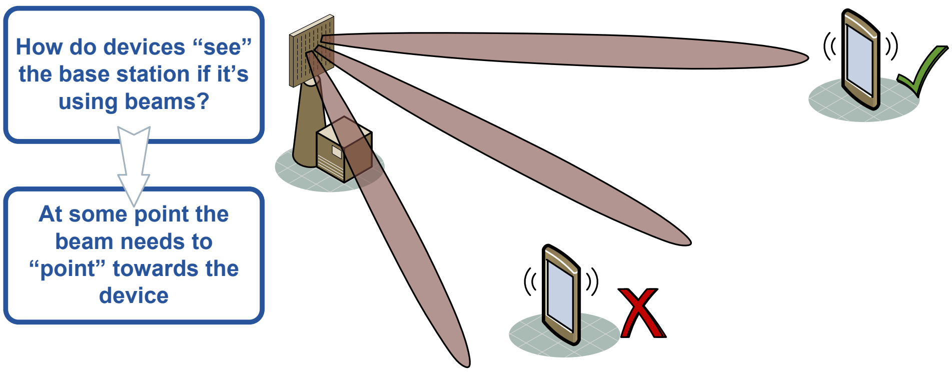


Figure 3-23 Issue with using Massive MIMO

Beam sweeping is just one aspect, there are other considerations related to Massive MIMO and beams; these are highlighted in Figure 3-24.

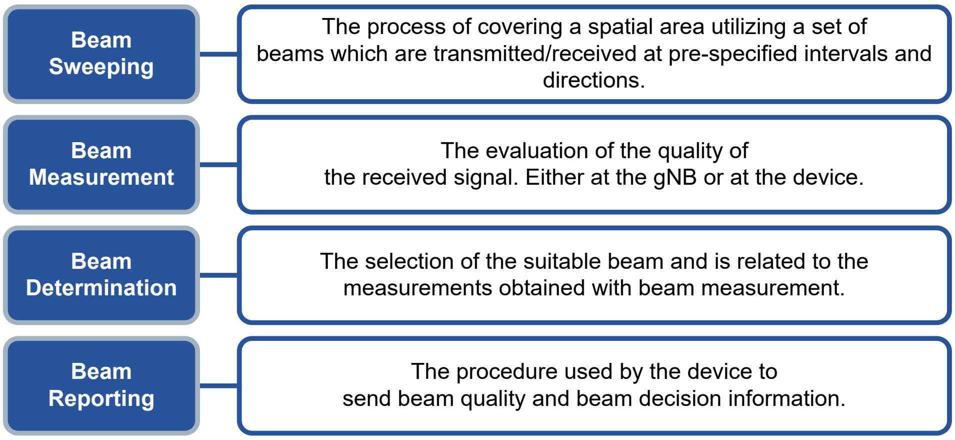


Figure 3-24 Beam Management

3.4.1 Beam Sweeping

The 5G NR system defines a SSB (Synchronization Signal Block). This includes NR synchronization signals and a PBCH (Physical Broadcast Channel). Figure 3-25 illustrates the basic concept of beam sweeping.

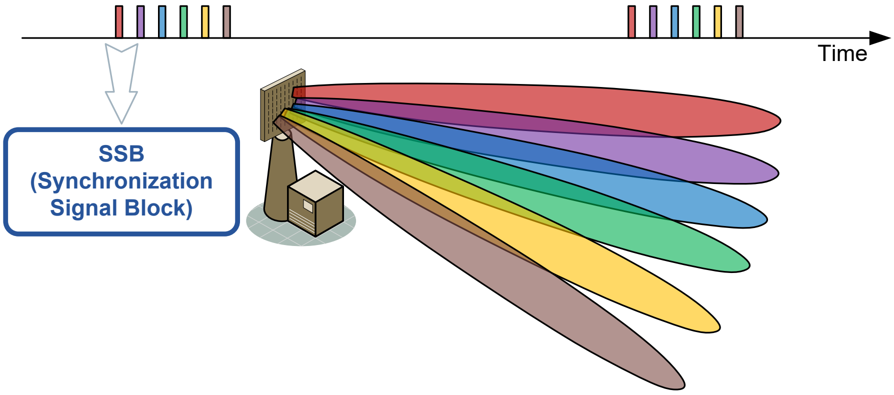


Figure 3-25 Beam Sweeping

Due to the narrow beams, it is important that the beam sweep covers both the azimuth of the cell's footprint, as well as the vertical footprint. In Sub 6GHz bands the number of SSB Beams is limited to either 4 or 8. Figure 3-26 illustrates an example of 4 SSB beams covering the cell.

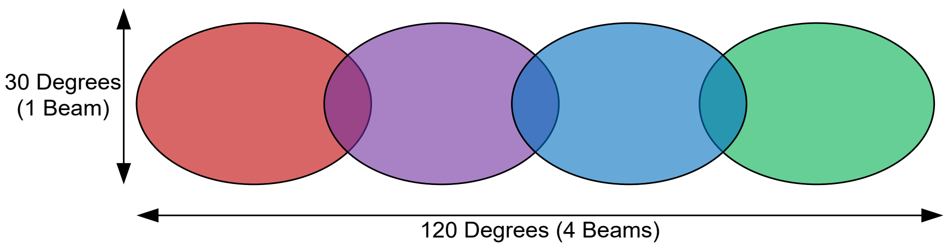


Figure 3-26 Beam Sweeping (4 Beams)

In contrast, Figure 3-27 illustrates an example using 64 beams. This configuration will be required at mmWave frequencies.

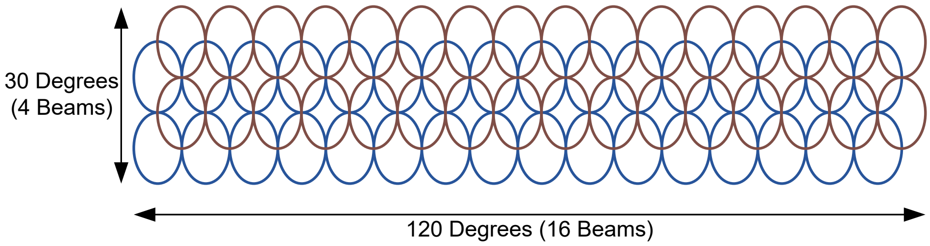


Figure 3-27 Beam Sweeping in 3D (64 Beams)

3.4.2 SS Block

The SSB (SS Block) is a key part of beam management. It includes the following:

- PSS (Primary Synchronization Signal).
- SSS (Secondary Synchronization Signal).
- PBCH (Physical Broadcast Channel).

Figure 3-28 illustrates how the SS Block consists of 4 OFDM symbols and occupies 240 subcarriers, i.e. 20 PRB (Physical Resource Block). In addition to the SSB, the downlink DMRS (Demodulation Reference Signals) are also utilized to determine the identity of a specific beam.

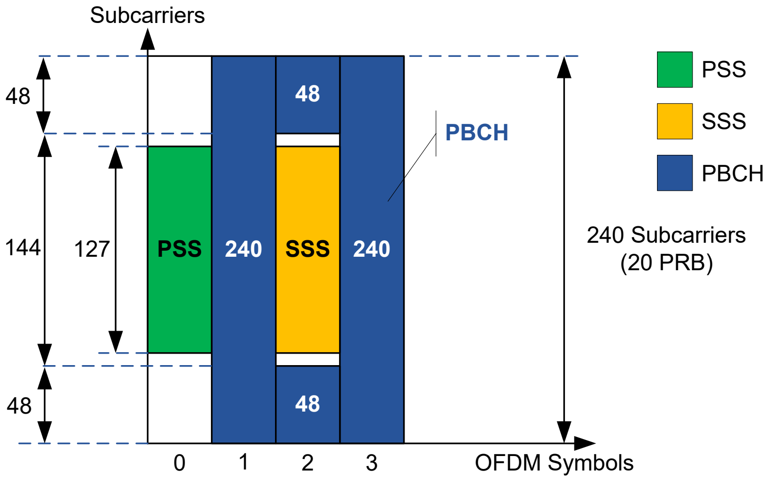


Figure 3-28 SS Block

3.4.3 Beam Management Reference Signals

Depending on the mode of the device, different reference signals are utilized, some of which aid beamforming and MIMO. Figure 3-29 illustrates the main reference signals used in 5G NR.

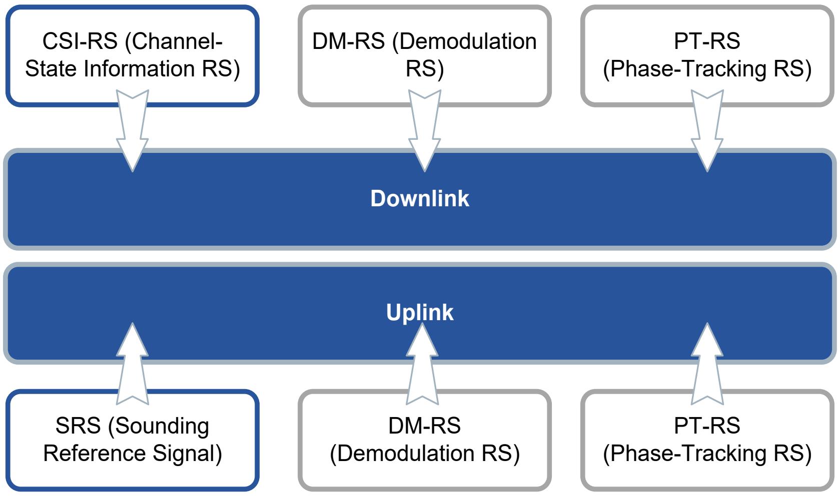


Figure 3-29 5G NR Reference Signals

Downlink Reference Signals include:

- CSI-RS (Channel State Information RS) - this can be used for estimation of CSI (Channel State Information) to further prepare feedback reporting to the base station, e.g. CQI (Channel Quality Indicator) for link adaptation, precoder-matrix/vector selection, etc. These can assist beamforming and scheduling for up to eight layers of transmission.
- DMRS (Demodulation Reference Signals) - this can be used for downlink channel estimation for coherent demodulation of PBCH, PDSCH (Physical Downlink Shared Channel) and PDCCH (Physical Downlink Control Channel). The DM-RS is mapped over 1 or 2 adjacent OFDM symbols which are “front-loaded”, and the additional DMRS is always present in the prefixed location.
- PTRS (Phase Tracking RS) - this is optionally present to help compensate for phase noise and may also help with doppler shift. It is present only in the resource blocks used for the PDSCH, and only if the higher-layer parameter indicates PTRS being used. It may be configured with different levels of Time Density and Frequency Density.

Uplink Reference Signals Include:

- SRS (Sounding RS) - this can be used for estimation of uplink CSI to assist uplink scheduling and uplink power control.
- DMRS (Demodulation Reference Signals) - this can be used for channel estimation for coherent demodulation of the PUSCH (Physical Uplink Shared Channel). Uplink DM-RS is mapped to physical resources according to the type given by higher-layer parameters.
- PTRS (Phase-Tracking RS) - this is present only in the resource blocks used for the PUSCH, and only if the higher-layer parameter indicates PTRS being used.

For beamforming assistance whilst connected on LTE and monitoring NR the SSB is utilized (PSS, SSS and PBCH DM-RS). In contrast, once NR is connected, the CSI-RS is utilized for the downlink and the SRS for the uplink. Collectively these aid beam management, as well as narrowing the beam towards a device.

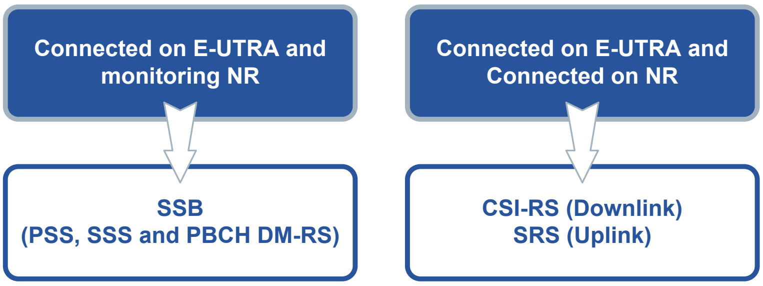


Figure 3-30 Beam Management Reference Signals

3.4.4 Transmission Configuration and Quasi Co-Location

The device can be configured with up to "M" TCI (Transmission Configuration Indicator) States by NR RRC. This enables it to decode PDSCH according to a detected PDCCH with DCI intended for the device and the given serving cell. The number of states "M" is dependent on the device capabilities.

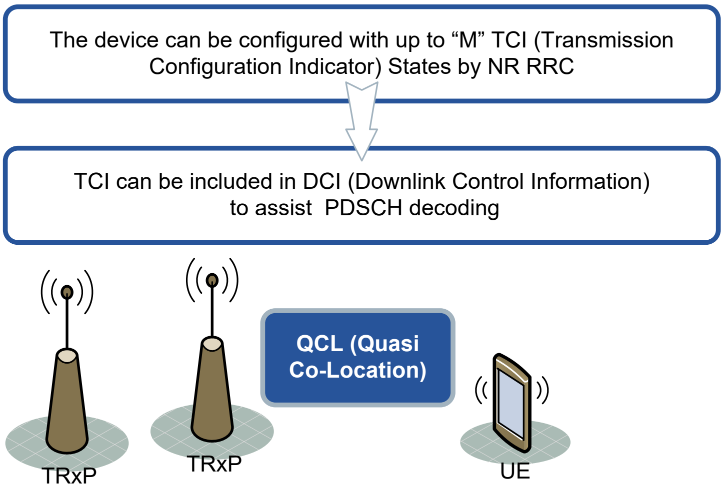


Figure 3-31 Transmission Configuration Indicator

Two antenna ports are said to be quasi co-located if the large-scale properties of the channel over which a symbol on one antenna port is conveyed can be inferred from the channel over which a symbol on the other antenna port is conveyed. The large-scale properties include one or more of delay spread, Doppler spread, Doppler shift, average gain, average delay, and spatial Rx parameters. When signalling is sent to the device these are grouped into one of the following types:

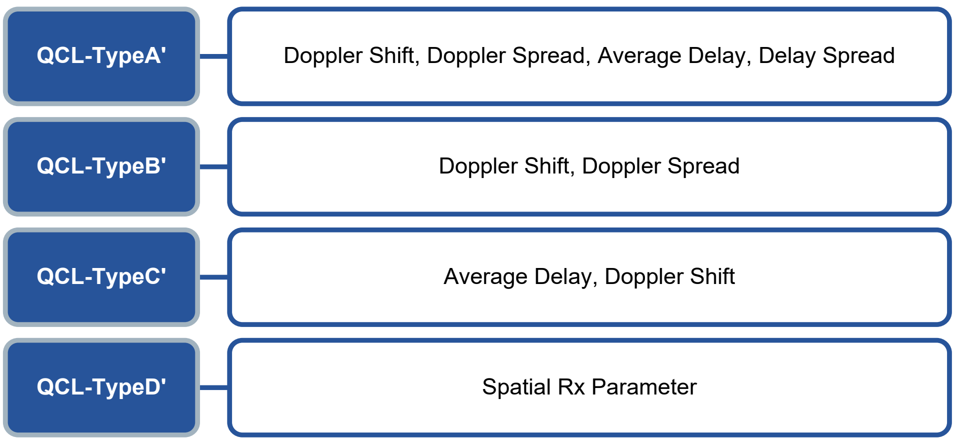


Figure 3-32 QCL Types

Figure 3-33 illustrates two TRxP (Transmission Reception Point), in this case two of the antenna ports on TRxP are QCL, whereas the other signal has a non-QCL relationship.

The TCI state information includes one RS set TCI-RS-SetConfig. Each TCI-RS-SetConfig contains parameters for configuring quasi co-location relationship between the reference signals in the RS set and the DM-RS port group of the PDSCH. The RS set contains a reference to either one or two DL RSs and an associated quasi co-location type for each one. For the case of two DL RSs, the QCL types cannot be the same, regardless of whether the references are to the same DL RS or different DL RSs.

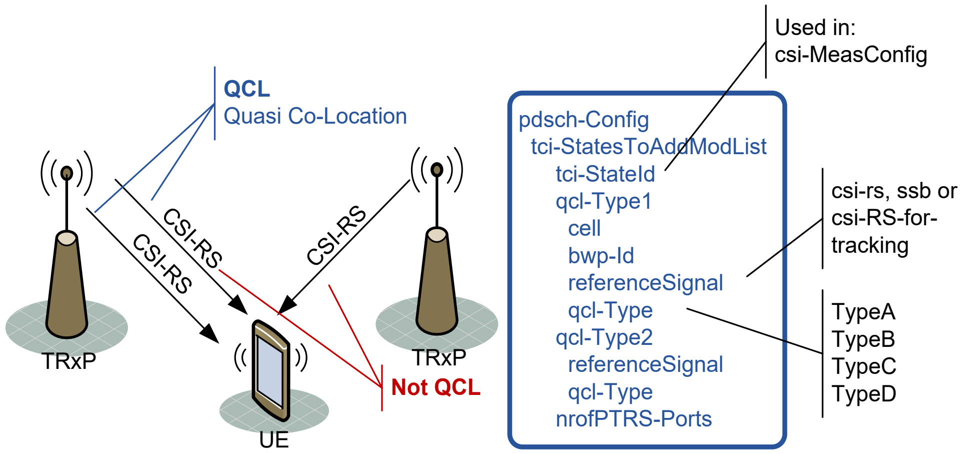


Figure 3-33 QCL Information in Transmission Configuration

3.4.5 Single and Multiple CSI-RS

NR supports a wide range of transmission and feedback permutations. Figure 3-34 illustrates two examples. The first is based on the en-gNB transmitting a single CSI-RS. Since NR supports a maximum of 32 ports for the CSI-RS, the feedback from the device can include the PMI (Precoding Matrix Indicator) to identify a port. In addition, other feedback such as the RI (Rank Indicator) and CQI (Channel Quality Indicator) can be sent. This technique is similar to “LTE Class A”.

The second example illustrates multiple CSI-RS, which identify the beams. Note that each beam can also include ports (in this example 8 ports). The device then utilizes a CRI (CSI-RS Resource Indicator) to identify the beam. This technique is similar to “LTE Class B”.

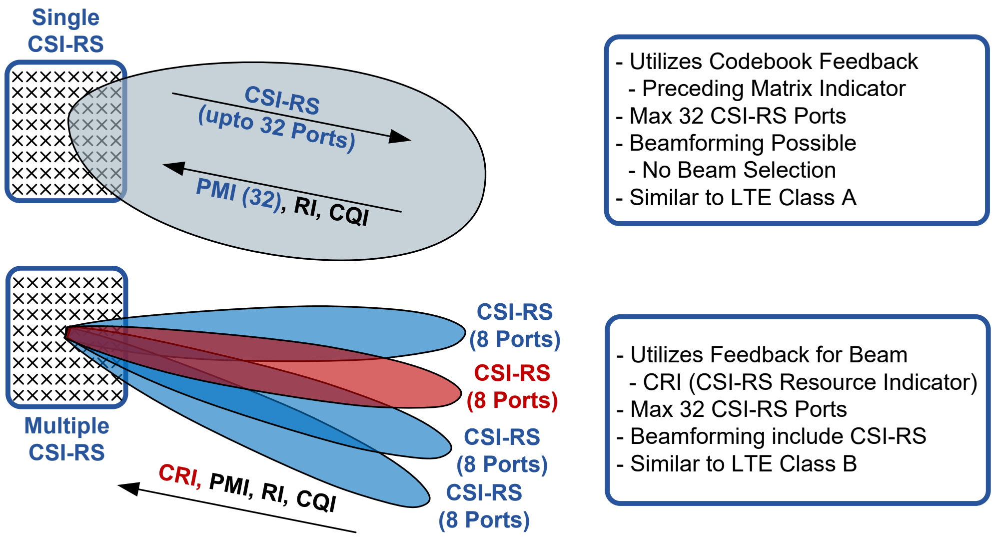


Figure 3-34 Sub-6GHz Beamforming with CSI-RS

3.4.6 Transmission Based on SRS

Like LTE, NR can also utilize SRS based transmission. As illustrated in Figure 3-35, the device can be configured to send SRS to the en-gNB. This technique assumes TDD reciprocity can be utilized, i.e. effects on the SRS in the uplink will be seen when the en-gNB schedules the downlink.

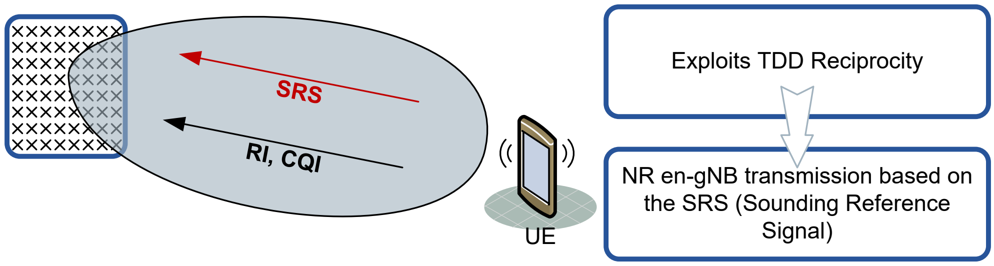


Figure 3-35 SRS Based Transmission

3.4.7 SS Burst and Burst Set

To understand the delivery of the SSB it is worth identifying the time related aspects, broadly these include:

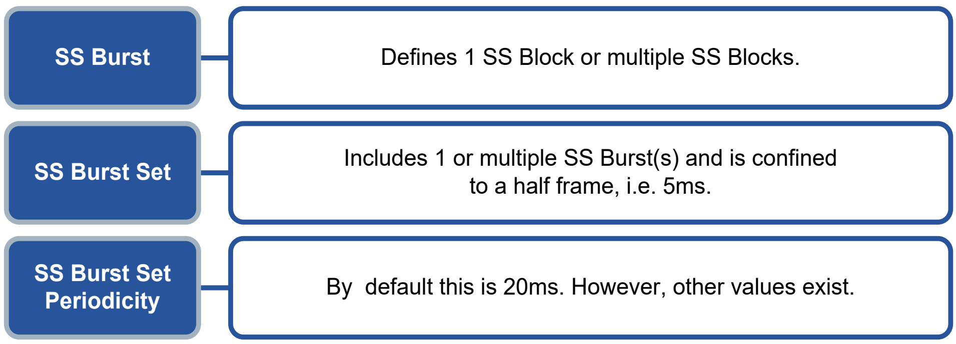


Figure 3-36 SS Burst and SS Burst Set

The total number of possible candidates for SSB Locations within a SS Burst Set is defined by L (Location). Values of Lmax are illustrated in Figure 3-37. It is also worth noting that not all SSB locations must be utilized.

Numerology	The total number of possible candidates for SSB Locations within a SS Burst Set is defined by L (Location), where Lmax can equal:
0	L=4 or L=8
1	L=4 or L=8
2	Cannot carry SSB
3	L=64
4	L=64

Figure 3-37 SSB Locations

3.4.8 SS Block Locations

The SSB can only be positioned on a specific GSCN (Global Synchronization Channel Number) frequency raster.

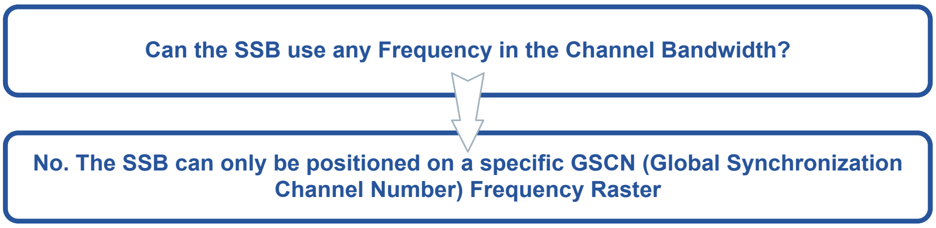


Figure 3-38 SSB Frequency Location

The Mpirical LearningZone includes details of the SS Block Frequency Raster.

In addition, there are five cases (Case A to E) defined for SS block locations in the time domain. Case A, B and C relate to the sub-6GHz band and are defined in Figure 3-39. Note that specific cases are allowed in a NR band, e.g. n78 supports Case C.

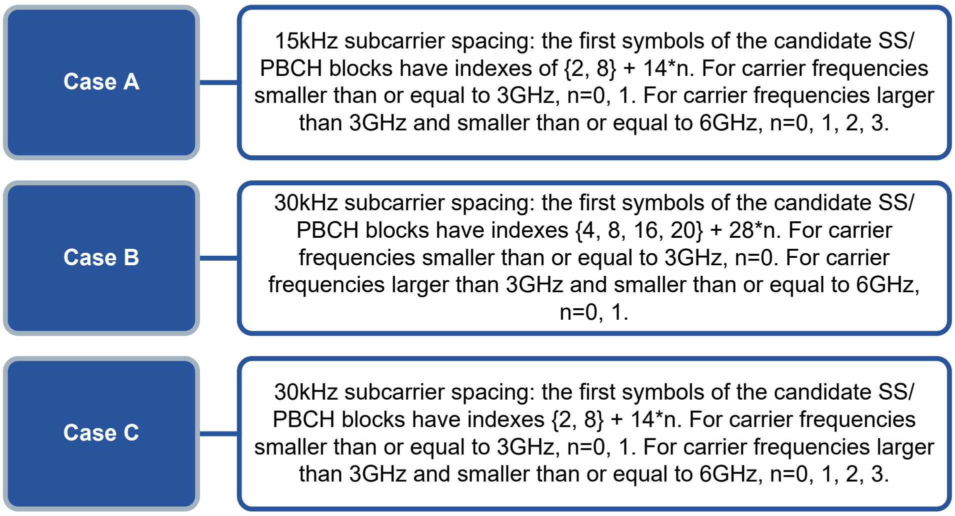


Figure 3-39 Sub 6GHz SS Block Locations

In term of visualization, Figure 3-40 illustrates the SS Block symbol locations for Case A, B and C. Note that only the first 1ms subframe is shown. In reality, the number of SS Block locations will span multiple subframes.

The blue and red shaded symbols relate to the time aspects of the SS Block, i.e. 4 OFDM symbols each.

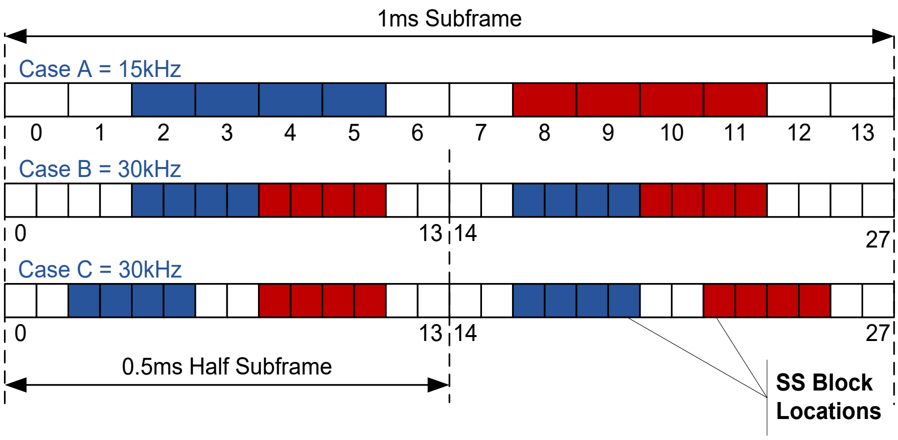


Figure 3-40 Case A, B and C SS Block Locations (less than 6GHz)

For LTE-NR coexistence the specifications indicate that a 30kHz subcarrier spacing should be used with a minimum of 10MHz bandwidth. This is so the system can be adapted to ensure the LTE RS (Reference Signal) are preserved. Figure 3-41 illustrates the four areas within the NR subframe which need to preserve LTE Reference Signals. As such, in areas where collisions occur, the NR SS Blocks are not transmitted by the en-gNB.

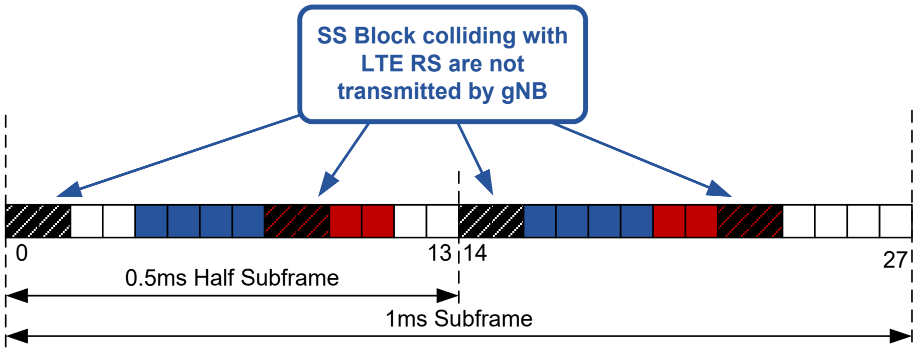


Figure 3-41 NR Coexistence with LTE

Figure 3-42 illustrates the SS Block locations for >6GHz. With Case D and Case E relating to 120kHz and 240kHz SCS respectively.

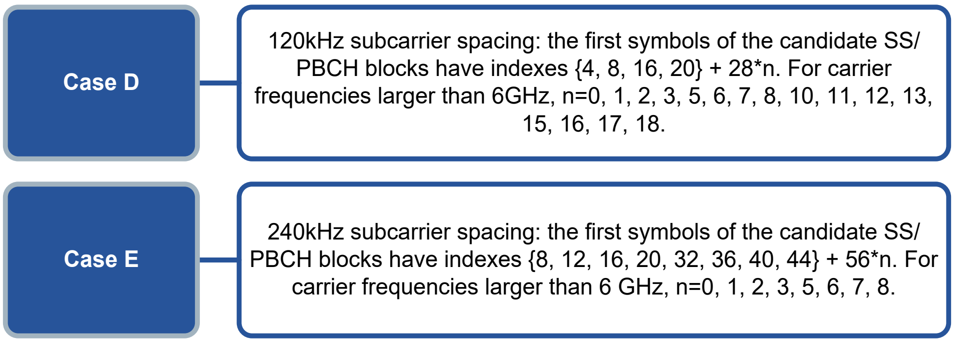


Figure 3-42 Larger than 6GHz SS Block Locations

In terms of visualization, Figure 3-43 illustrates Case D and Case E SS Block locations for the 120kHz and 240kHz slot sizes.

The shaded symbols all relate to symbols where the SS Blocks could be located.

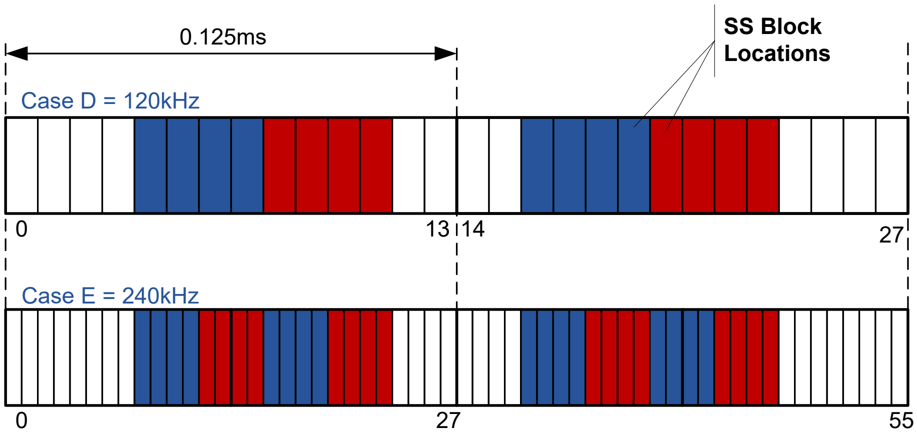


Figure 3-43 Case D and E SS Block Locations (Larger than 6GHz)

The actual number of SS Block locations is related to SCS with the Lmax being 4, 8 or 64. Figure 3-44 illustrates the potential SS Block locations.

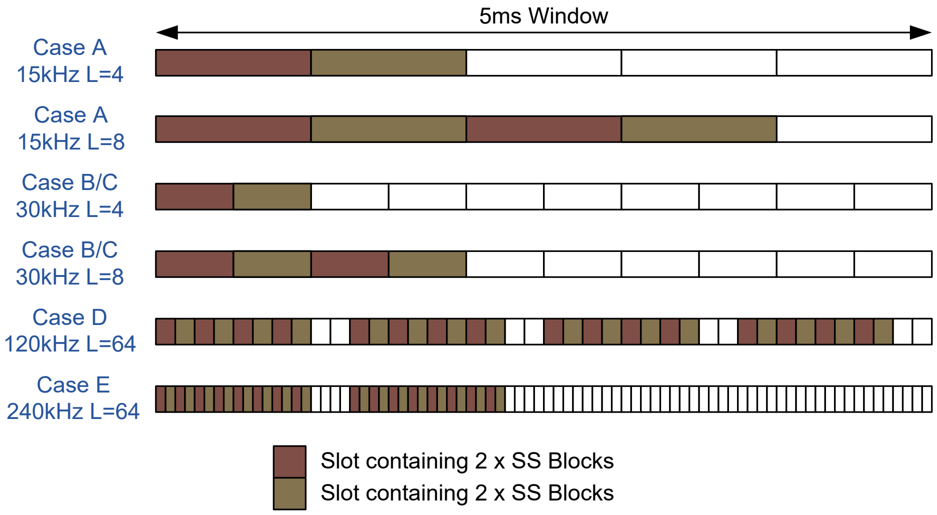


Figure 3-44 SS Block Location (L=4, 8 or 64)

3.4.9 SS/PBCH Block Index Indication

The SS Block index increments from 0 to L-1 within the SS Burst Set (5ms). Since the Lmax value is either 4, 8 or 64 the maximum number of bits required for the index is 6. As such, the determination of the SS Block index is achieved by decoding two parameters:

- DMRS Sequence - enables the encoding/mapping of the 3bits LSB (Least Significant Bits) of the SS Block Index (b_2, b_1, b_0).
- PBCH Scrambling Sequence - enables the encoding/mapping of the 3bits MSB (Most Significant Bit) of the SS Block Index (b_5, b_4, b_3).

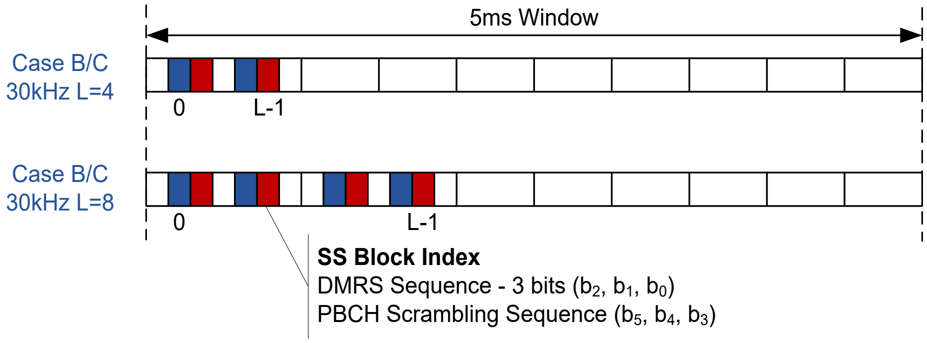


Figure 3-45 SS/PBCH Block Index Example

3.4.10 Beam Measurement, Determination and Reporting

During the initial discovery procedure, beam measurement and beam determination is based on the SS/PBCH Block. Figure 3-46 illustrates how a downlink SS block with a SS Block index(s) maps to uplink resources, i.e. a PRACH occasion. This mapping is provided as part of NR System Information.

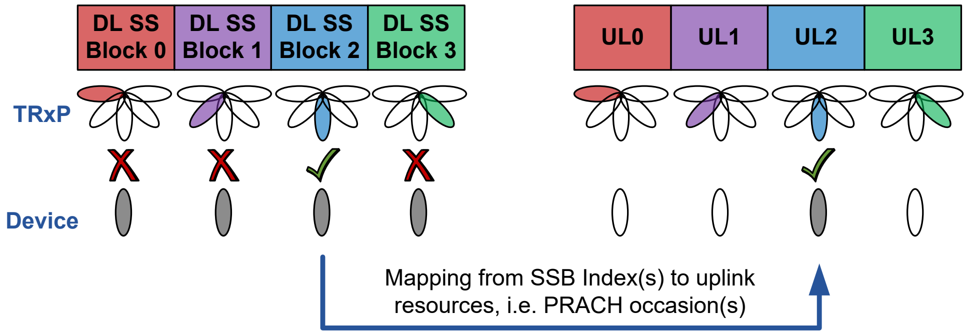


Figure 3-46 Beam Management

Note that for EN-DC operation, since the device does not establish the RRC connection towards the en-gNB, the initial beam reporting process will go via the LTE master node. This in turn can communicate with the en-gNB to schedule RACH resources, as illustrated in Figure 3-47.

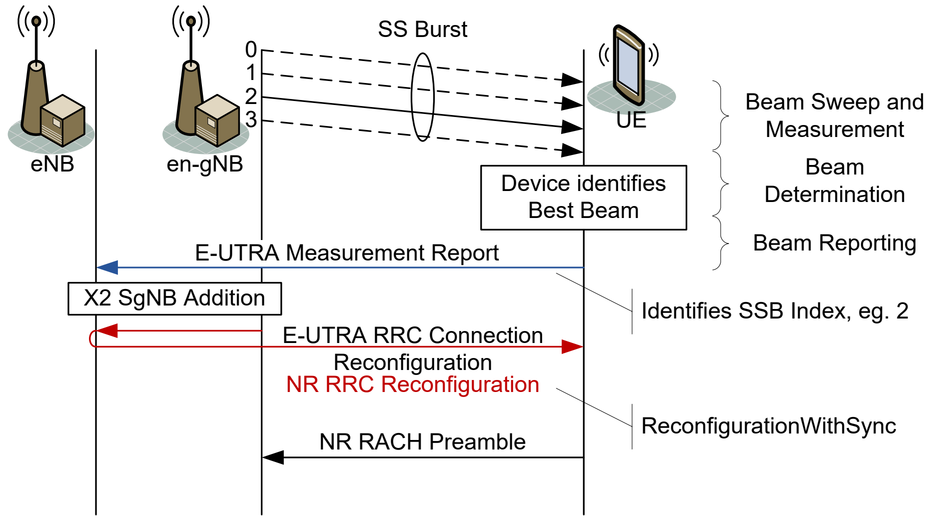


Figure 3-47 EN-DC Beam Measurement, Determination and Reporting

3.5 Transmission and Ports in NR

3.5.1 Downlink Transmission

3.5.1.1 Codewords

In terms of 5G NR specifics, the number of codewords per PDSCH (Physical Downlink Shared Channel) assignment per device is:

- 1 codeword for 1 to 4 layer transmission.
- 2 codewords for 5 to 8 layer transmission.

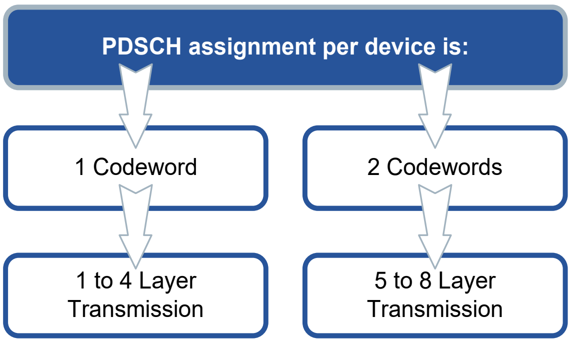


Figure 3-48 Codewords for PDSCH

3.5.1.2 DMRS Ports

Devices are higher layer configured with 2 DMRS configurations for “front-loaded” CP-OFDM:

- Type/Configuration 1 - Up to 8 orthogonal DL DMRS ports (1 or 2 symbols).
- Type/Configuration 2 - Up to 12 orthogonal DL DMRS (1 or 2 symbols).

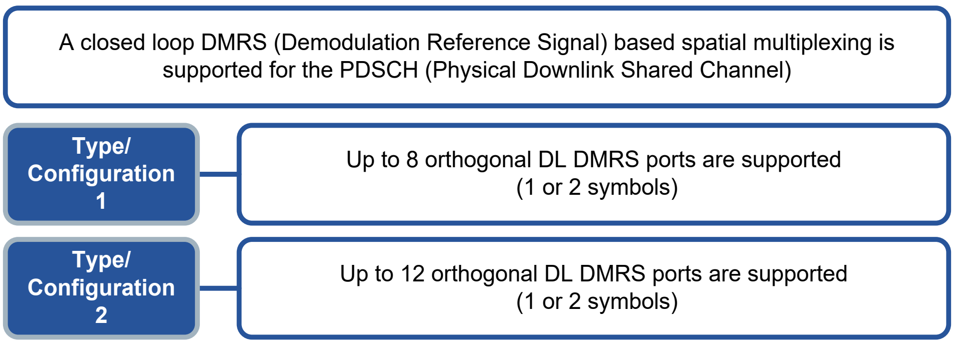


Figure 3-49 DMRS configurations for “front-loaded” CP-OFDM

Up to 8 orthogonal DL DMRS ports per device are supported for SU-MIMO and up to 4 orthogonal DL DMRS ports per device are supported for MU-MIMO.

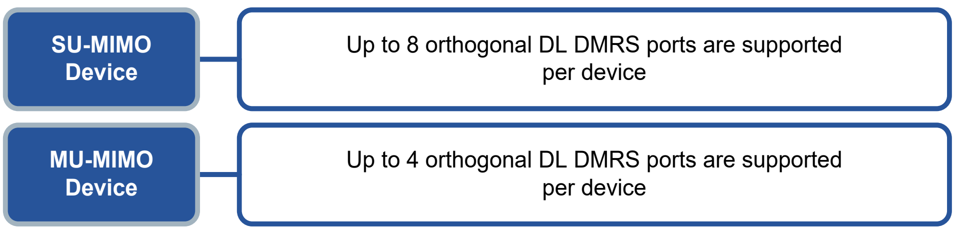


Figure 3-50 DMRS Ports for SU-MIMO and MU-MIMO

The DMRS and corresponding PDSCH are transmitted using the same precoding matrix and the UE does not need to know the precoding matrix to demodulate the transmission. The transmitter may use a different precoder matrix for different parts of the transmission bandwidth, resulting in frequency selective precoding.

3.5.2 Uplink Transmission

Two transmission schemes are supported for PUSCH:

- Codebook based transmission.
- Non-Codebook based transmission.

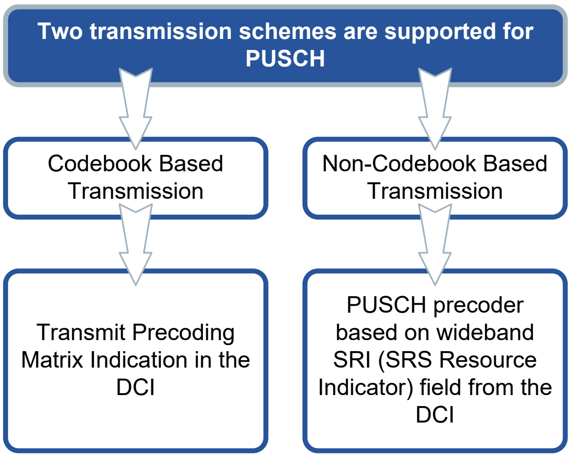


Figure 3-51 Uplink Transmission

For codebook based transmission, the gNB provides the device with a transmit precoding matrix indication in the DCI (Downlink Control Information). The device uses the indication to select the PUSCH transmit precoder from the codebook.

For non-codebook based transmission, the device determines its PUSCH precoder based on the wideband SRI (Sounding Reference Signal Resource Indicator) field from the DCI.

Other key aspects for uplink transmission:

- Closed loop DMRS based spatial multiplexing is supported for PUSCH.
- Up to 4 layer transmissions are supported for SU-MIMO with CP-OFDM using 1 codeword.
- When transform precoding is used (DFT-s-OFDM), only a single MIMO layer transmission is supported.

3.5.3 NR Downlink Antenna Ports

5G NR encompasses a range of antenna port numbers to identify the different types of downlink transmission. These are defined in Figure 3-52.

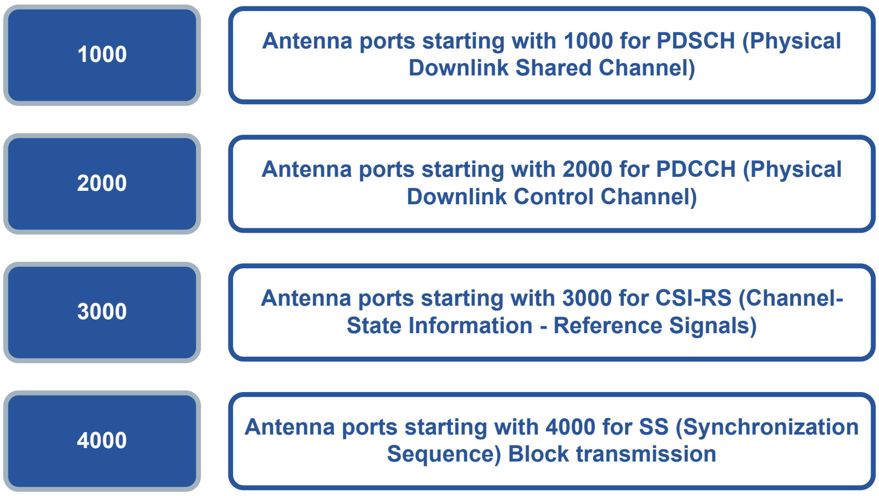


Figure 3-52 5G NR Downlink Antenna Ports

As an example, CSI-RS port numbering would be:

- 2 antenna ports {3000, 3001}.
- 4 antenna ports {3000, 3001, 3002, 3003}.
- 8 antenna ports {3000, 3001, …, 3007}.
- 12 antenna ports {3000, 3001, …, 3011}.
- 16 antenna ports {3000, 3001, …, 3015}.
- 24 antenna ports {3000, 3001, …, 3023}.
- 32 antenna ports {3000, 3001, …, 3031}.

3.5.4 NR Uplink Antenna Ports

The uplink also has defined antenna ports, these are outlined in Figure 3-53.

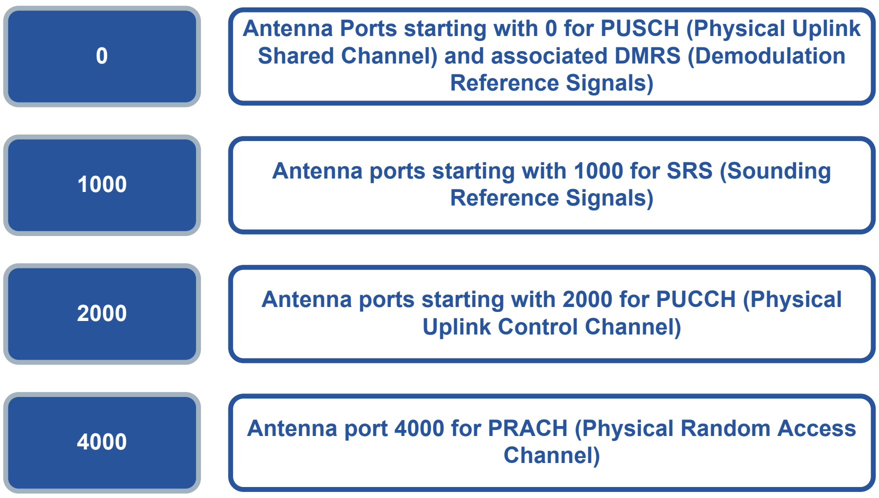


Figure 3-53 5G NR Uplink Antenna Ports

4 5G Physical Layer and Channels Introduction

4.1 NR Channels

Prior to defining the physical layer, it is worth defining the types of NR channels and reference signals. Like LTE, the terminology of Logical Channels, Transport Channels and Physical Channels is utilized.

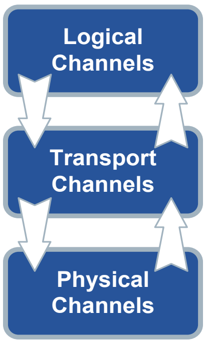


Figure 4-1 NR Channels

4.1.1 Logical Channels

Logical channels for 5G NR can be divided into two groups, namely Control Channels and Traffic Channels.

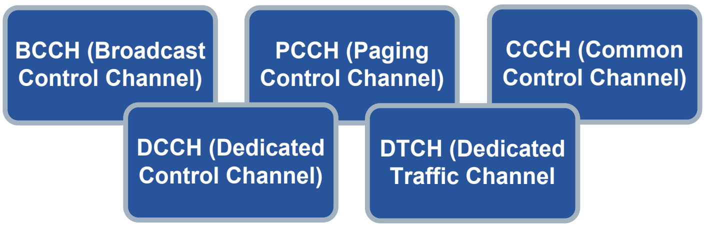


Figure 4-2 NR Logical Channels

Control Channels

The various forms of these control channels are summarized.

- BCCH (Broadcast Control Channel) - this is a downlink channel used for the broadcast of SI (System Information).
- PCCH (Paging Control Channel) - this is a downlink channel for the transfer of paging information to the device. It can also be used to transfer system information change notifications and indications of ongoing PWS (Public Warning System) broadcasts.
- CCCH (Common Control Channel) - this is used by a device to establish or re-establish an RRC (Radio Resource Control) connection. This is referred to as SRB (Signalling Radio Bearer) 0.
- DCCH (Dedicated Control Channel) - this is a two-way channel for the transfer of control information when the device has an RRC connection. SRBs when DCCH is activated include:
  - SRB 1 - this is used for NR RRC messages.
  - SRB 2 - this is used for NR NAS (Non Access Stratum) messages and has a lower priority than SRB1.
  - SRB 3 - this is from the Secondary RAN node and can be used to configure measurements, MAC, RLC, PDCP and physical layer parameters, as well as RLF (Radio Link Failure) parameters.

Figure 4-3 illustrates SRB's for 5G operation, as well as illustrating 5G DC (Dual Connectivity). Note that SRB3 is optional when in dual connectivity and if it is not present and signalling from the secondary RAN node is passed across the Xn reference point and piggy backed in SRB1.

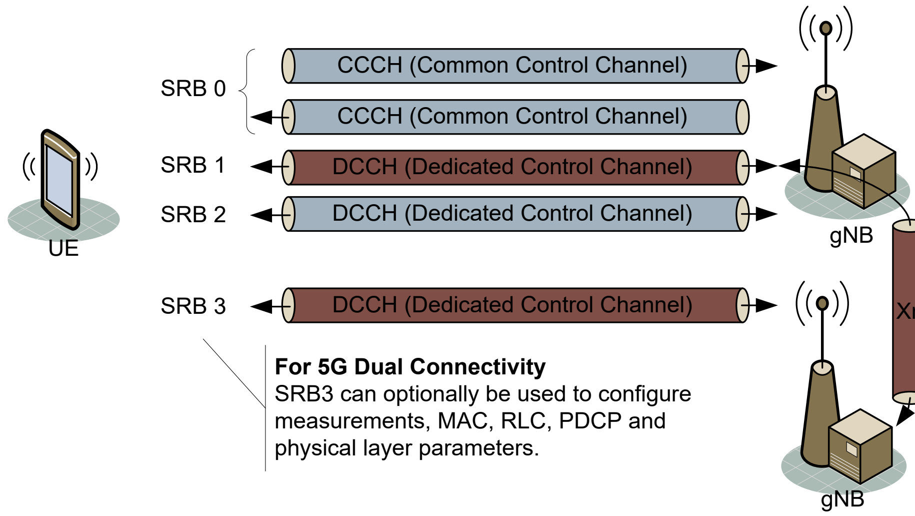


Figure 4-3 SRB's for 5G and 5G-DC

Note that if MCG (Master Cell Group) split SRB is activated, two additional variants exist:

- SRB1S - this is the SCG part of MCG split SRB1.
- SRB2S - this is the SCG part of MCG split SRB2.

When operating EN-DC, SRB0, 1 and 2 are LTE signalling bearers. SRB 3 is again optional and if not present the NR RRC messages are transferred on the X2 interface and piggybacked inside an LTE RRC message on SRB1.

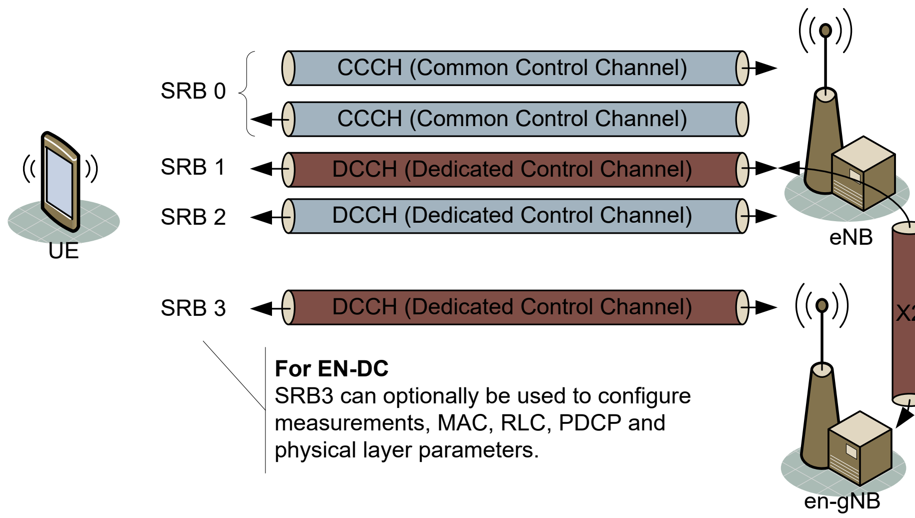


Figure 4-4 Signalling Radio Bearers (EN-DC Operation)

Traffic Channels

In 5G NR there is only one Traffic Channel:

- DTCH (Dedicated Traffic Channel) - this is a point to point channel that may exist in the uplink or downlink. It is part of the DRB (Data Radio Bearer) assigned to a device.

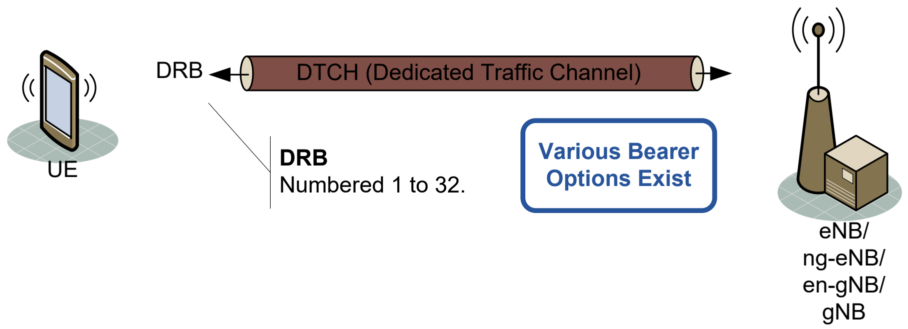


Figure 4-5 Dedicated Traffic Channels

4.1.2 Transport Channels

The 5G NR physical layer provides a transport service to the MAC layer. The physical layer service is dependent on the type and characteristics of the traffic to be transported over the air interface. The channels that offer these services are classified as Transport Channels.

- BCH (Broadcast Channel) - this is a broadcast channel which is part of the SS (Synchronization Signal) Block. It includes the MIB (Master Information Block).
- DL-SCH (Downlink - Shared Channel) - this channel supports dynamic scheduling and dynamic link adaptation by varying the antenna mapping, modulation, coding and resource/power allocation. In addition, it supports HARQ (Hybrid Automatic Repeat Request) operation to improve performance.
- PCH (Paging Channel) - this channel is used to carry the PCCH. It utilizes DRX (Discontinuous Reception) to improve the device's battery life.
- UL-SCH (Uplink - Shared Channel) - this is similar to the DL-SCH, supporting dynamic scheduling and dynamic link adaptation by varying the antenna mapping, modulation, coding and resource/power allocation. In addition, it supports HARQ (Hybrid Automatic Repeat Request) operation to improve performance. This channel also supports DTX (Discontinuous Transmission) for device power saving.
- RACH (Random Access Channel) - this channel carries limited information and is used in conjunction with Physical Channels and preambles (probes) to provide contention resolution procedures.

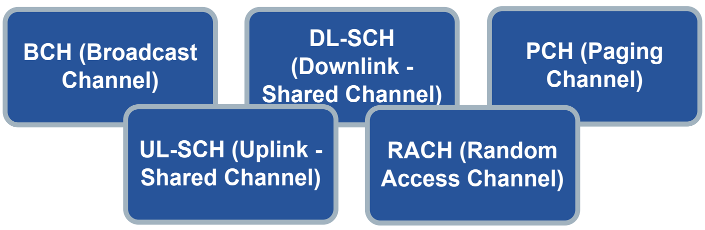


Figure 4-6 NR Transport Channels

4.1.3 Mapping Logical Channels into Transport Channels

To provide flexibility, as well as multiplexing multiple bearers together, Logical Channels may be mapped to one or more Transport Channels. These in turn are mapped into Physical Channels. This mapping is shown in Figure 4-7.

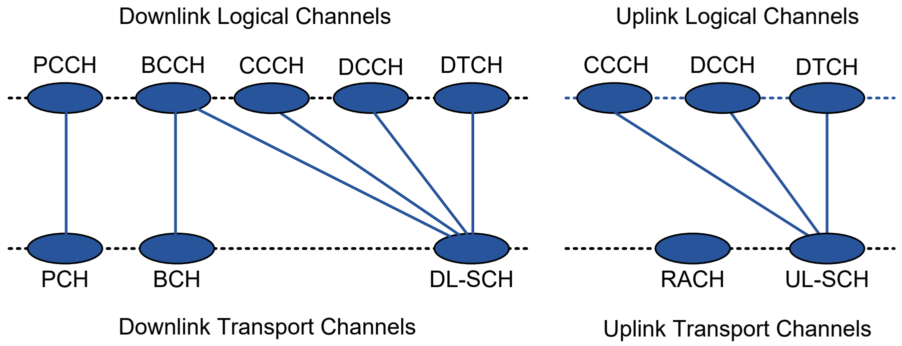


Figure 4-7 Mapping Logical Channels into Transport Channels

4.1.4 Physical Channels

The 5G NR physical layer defines various Physical Channels. The Physical Channels defined for the downlink are illustrated in Figure 4-8.

PBCH (Physical Broadcast Channel)	This is used to carry the BCH (Broadcast Channel) which includes the MIB (Master Information Block).
PDSCH (Physical Downlink Shared Channel)	This is used to deliver TB (Transport Blocks) from the various downlink transport channels. As such, it can carry both User Plane and Control Plane information.
PDCCH (Physical Downlink Control Channel)	This is used to carry the DCI (Downlink Control Information). In so doing, both downlink and uplink scheduling messages, as well as other control information can be sent.

Figure 4-8 NR Downlink Physical Channels

The physical channels defined for the uplink are illustrated in Figure 4-9.

PRACH (Physical Random Access Channel)	This is used by devices wanting to access a NR cell. It is also used as part of beam failure recovery procedures.
PUCCH (Physical Uplink Control Channel)	This is used to carry various feedback from the device to the gNB. The information is identified collectively as UCI (Uplink Control Information).
PUSCH (Physical Uplink Shared Channel)	This is used to deliver TB (Transport Blocks) from the various uplink transport channels. As such, it can carry both User Plane and Control Plane information. It also may include UCI.

Figure 4-9 NR Uplink Physical Channels

Control Formats

In order to assist the 5G scheduler the physical layer also defines DCI (Downlink Control Information) and UCI (Uplink Control Information).

DCI (Downlink Control Information)	Various DCI Formats are defined for both downlink and uplink resource allocation. In addition, specific DCI formats also exist for features related to slot format and power control.
UCI (Uplink Control Information)	UCI carries a combination of CSI (Channel State Information), ACK/NAK and/or SR (Scheduling Requests).

Figure 4-10 Control Formats

The DCI is carried in the PDCCH and various formats are used to enable both downlink and uplink scheduling. In contrast, the UCI is sent in the uplink in the PUCCH, or if the device is utilizing the PUSCH, UCI is multiplexed into that transmission.

4.1.5 Mapping Transport Channels to Physical Channels

The mapping of Transport Channels to/from Physical Channels is illustrated in Figure 4-11.

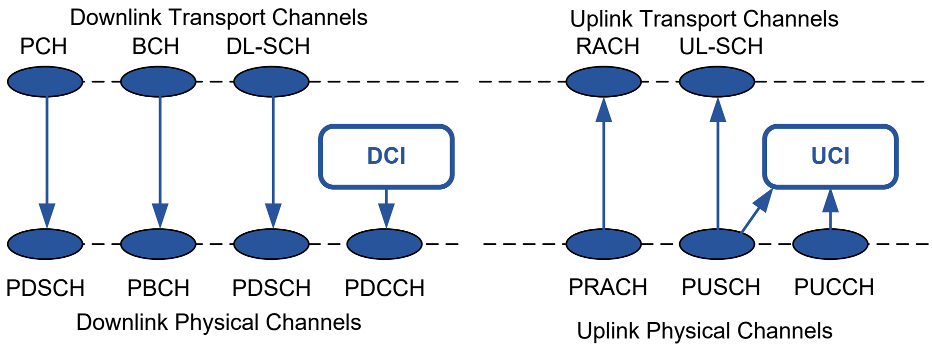


Figure 4-11 NR Transport to Physical Layer Mapping

In addition to carrying transport channels, PDCCH and PUCCH transport DCI (Downlink Control Information) and UCI (Uplink Control Information) respectively. In addition, the PUSCH is also able to multiplex UL-SCH and UCI. The DCI is used to schedule resources, e.g. the PDSCH or PUSCH, whereas the UCI carries feedback such as CSI (Channel State Information) or ACK/NACK, as well as device triggered SR (Scheduling Request).

4.1.6 Synchronization and Reference Signals

In addition to the various channels, the NR physical layer also defines SS (Synchronization Signal) and RS (Reference Signal). Figure 4-12 illustrates these, along with a brief description.

PSS (Primary Synchronization Signal)	This is a specific physical layer signal which assists in cell acquisition and synchronization. It carries part of the NR PCI (Physical Cell Identity).
SSS (Secondary Synchronization Signal)	This is a specific physical layer signal which, with the PSS, is used to determine the PCI. It also assists in radio frame synchronization.
CSI-RS (Channel State Information RS)	The CSI (Channel State Information) is part of a mechanism that enable a device to measure the radio channel and report back to the gNB.
DM-RS (Demodulation RS)	The Demodulation RS are used with the PBCH, PDSCH and PUSCH. They are used to assist in the decoding of the channel.
SRS (Sounding RS)	The uplink Sounding Reference Signal is sent by devices to enable the gNB to better evaluate the uplink. It can also be linked to uplink antenna switching.
PTRS (Phase Tracking RS)	This is activated when a combination of high order modulation and high frequencies (FR2) are being used. In so doing it combats the known issue of CPE (Common Phase Error).

Figure 4-12 NR Synchronization and Reference Signals

4.2 NR Physical Layer Processing

The various logical and transport channels are mapped to NR physical channels. However, depending on the physical channel various physical layer processing can be performed.

4.2.1 Key Specifications

Like LTE, the NR physical layer is very complex with many 3GPP specifications detailing the NR structure and operation. Figure 4-13 illustrates the main 3GPP specifications for the NR physical layer.

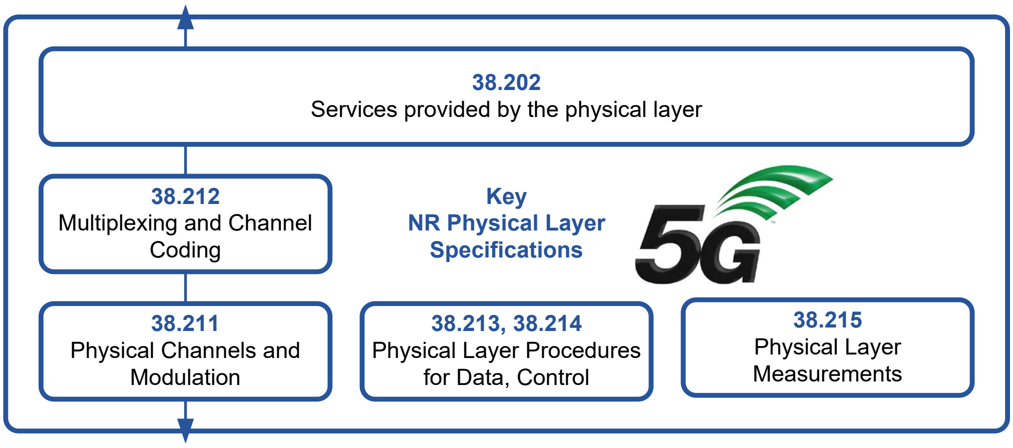


Figure 4-13 Key NR Physical Layer Specifications

The transport channel information arriving from the MAC layer is sent via two processes:

- Multiplexing and Channel Coding - this is typically referred to as “Code Block Generation”.
- Physical Channel and Modulation - this is typically referred to as the “Downlink Processing Chain” or “Uplink Processing Chain”.

4.2.2 Code Block Generation

Depending on the physical channel various processes are undertaken to ensure the TB (Transport Block) is correctly error protected and sized for a given allocation.

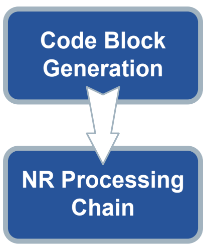


Figure 4-14 NR Physical Layer Processing

Figure 4-15 illustrates the basic terminology used to create a CB (Code Block). Note that some channels have a few extra processes/stages.

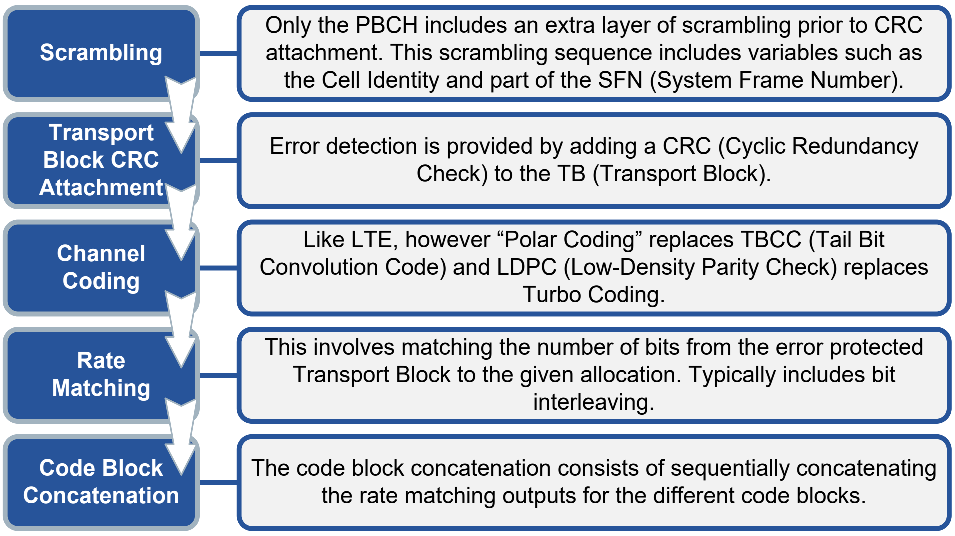


Figure 4-15 Code Block Generation

4.2.3 Code Block Group

Like LTE, 5G NR supports huge TB (Transport Blocks) which can be split into multiple CB (Code Blocks). In addition, 5G NR also defines a CBG (Code Block Group). As illustrated in Figure 4-16, multiple Code Blocks can be in a Code Block Group, with the maximum number of CBG's for a transport block being specified by RRC. The advantage of using Code Block Groups is that the system can indicate ACK/NACK and retransmission of data at the CBG level.

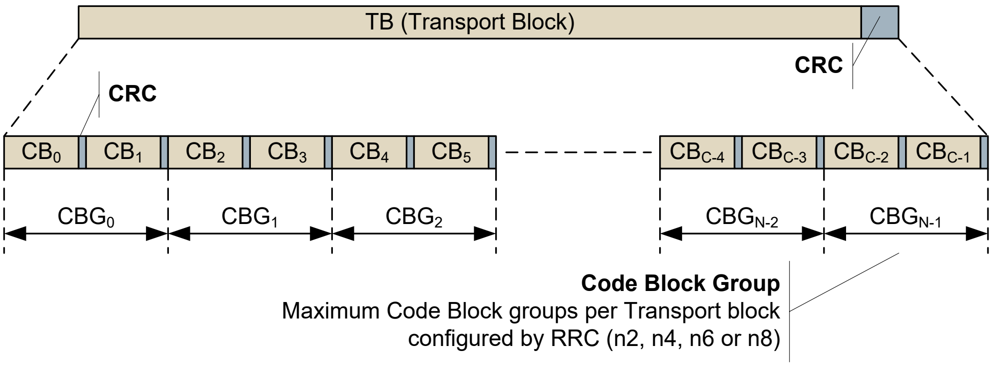


Figure 4-16 Code Block Group

4.2.4 Processing Chain

Depending on the channel type, as well as direction, the output from the Code Block Concatenation still needs to traverse through various stages before reaching the antenna ports. Figure 4-17 illustrates an example of the downlink processing chain. The stages include:

- Scrambling - as its name suggests, this scrambles the Code Block data. The purpose of this is to improve interference and minimize "bursts" in the transmission.
- Modulation Mapper - 5G NR supports various modulation schemes up to 256 QAM; as such the scrambled binary input is converted to a complex number sequence.
- Layer Mapper - 5G NR supports up to 8 layers (2 codewords) transmission. This is linked to the process of antenna port mapping.

- Resource Element Mapper - based on the antenna port number, VRB (Virtual Resource Blocks) are created which can then be mapped to PRB (Physical Resource Block), with or without interleaving.
- OFDM Signal Generation - the final stage is the creation of the OFDM (Orthogonal Frequency Division Multiplexing) signal.

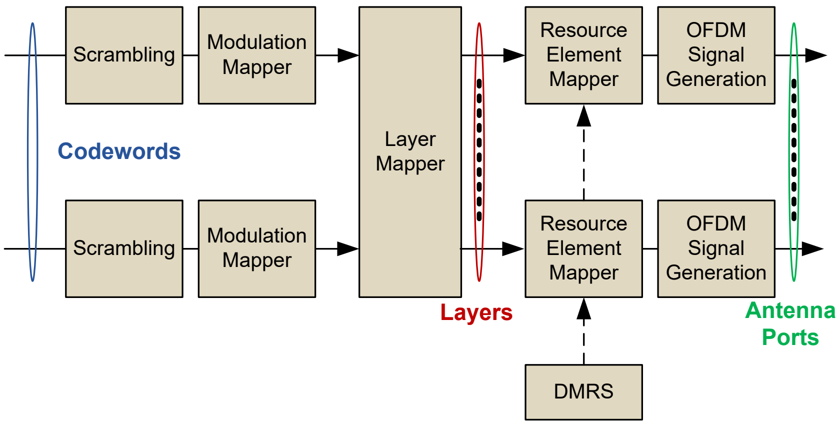


Figure 4-17 5G NR Downlink Processing Chain

Figure 4-18 illustrates an example of the uplink processing chain (CP-OFDM).

The main additions in the uplink are:

- Precoding - this provides an extra process related to mapping layers to the antenna ports.
- Transform Precoder - this is related to DFT-s-OFDM (Discrete Fourier Transform - spread - Orthogonal Frequency Division Multiplexing) transmission and therefore if active is performed prior to the precoding stage (not shown in Figure 4-18).

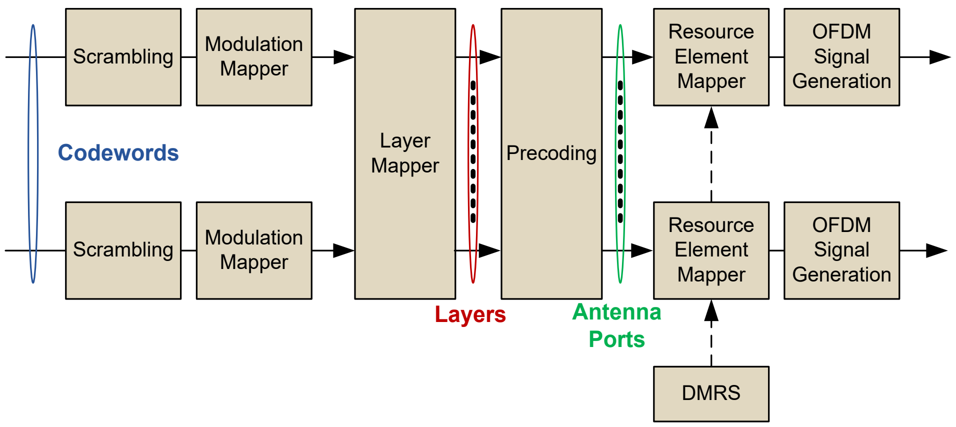


Figure 4-18 5G NR Uplink Processing Chain

5 NR Downlink Physical Channels and Signals

5.1 NR Downlink Synchronization Signals

The downlink in 5G NR is based on CP-OFDM with the channel being scalable. However, initially the device may be unaware of the downlink cell configuration. Consequently, synchronization and cell identity information must appear on the downlink in a consistent place irrespective of the radio spectrum configuration. The two synchronization signals are the PSS (Primary Synchronization Signal) and SSS (Secondary Synchronization Signal). These provide symbol synchronization, as well as being utilized to derive the N_{ID}^{Cell} (Cell Identity), which is between 0 and 1007. This is also known as the PCI (Physical Cell Identity).

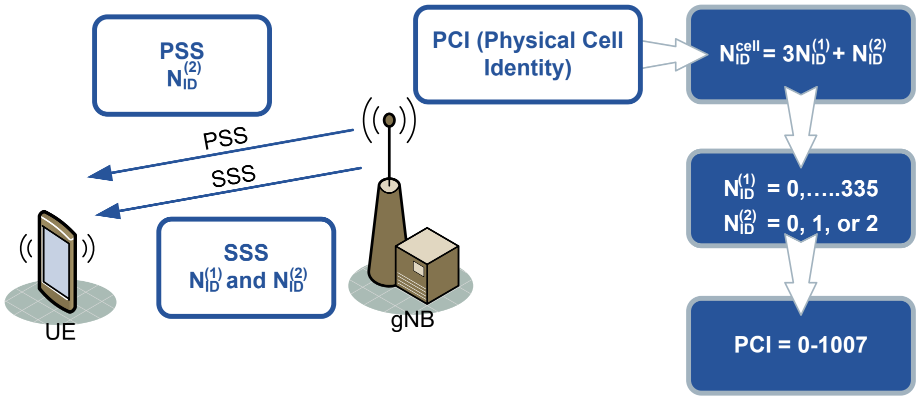


Figure 5-1 Downlink Synchronization Signals

The PSS can be used to derive $N_{ID}^{(2)}$, whereas decoding the SSS enables the device to determine both $N_{ID}^{(1)}$ and $N_{ID}^{(2)}$. The device requires these to correctly decode the PBCH (Physical Broadcast Channel), as well as to identify the location of the PBCH DMRS (Demodulation Reference Signal). Note that the beam identification, also known as the SS (Synchronization Signal) Block Index, is linked to the DMRS sequence, and in some cases the PBCH scrambling sequence.

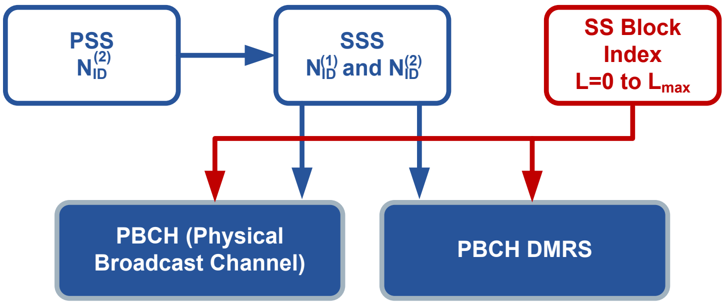


Figure 5-2 Using the PSS and SSS

Together the PSS, SSS, PBCH and PBCH DMRS are sent on antenna port 4000.

5.1.1 PSS and SSS

The PSS, SSS and PBCH are transmitted as a SSB (SS/PBCH Block), as illustrated in Figure 5-3.

The PSS is made up of a 127 m-Sequence which includes $N_{ID}^{(2)}$ as part of the sequence generation. This maps to the 127 subcarriers, with the remaining subcarrier "set to 0".

Similarly, the SSS is also a 127 m-Sequence and is mapped to the same 127 subcarriers, however is 2 symbols later. It is generated using both $N_{ID}^{(1)}$ and $N_{ID}^{(2)}$.

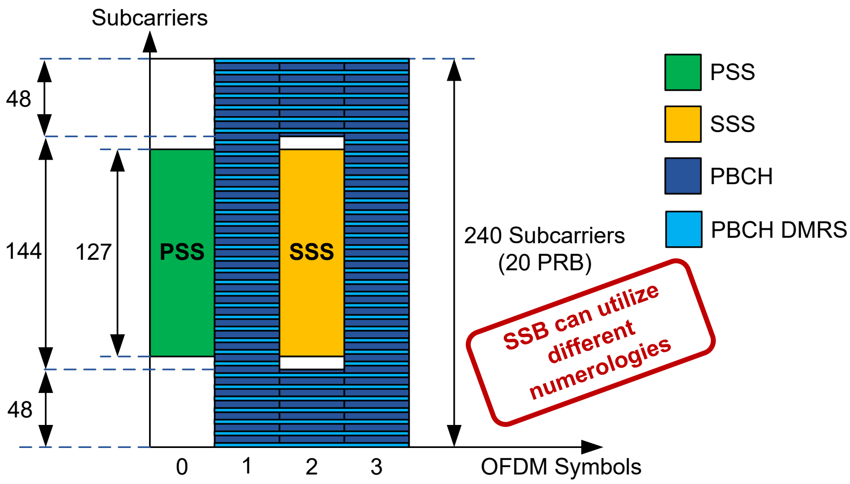


Figure 5-3 SS Block

Figure 5-4 illustrates an example of a 50MHz carrier with a large number of PRB (Physical Resource Block), these are numbered from 0 in terms of a CRB (Common Resource Block). In this example, a 30kHz SCS (Sub Carrier Spacing), i.e. μ=1, is being show with 4 SSB Beams (L=0 to 3). Note that the position of the SS/PBCH doesn't have to be on the centre frequency, in fact it occurs on a raster based on the GSCN (Global Synchronization Channel Number). In addition, the periodicity of the SS/PBCH can be as little as every 5ms, however the default is 20ms.

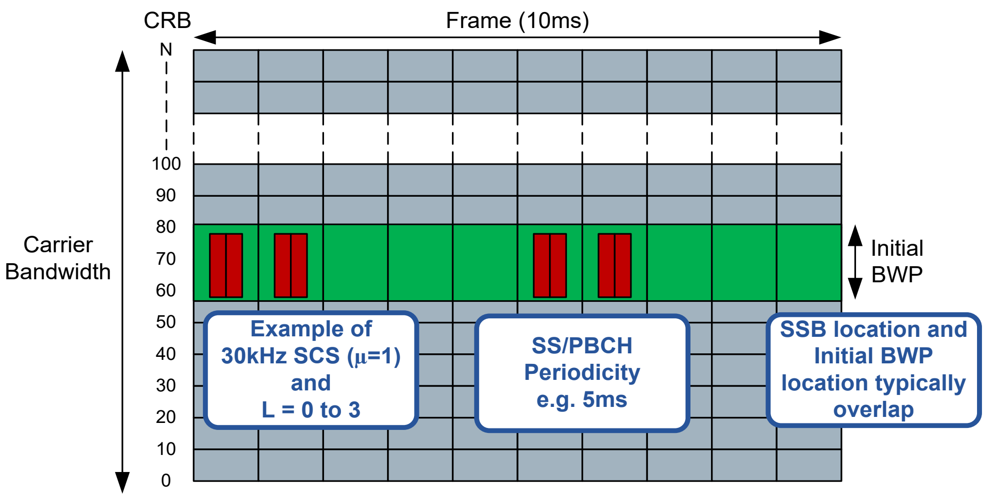


Figure 5-4 SSB Location Example

The SSB is typically co-located near to the Initial BWP (Bandwidth Part). The example illustrated in Figure 5-4 includes the SSB (20 PRBs) and an Initial BWP of 24 PRBs highlighted in green. The Initial BWP location/offset is identified in the MIB (Master Information Block) which is carried by the PBCH. A device then monitors the Initial BWP for the RMSI (Remainder Minimum System Information). It is worth noting that the SSB PRB location can be offset from the CRB mapping. As such the PBCH includes an indication of K_{SSB} (SSB Subcarrier Offset), which depending on various configurations may be multiples of 15kHz or 60kHz.

5.2 NR Physical Broadcast Channel

The main role of the PBCH is to transport the MIB (Master Information Block), with data arriving at the coding unit as one transport block every 80ms. In addition to the MIB payload (24bits), L1 (Layer 1) Information is also included.

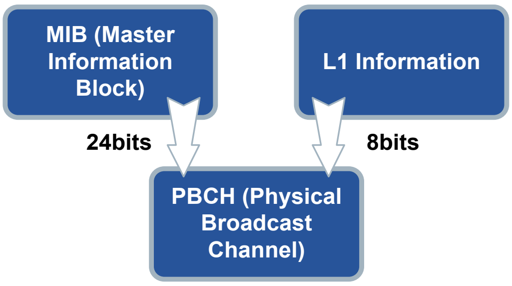


Figure 5-5 Physical Broadcast Channel

5.2.1 Master Information Block

Figure 5-8 illustrates the various parameters of the MIB.

Field	Size (bits)	Description
MSB SFN	6	MSB 10bit SFN
subCarrierSpacingCommon	1	15kHz/30kHz or 60kHz/120kHz for SIB1
ssb-subcarrierOffset	4	LSB's of K_{SSB}
dmrs-TypeA-Position	1	{pos2, pos3} for PDSCH
pdcchConfigSIB1	8	(0..255) RMSI CORESET
cellBarred	1	{barred, notBarred}
intraFreqReselection	1	{allowed, notAllowed}
Spare	2	Reserved

Figure 5-6 MIB Payload

Key parameters include:

- systemFrameNumber - this 6bit parameter identifies the MSB (Most Significant Bits) of the current 10bit SFN (System Frame Number).
- subCarrierSpacingCommon - this indicates the SCS (Subcarrier Spacing) for SIB1, initial access messages and broadcast SI (System Information) messages. If the device acquires this MIB on a carrier frequency <6GHz, the values 15kHz and 30kHz are applicable. If the device acquires this MIB on a carrier frequency >6GHz, the values 60kHz and 120kHz are applicable.
- ssb-SubcarrierOffset - also known as K_{SSB}, this is the frequency domain offset between SSB and the overall resource block grid in number of subcarriers. Note: this field only includes the 4 LSB (Least Significant Bits).
- dmrs-TypeA-Position - this defines the position of (first) downlink DMRS, identified as pos2 or pos3, i.e. symbol 2 or symbol 3.
- pdcch-ConfigSIB1 - this determines a bandwidth for PDCCH/SIB, a common CORESET (Control Resource Set), a common search space

and necessary PDCCH parameters. It relates to finding the RMSI (Remaining Minimum System Information), i.e. SIB1.

- cellBarred - this is an indication on whether the cell is barred or not.
- intraFreqReselection - this controls cell reselection to intra-frequency cells when the highest ranked cell is barred or treated as barred by the device.

5.2.2 PBCH Payload

In addition to the MIB, the PBCH payload also includes additional Layer 1 timing information, as well as possible beam extension bits for the SS/PBCH Block Index and K_{SSB}. Figure 5-7 illustrates the mapping of these additional 8bits.

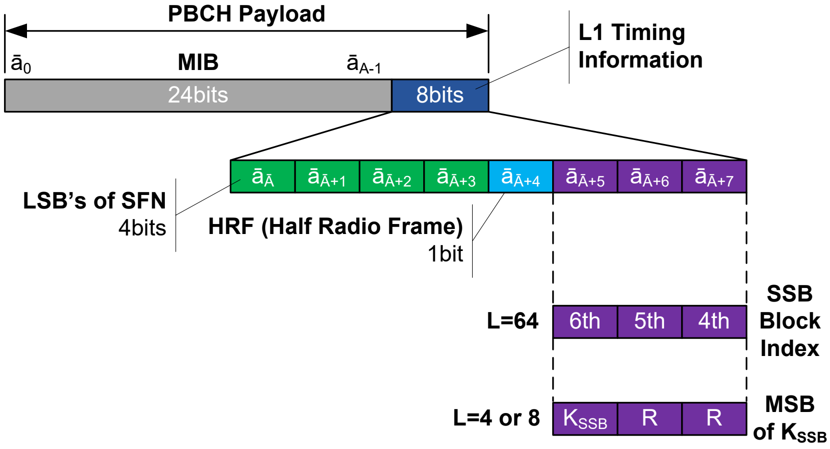


Figure 5-7 PBCH L1 Timing Information

In terms of Layer 1 timing information, the 4 LSBs of the SFN are included, as well as the HRF (Half Radio Frame) bit. The encoding of the last 3 bits varies depending on the maximum number of beams. If L=64, then the 3 bits are used to represent the 6th, 5th and 4th bits of the SS/PBCH Block Index. These would be needed to represent up to 64 beams indexes. However, if L=4 or 8, then only one bit from the final 3 is required. This will be used to encode the MSB of the K_{SSB} parameter (which goes with the 4 LSBs been included in the MIB).

5.2.3 PBCH Physical Layer Processing

Prior to the PBCH Payload being processed the MIB (24bits) and PBCH Timing Information (8bits) are interleaved, before passing via various physical layer processing stages:

- Scrambling - this process includes scrambling based on the PCI, as well as the inputs related to the SFN and L_{max} parameters.
- CRC Attachment - the PBCH utilizes a 24bit CRC (Cyclic Redundancy Check).
- Polar Coding - this provides the necessary channel coding for the channel.
- Rate Matching - this ensures the output is 864 bits.
- Scrambling - this provides bit stream scrambling using the LSBs of the SS/PBCH Block Index.
- Modulation - this is based on QPSK (Quadrature Phase Shift Keying). The 864bits require 432 symbols.

- Resource Element Mapping - the final stage is mapping the PBCH onto the correct RE (Resource Elements).

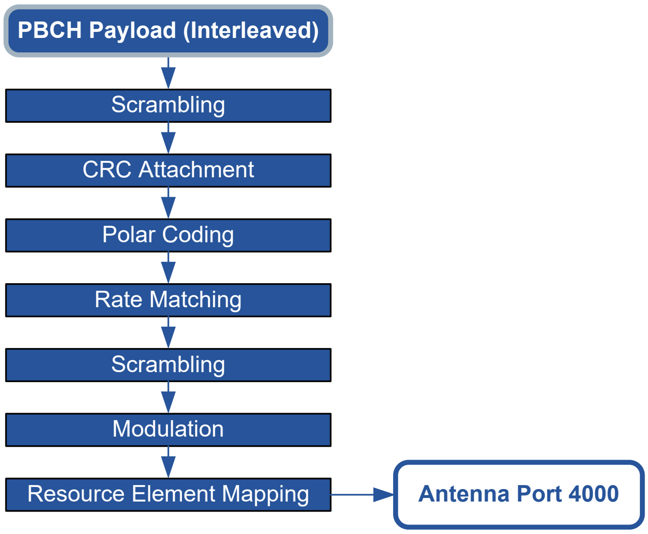


Figure 5-8 PBCH/MIB Processing

5.2.4 DMRS for PBCH

NR does not include cell reference signals like LTE. As such, the PBCH, PDSCH and PUSCH require their own DMRS. For the PBCH, the DMRS is mapped into one of four locations based on a mod4 shift related to the N_{ID}^{Cell}. A total of 144 symbols related to the PBCH DMRS are utilized. Figure 5-9 illustrates this concept, were $\mathcal{V}$ = 0, as well as illustrating the other positions available.

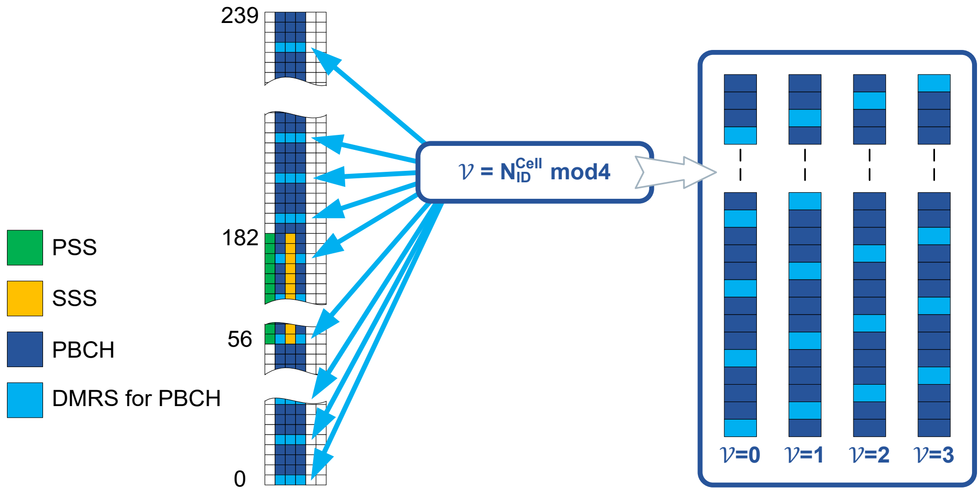


Figure 5-9 DMRS Location for PBCH

5.3 NR Physical Downlink Control Channel

The PDCCH carries the DCI (Downlink Control Information), i.e. the resource allocation. It is scheduled based on a RNTI (Radio Network Temporary Identifier). As illustrated in Figure 5-10, the DCI is mapped into 1 or more CCE (Control Channel Elements), with each CCE consisting of 6 REG (Resource Element Groups). Each REG equates to 1 PRB (12 subcarriers) x one OFDM symbol.

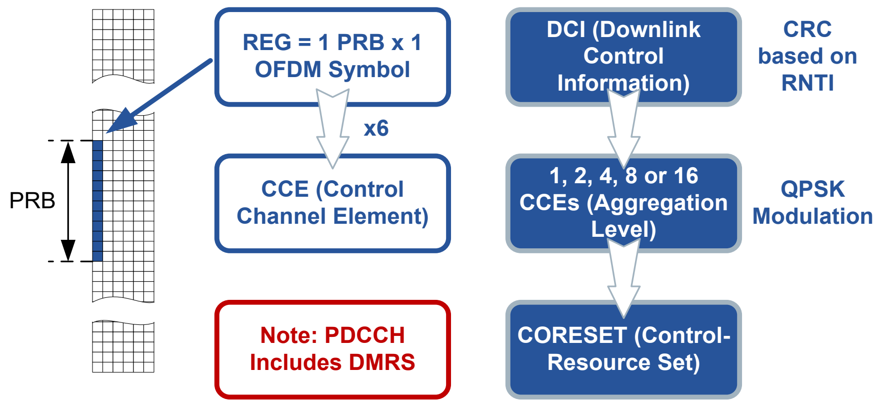


Figure 5-10 PDCCH Mapping

The CCE aggregation levels (1, 2, 4, 8 or 16) define the possible grouping for large DCI formats, with higher aggregation levels providing more error protection. These pre-defined aggregation levels enable devices to search for potential DCI formats/messages, since each includes a CRC which has been scrambled based on a RNTI. This is sometimes referred to as "masking with the RNTI".

5.3.1 PDCCH Physical Layer Processing

Figure 5-11 illustrates the physical layer processing stages for the PDCCH. It includes the CRC attachment linked to the RNTI, as well as channel coding, in the form of Polar Coding. Once the coded data is rate matched to the correct number of bits it is then scrambled based on a combination of RNTI and PCI.

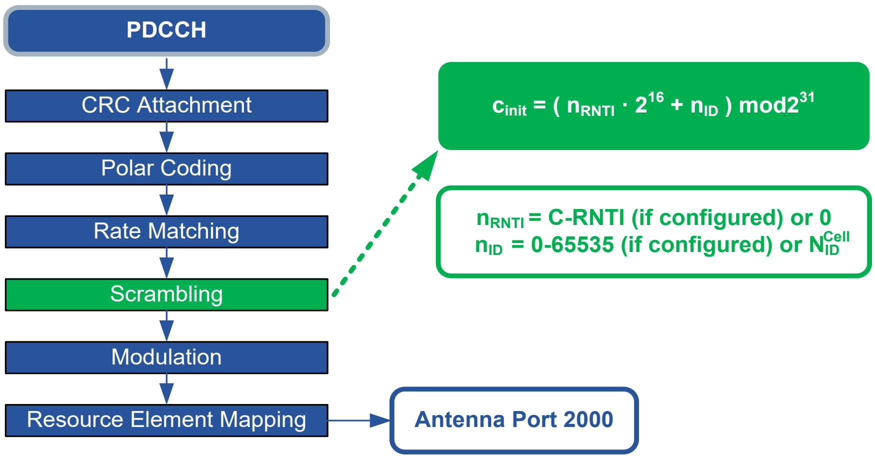


Figure 5-11 Scrambling for PDCCH

The scrambled information is the modulated (QPSK) and mapped to Resource Elements on antenna port 2000.

5.3.2 PDCCH Features

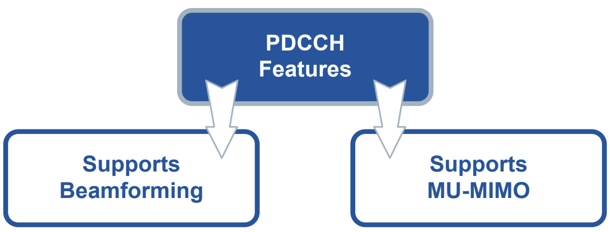


Figure 5-12 PDCCH Features

It is also worth noting that the PDCCH supports beamforming and MU-MIMO (Multi-User MIMO).

PDCCH Beamforming

Figure 5-13 illustrates the basic concept of PDCCH beamforming. When the PDCCH contains scheduling information for multiple devices, e.g. broadcast or paging information, the PDCCH beamwidth needs to be wider than if the PDCCH was related to a UE-Specific.

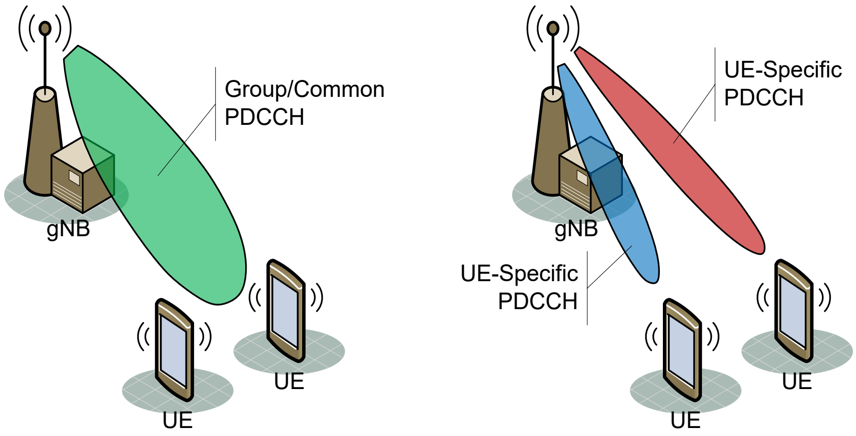


Figure 5-13 Beamforming PDCCH

PDCCH MU-MIMO

MU-MIMO is supported on the NR PDCCH using non-orthogonal DMRS. These are not ideal for inter-layer interference however the higher layers are able to allocate devices different scrambling identities (pdcch-DMRS-ScramblingID), as illustrated in Figure 5-14.

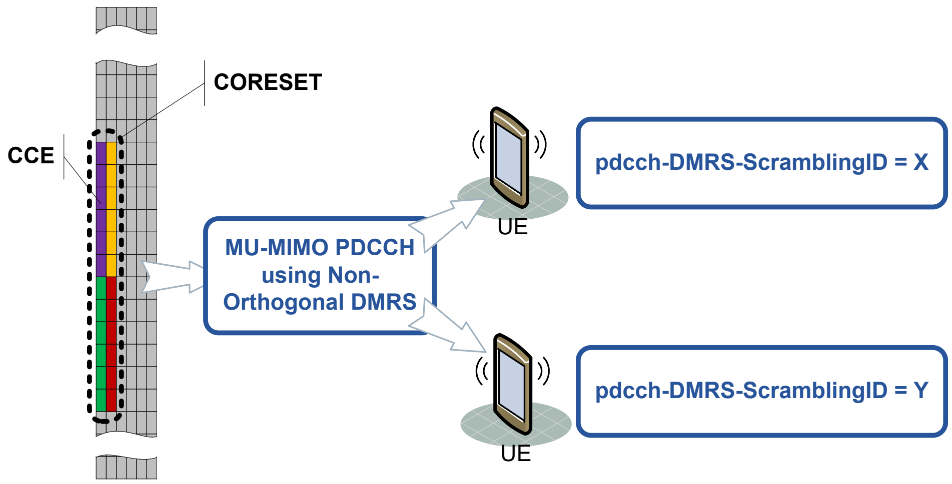


Figure 5-14 PDCCH MU-MIMO

5.3.3 CORESET

In addition to a CCE, 5G NR defines a CORESET (Control-Resource Set) for the PDCCH. This consists of frequency domain resource blocks, given by the higher-layer parameter “frequencyDomainResources”. This is a bitmap for the BWP (Bandwidth Part), with each bit relating to 6REGs. In the time domain, the higher-layer parameter “duration”, defines 1, 2 or 3 symbols. Note that the duration of 3 symbols (symbols 0, 1, and 2) is only supported if the DL-DMRS-typeA-pos equals 3, i.e. the position of the downlink DMRS is in symbol 3 and therefore does not impact the CORESET.

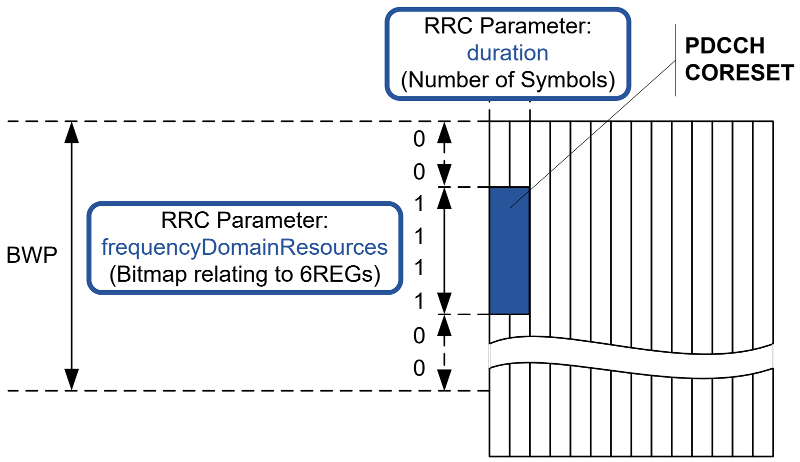


Figure 5-15 CORESET

5.3.4 CORESET Configuration

The CORESET is configured per BWP. Figure 5-16 illustrates an example of the BWP and the PDCCH configuration. Note that depending on the scenario, there are various places for these parameters, for example similar information can be found as part of the initialDownlinkBWP or downlinkBWP-ToAddModList parameters. In addition, note that both “Common” and “Dedicated” PDCCH Configurations exist.

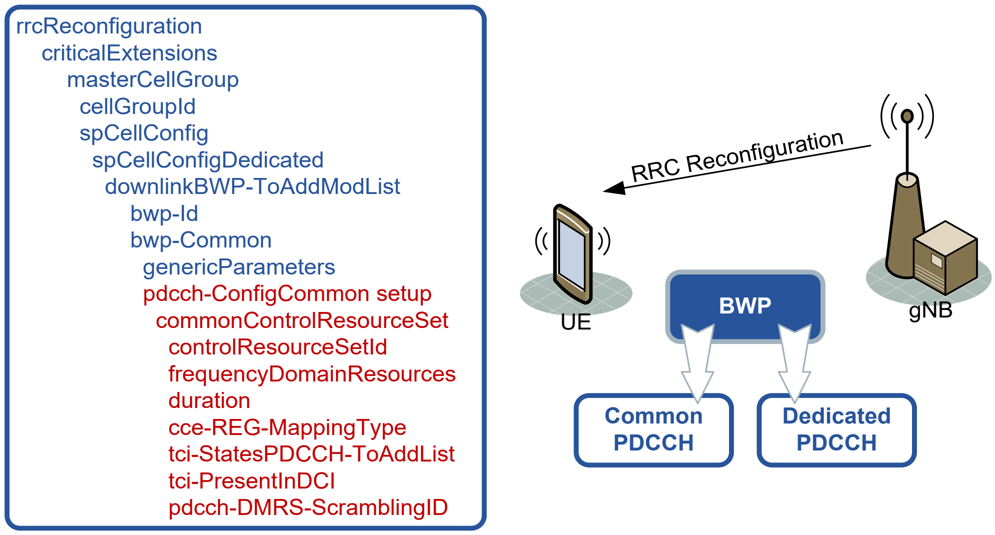


Figure 5-16 CORESET Configuration (Common Setup)

5.3.5 CORESET Configuration for EN-DC

For EN-DC operation, once the device has the E-UTRA SRB established, a LTE RRC Connection Reconfiguration message can be sent to the device which includes a NR RRC Reconfiguration message, however this is embedded in the nr-Config-r15 parameter as illustrated in Figure 5-17. It also illustrates how the parameters are passed to the device via the X2 interface. Note that parameters nr-Config-r15 and nr-RadioBearerConfig-r15 are used in different EN-DC procedures. In some scenarios, one of these parameters is used. However, in other scenarios both parameters may be used.

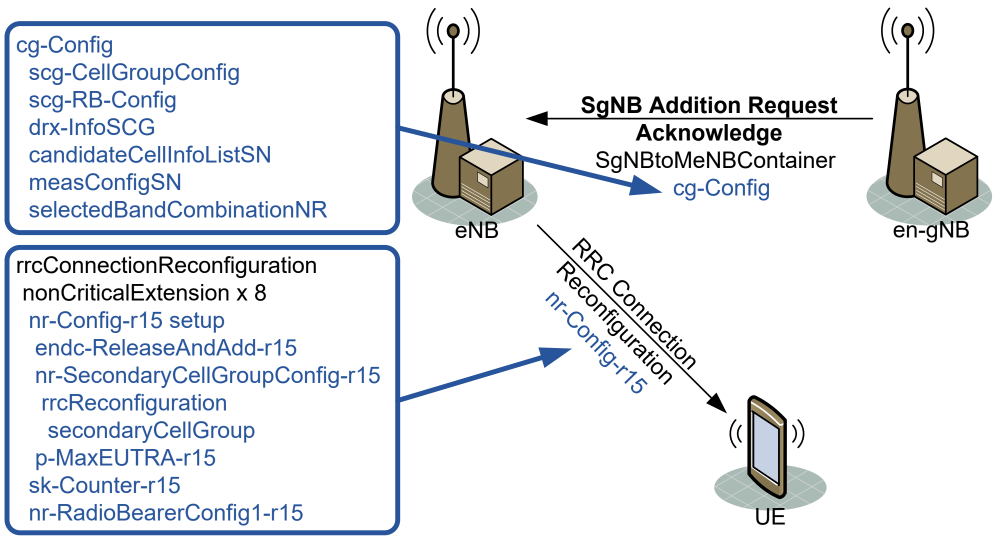


Figure 5-17 NR Parameters in E-UTRA RRC

Figure 5-18 illustrates an example location of the BWP and the PDCCH configuration.

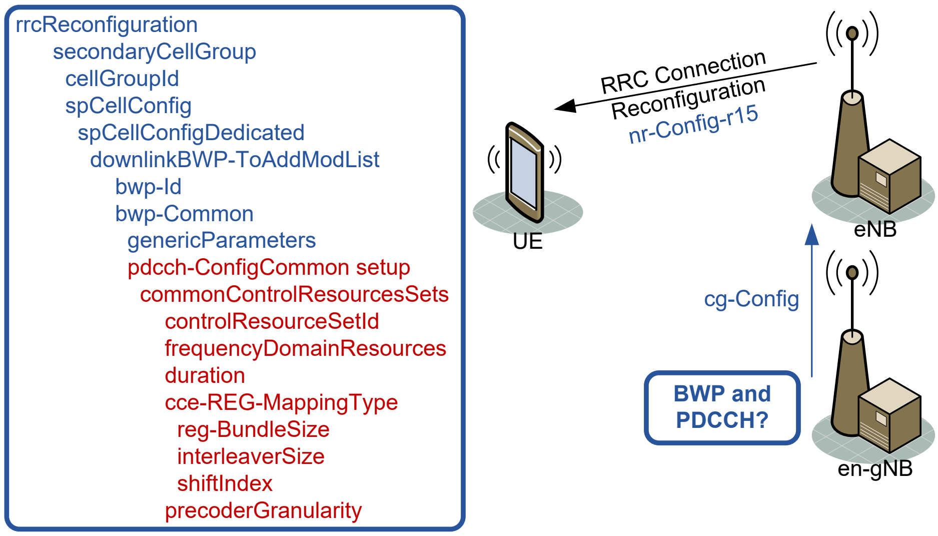


Figure 5-18 CORESET Configuration (via SRB1)

5.3.6 Other PDCCH Usages

In addition to normal scheduling, the PDCCH can also be utilized to switch slot formats and trigger pre-emption.

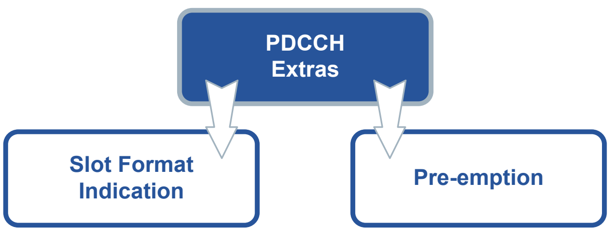


Figure 5-19 PDCCH Extras

PDCCH for SFI (Slot Format Indication)

The system may also configure a group PDCCH for a cell. This is to indicate the SFI (Slot Format Indication) index, which maps to a slot format combination previously defined to the device. Figure 5-20 illustrates an example of a slot format, as well as a separate example with two slot format combinations, e.g. 0+28 for high downlink usage and 34+1 for high uplink usage.

Note that up to 256 slot formats can be concatenated to create a slot format combination. With the slot format combination identity (SFI index) ranging from 0 to 4095.

In addition to configuring the slot format combinations on a cell, the system will also allocate a SFI-RNTI (Slot Format Indication RNTI). This will be utilized on the PDCCH using a specific format (Format 2_0).

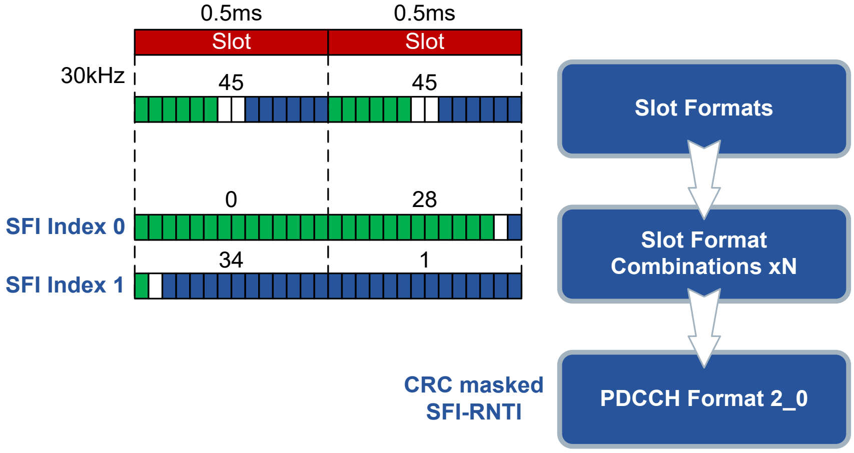


Figure 5-20 Slot Format Indicator

5.3.6.1 PDCCH for Pre-emption

The system may also configure a PDCCH for downlink pre-emption indications in a cell. Figure 5-21 illustrates the main downlink pre-emption setup parameters configured by a NR RRC Reconfiguration message.

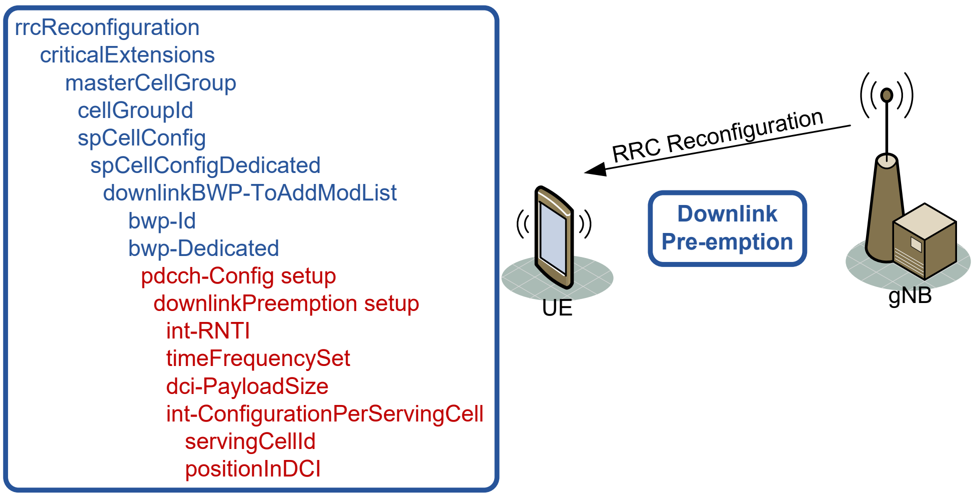


Figure 5-21 PDCCH for Pre-emption

If configured, the device will be provided with an INT-RNTI (Interruption RNTI) which enables it to monitor the PDCCH conveying DCI Format 2_1. The timeFrequencySet parameter indicates set0 or set1 which corresponds to how the 14bits per cell are interoperated, as seen in Figure 5-22. In this example there are 2 serving cells in the “Set of Serving Cells”, each is given a “positioninDCI” - which will be in multiples of 14bits. Each of the 14bits for a serving cell then carries a bitmap to the corresponding symbol group and possible PRB subset.

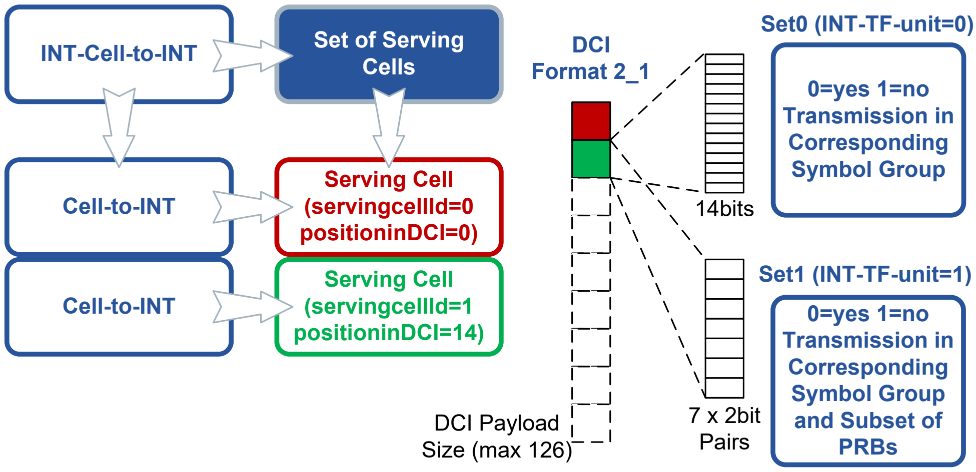


Figure 5-22 DCI Format 2_1

5.4 NR Physical Downlink Shared Channel

The NR PDSCH is used to deliver Transport Blocks from the gNB to the device. Figure 5-23 illustrates the main physical layer processes that are performed. Most of these are like LTE PDSCH, however they differ in the fine detail. In addition, the NR PDSCH utilizes LDPC (Low-Density Parity Check) coding instead of the Turbo Coding used by LTE.

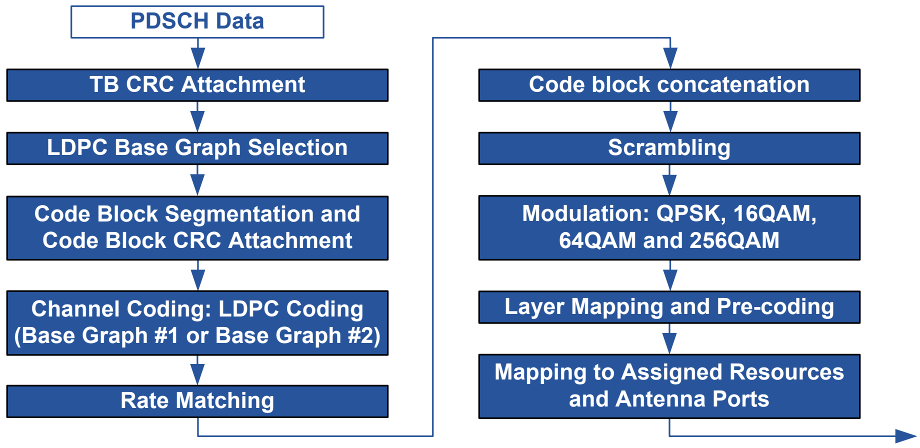


Figure 5-23 PDSCH Physical Layer Processing

The PDSCH is configured using RRC signalling, namely the PDSCH-Config parameter. This is included as part of the InitialDownlinkBWP or BWP-DownlinkDedicated parameters. In addition, there are limited PDSCH configuration details included as part of the PDSCH-ConfigCommon parameter.

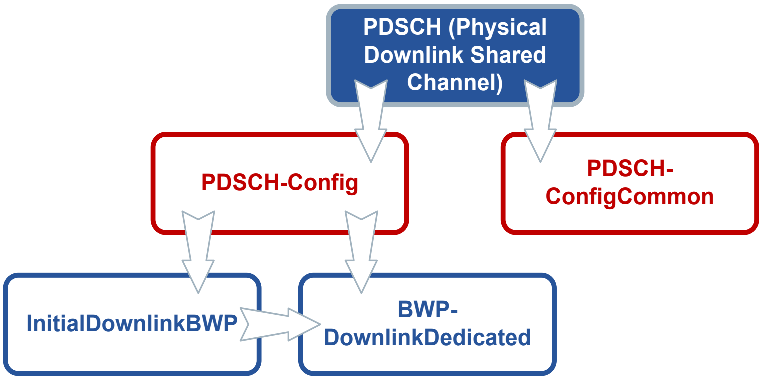


Figure 5-24 Configuring PDSCH

The PDSCH-Config parameter itself contains many other parameters. These are highlighted in Figure 5-25.

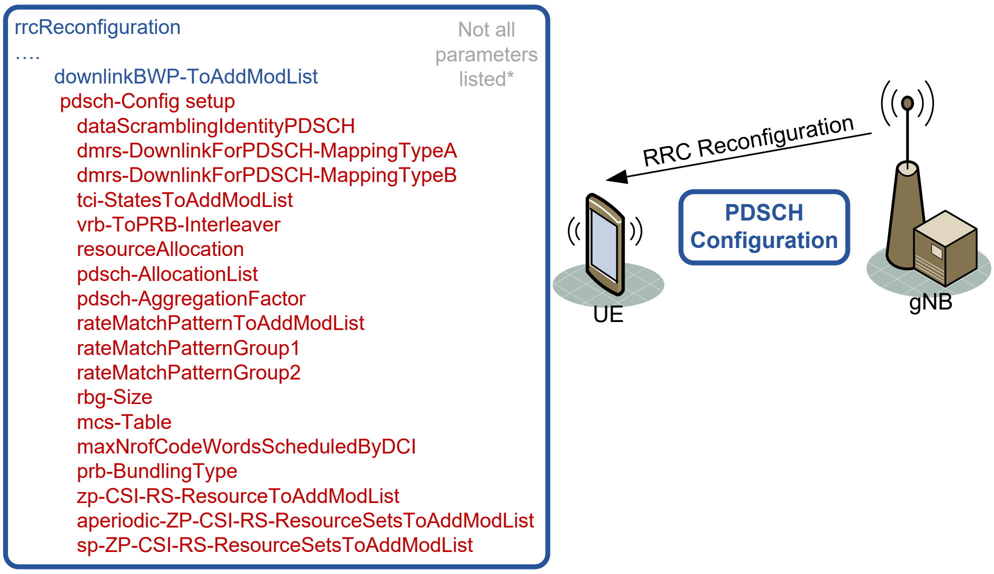


Figure 5-25 PDSCH Configuration Setup (Dedicated)

There are many other parameters related to the PDSCH, however the main ones highlighted include:

- dataScramblingIdentityPDSCH - this is an identifier used to initiate data scrambling (c_init) for PDSCH.
- dmrs-DownlinkForPDSCH-MappingTypeA - this is the DMRS configuration for PDSCH transmissions using PDSCH mapping type A.
- dmrs-DownlinkForPDSCH-MappingTypeB - this is the DMRS configuration for PDSCH transmissions using PDSCH mapping type B.
- tci-StatesToAddModList - this is a list of TCI (Transmission Configuration Indicator) states for dynamically indicating (over DCI) a transmission configuration which includes QCL (Quasi Co-Location) relationships between the DL RSs in one RS set and the PDSCH DMRS ports.
- vrb-ToPRB-Interleaver - this indicates the interleaving unit and is configurable between 2 and 4 PRBs.
- resourceAllocation - this relates to the configuration of resource allocation type 0 and resource allocation type 1 for non-fallback DCI.

- pdsch-AllocationList - this is a list of time domain configurations for timing of DL assignment to DL data. If configured, these values override the values received in corresponding PDSCH-ConfigCommon.
- pdsch-AggregationFactor - this indicates the number of repetitions for data.
- rateMatchPatternToAddModList - this defines the resource patterns which the device should rate match PDSCH around.
- rateMatchPatternGroup1 - this parameter relates to Rate Matching.
- rateMatchPatternGroup2 - this parameter relates to Rate Matching.
- rbg-Size - this provides a selection between “config 1” and “config 2” for RBG (Resource Block Group) size for PDSCH, i.e. part of resource allocation.
- mcs-Table - this indicates which MCS (Modulation and Coding Scheme) table the device should use for the PDSCH (QAM64 or QAM256).
- maxNrofCodeWordsScheduledByDCI - maximum number of code words that a single DCI may schedule. This changes the number of MCS/RV/NDI bits in the DCI message from 1 to 2.
- prb-BundlingType - indicates the PRB bundle type and bundle size(s). If "dynamic" is chosen, the actual BundleSizeSet to use is indicated via DCI.
- zp-CSI-RS-ResourceToAddModList - this is a list of ZP (Zero Power) CSI-RS resources used for PDSCH rate-matching.
- aperiodic-ZP-CSI-RS-ResourceSetsToAddModList - this identifies CSI-RS parameters which are scheduled by the DCI.
- sp-ZP-CSI-RS-ResourceSetsToAddModList - this identifies CSI-RS parameters which are scheduled by the MAC CE (Control Element).

5.4.1 PDSCH DMRS

The NR PDSCH utilizes front loaded DMRS symbols which are beneficial in terms of improving low latency operation, as well as MIMO. However, there are many configuration options and permutations.

Firstly, there are two DMRS types defined, namely: Type A and Type B. These are configured as part for the PDSCH configuration (Dedicated or Common) and relate to a slot based or non-slot based mapping.

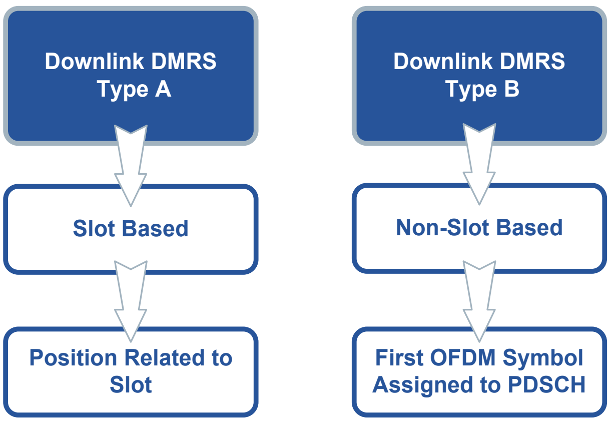


Figure 5-26 Downlink DMRS Types

Figure 5-27 illustrates the key parameters that are utilized for DMRS configuration.

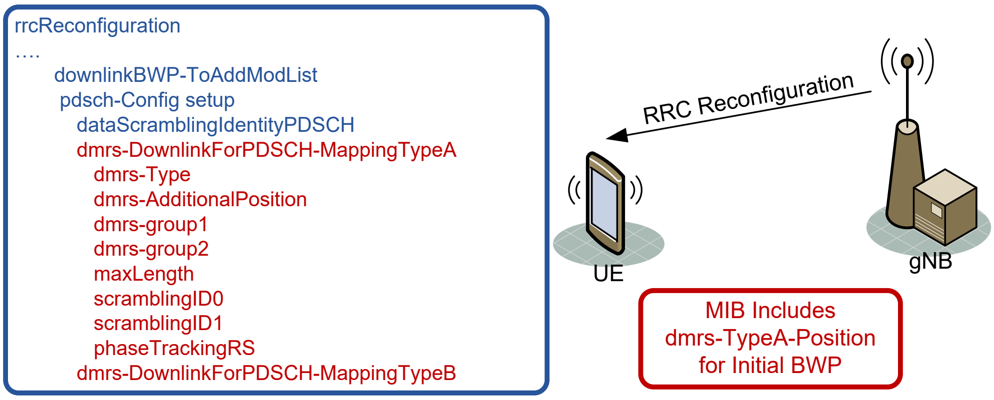


Figure 5-27 DMRS Configuration Parameters

These include:

- dmrs-Type - this can indicate type 2. If the field is absent, the device uses DMRS type 1.
- dmrs-AdditionalPosition - four values represent the cases of 1+0, 1+1, 1+1+1, 1+1+1+1 non-adjacent OFDM symbols for DL. If the field is absent, the device applies the value “pos2”.
- dmrs-group1 - DMRS groups that are Quasi Co-Located, i.e. group 1.
- dmrs-group2 - DMRS groups that are Quasi Co-Located, i.e. group 2.
- maxLength - the maximum number of OFDM symbols for DL front loaded DMRS. “len1” or “len2” corresponds to symbols. If the field is absent, the device applies value “len1”.
- scramblingID0 - DL DMRS scrambling initialization. When the field is absent the device applies the value Physical Cell ID configured for this serving cell. Relates to a physical parameter n_SCID 0.
- scramblingID1 - DL DMRS scrambling initialization. When the field is absent the device applies the value Physical Cell ID configured for this serving cell. Relates to a physical parameter n_SCID 1.
- phaseTrackingRS - configures downlink PTRS (Phase Tracking RS).

In addition, the device will also receive the “dmrs-TypeA-Position” parameter in the MIB. This identifies the position of the (first) downlink DM-RS and can be set to “pos2” or “pos3”. Figure 5-28 illustrates the difference between Type A (which can be in symbol 2 or 3) and Type B, which is always at the start of the PDSCH resource allocation.

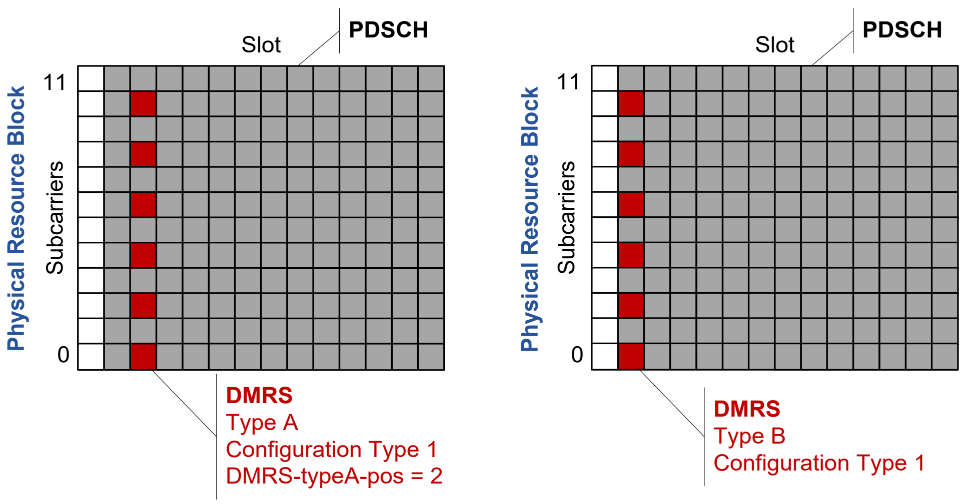


Figure 5-28 DMRS Type A vs Type B

In addition to specifying Type A or B, there is also a configuration type, which is illustrated in Figure 5-29 for Type A.

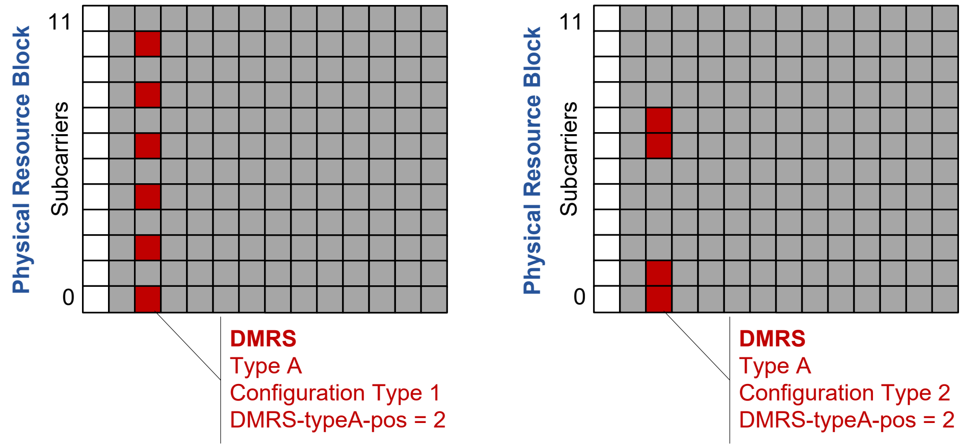


Figure 5-29 PDSCH DRMS Configurations (Type A)

It is also possible to extend, as well as add more DMRS. This is typically done for specific scenarios, e.g. high speed or certain environments. Utilizing more DMRS impacts the amount of Resource Elements for the PDSCH, i.e. reduces the throughput.

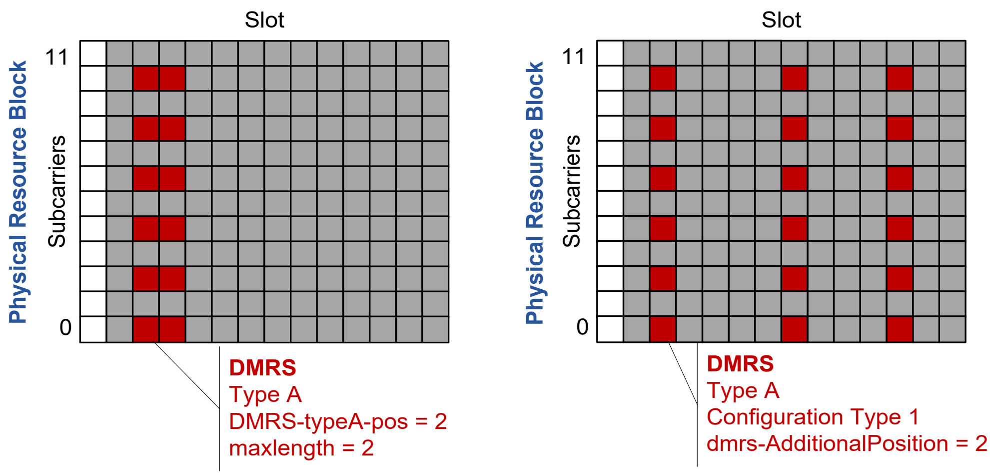


Figure 5-30 Additional DMRS Configuration Examples

6 NR Uplink Physical Channels

6.1 NR Physical Random Access Channel

Like LTE, there are three uplink physical channels.

Figure 6-1 NR Uplink Physical Channels

The main role of the NR PRACH (Physical Random Access Channel) is to transport the NR PRACH preamble sequences, with the maximum number of NR PRACH sequences for a cell set to 64. Various configuration parameters define which can be used and where/how they can be sent by the device. To ensure that each cell has a different set of 64 sequences, there is a defined process to generate them.

6.1.1 Preamble Sequence Generation

Initially, the device generates a Zadoff Chu sequence using a NR PRACH rootSequenceIndex; this is sometimes referred to as the base sequence. The NR PRACH rootSequenceIndex value is sent by the cell as part of the PRACH/RACH configuration parameters for a BWP. Next, the 64 different sequences are generated by performing a cyclic shift of the base sequence, with the cyclic shift interval determined by a parameter Ncs. Unfortunately, the Ncs value is determined from various lookup tables which require the other parameters, specifically: zeroCorrelationZoneConfig, PRACH SCS, as well as the use of an Unrestricted Set or Restricted Set (Type A or B).

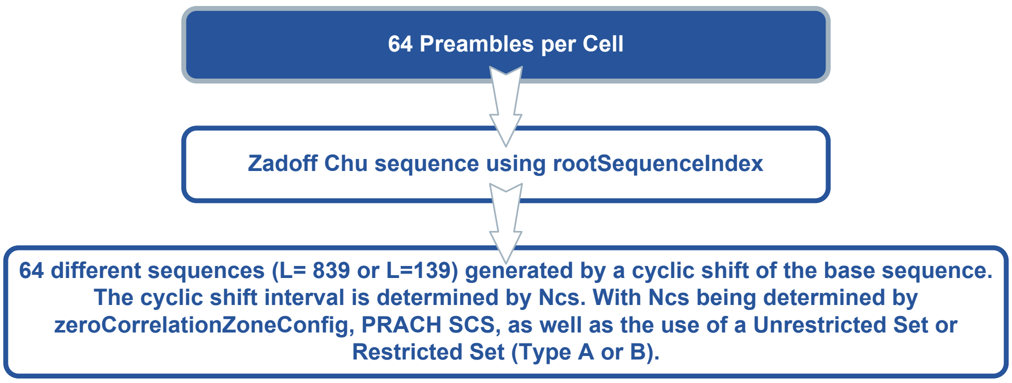


Figure 6-2 NR PRACH Preamble Generation

6.1.2 Configuring RACH/PRACH

The RACH/PRACH parameters will be obtained by the device from reading SIB1 (System Information Type 1) or as BWP Common parameters. Figure 6-3 illustrates an example of the key parameters included as part of the RACH configuration. Note that the RACH Configuration Common parameter can be sent nested in other parameters; the main one is identified as “reconfigurationWithSync”.

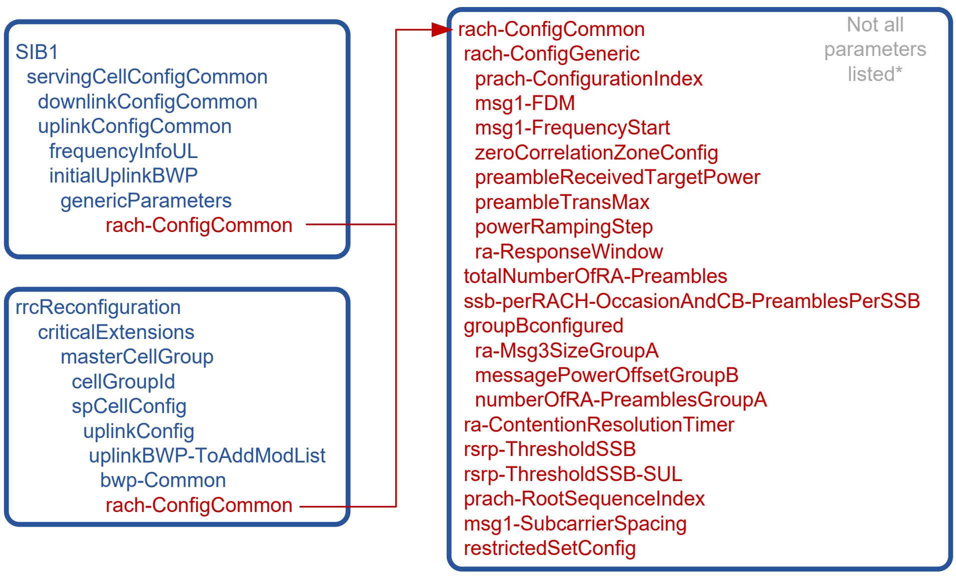


Figure 6-3 Example of NR RACH/PRACH Configuration

6.1.3 NR PRACH Configuration Index

One key part of the RACH configuration is the “prach-ConfigurationIndex” parameter. This parameter is used by the device to determine when it can transmit the PRACH Preamble. In addition, it also identifies the preamble format it should transmit. There are three tables for mapping the prach-ConfigurationIndex; these relate to different frequency ranges, as well as paired/unpaired spectrum.

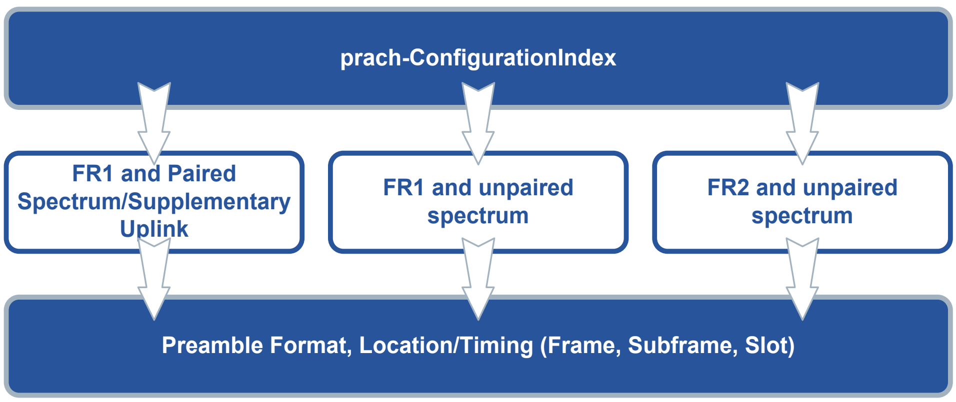


Figure 6-4 PRACH Configuration Index

6.1.4 Preamble Formats

One key parameter identified by the prach-ConfigurationIndex tables is the Preamble Format. There are different formats which also relate to the two sequence lengths, as illustrated in Figure 6-5.

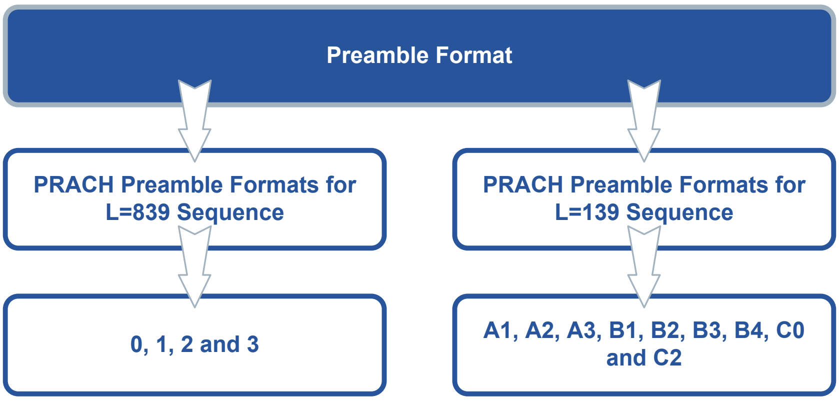
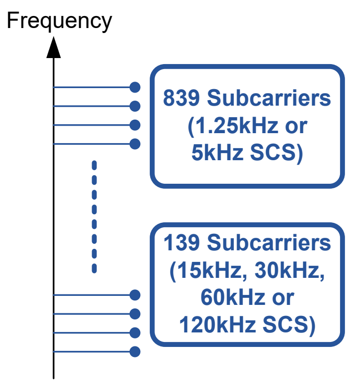


Figure 6-5 Preamble Formats

6.1.5 Preamble Sequence

The preamble sequence length maps to the number of subcarriers utilized, as illustrated in Figure 6-6. However, only certain combinations of sequence length, PRACH subcarrier spacing and PUSCH SCS are permitted.



L_{RA}	Δf^{RA}	Δf *PUSCH*	Equivalent PRBs
839	1.25kHz	15kHz	6
839	1.25kHz	30kHz	3
839	1.25kHz	60kHz	2
839	5kHz	15kHz	24
839	5kHz	30kHz	12
839	5kHz	60kHz	6
139	15kHz	15kHz	12
139	15kHz	30kHz	6
139	15kHz	60kHz	3
139	30kHz	15kHz	24
139	30kHz	30kHz	12
139	30kHz	60kHz	6
139	60kHz	60kHz	12
139	60kHz	120kHz	6
139	120kHz	60kHz	24
139	120kHz	120kHz	12

Figure 6-6 PRACH Subcarrier Spacing vs PUSCH SCS

When the subcarrier spacing of PRACH preamble is 1.25kHz or 5kHz, a long sequence (L = 839) is used. The constant $\kappa = T_S/T_C = 64$.

Format	L_{RA}	Δf^{RA}	N_u	N_{CP}^{RA}	Max Cell Radius	Use Case
0	839	1.25kHz	24576κ	3168κ	14.5 km	LTE Refarming
1	839	1.25kHz	$2\cdot 24576\kappa$	21024κ	100.1 km	Large Cell
2	839	1.25kHz	$4\cdot 24576\kappa$	4688κ	21.9 km	Weak Coverage
3	839	5kHz	$4\cdot 6144\kappa$	3168κ	14.5 km	High Speed

Figure 6-7 PRACH Preamble Formats for *L*=839 Sequence

6.1.6 NR PRACH Format 0 Example

To better understand the figures in the table, an example of PRACH Format 0 is illustrated in Figure 6-8. The 839 subcarriers, spaced by 1.25kHz, carry the preamble sequence. In the time domain, the T_{CP} (Cyclic Prefix Duration) is

3168 κ NR time units, which equates to ~103.2μs. This in terms of delay spread equates to 2.998x10^8 x ~103.2μs = ~30km. However, the key part is the GP (Guard Period), this relates to 2.998x10^8 x ~96.9μs = ~29km. Which equates to a max cell size of ~14.5km.

Format	L_{RA}	Δf^{RA}	N_u	N_{CP}^{RA}	Max Cell Radius	Use Case
0	839	1.25kHz	24576κ	3168κ	14.5 km	LTE Refarming

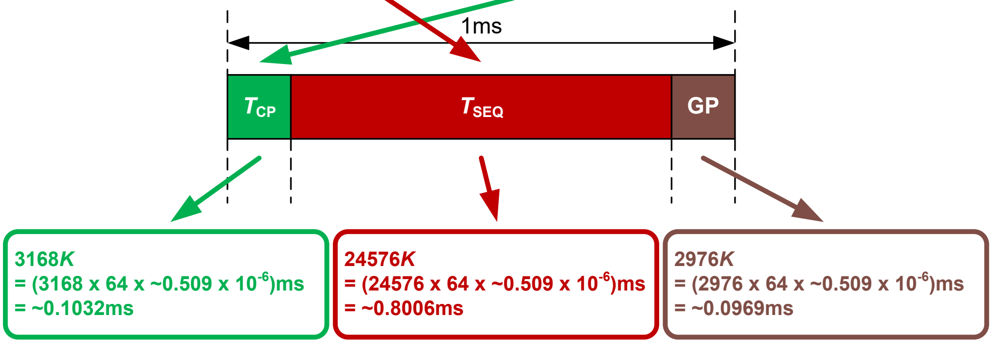


Figure 6-8 PRACH Format 0 Example

6.1.7 NR PRACH Format - CP Size

Figure 6-9 illustrates the comparison of the 4 PRACH Preamble Formats for *L*=839 Sequence. Key factors are the size of the CP, for handling multipath, the Guard Period for RTD (Round Trip Delay) and maximum cell size.

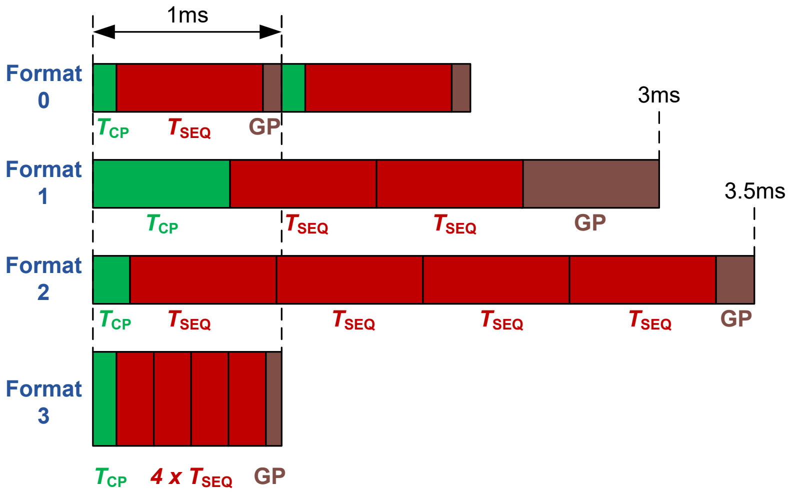


Figure 6-9 PRACH Format 0 to 3

The PRACH preamble formats for the short sequences L=139 are illustrated in Figure 6-10.

Format	L_{RA}	Δf^{RA}	N_u	N_{CP}^{RA}	Use Case
A1	139	$15 \cdot 2^{\mu}$ kHz	$2 \cdot 2048\kappa \cdot 2^{-\mu}$	$288\kappa \cdot 2^{-\mu}$	Very Small Cell
A2	139	$15 \cdot 2^{\mu}$ kHz	$4 \cdot 2048\kappa \cdot 2^{-\mu}$	$576\kappa \cdot 2^{-\mu}$	Small Cell
A3	139	$15 \cdot 2^{\mu}$ kHz	$6 \cdot 2048\kappa \cdot 2^{-\mu}$	$864\kappa \cdot 2^{-\mu}$	Normal Cell
B1	139	$15 \cdot 2^{\mu}$ kHz	$2 \cdot 2048\kappa \cdot 2^{-\mu}$	$216\kappa \cdot 2^{-\mu}$	Small Cell
B2	139	$15 \cdot 2^{\mu}$ kHz	$4 \cdot 2048\kappa \cdot 2^{-\mu}$	$360\kappa \cdot 2^{-\mu}$	Normal Cell
B3	139	$15 \cdot 2^{\mu}$ kHz	$6 \cdot 2048\kappa \cdot 2^{-\mu}$	$504\kappa \cdot 2^{-\mu}$	Normal Cell
B4	139	$15 \cdot 2^{\mu}$ kHz	$12 \cdot 2048\kappa \cdot 2^{-\mu}$	$936\kappa \cdot 2^{-\mu}$	Normal Cell
C0	139	$15 \cdot 2^{\mu}$ kHz	$2048\kappa \cdot 2^{-\mu}$	$1040\kappa \cdot 2^{-\mu}$	Normal Cell
C2	139	$15 \cdot 2^{\mu}$ kHz	$2048\kappa \cdot 2^{-\mu}$	$2048\kappa \cdot 2^{-\mu}$	Normal Cell

Figure 6-10 PRACH Preamble Formats for *L*=139 Sequence

6.2 NR Physical Uplink Shared Channel

The NR PUSCH (Physical Uplink Shared Channel) is used to deliver Transport Blocks from the device to the gNB. There are two uplink options:

- CP-OFDM - this method is ideally suited for MIMO. In this operation the PUSCH can support QPSK, 16QAM, 64QAM or 256QAM.
- DFT-s-OFDM - this method is suited for low power devices, e.g. IoT devices. It can only utilize a single layer transmission. In this operation the PUSCH can support π/2 BPSK, 16QAM, 64QAM or 256QAM.

In addition, the PUSCH is also able to multiplex UCI (Uplink Control Information). Therefore, an additional “Data and Control Multiplexing” stage is added in the physical layer process. Finally, the PUSCH supports two transmission schemes:

- Codebook based - the gNB provides the device with a transmit precoding matrix indication in the DCI.
- Non-Codebook based - the Device determines its PUSCH precoder based on wideband SRI (Sounding Reference Signal Resource Indicator) field from the DCI.

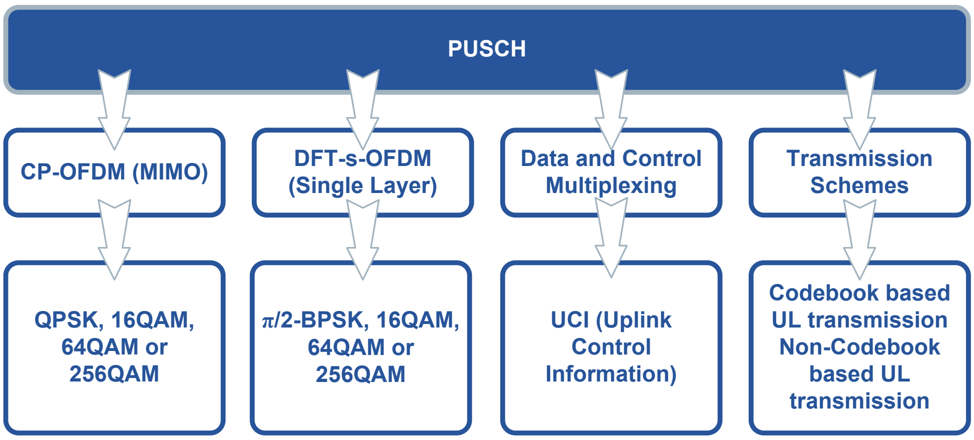


Figure 6-11 NR Physical Uplink Shared Channel

6.2.1 NR PUSCH Processing Chain

The higher layer concepts are like the PDSCH however differ in the detail. Figure 6-12 illustrates the CP-OFDM physical layer processing stages. Note that for DFT-s-OFDM, an additional Transform Precoding stage is added.

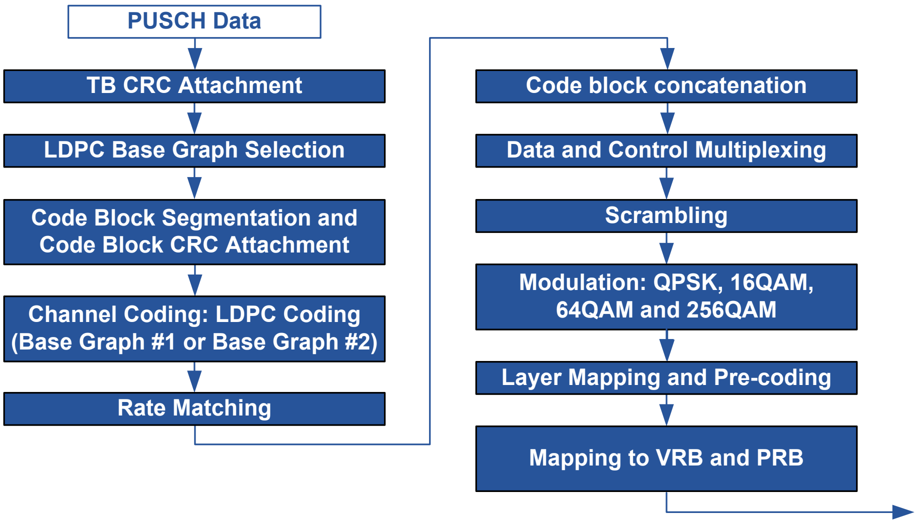


Figure 6-12 NR PUSCH Physical Layer Processing

6.2.2 Configuring NR PUSCH

The PUSCH is configured using RRC signalling, namely the PUSCH-Config parameter, which is as part of the BWP-UplinkDedicated parameter. Note that there is also a PUSCH-ConfigCommon parameter - however, as its name suggests, only carries common PUSCH information.

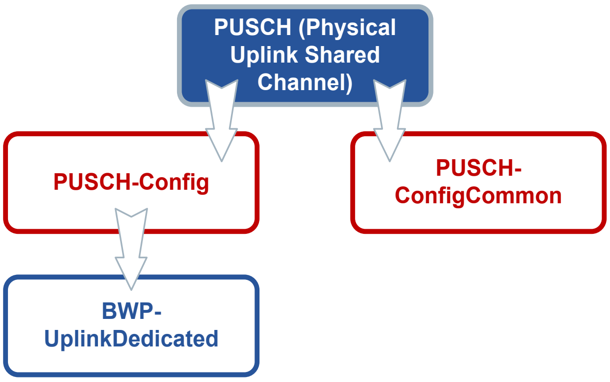


Figure 6-13 Configuring PDSCH

Figure 6-14 illustrates an example of the main PUSCH-Config parameters. These include:

- dataScramblingIdentityPUSCH - this is an identifier used to initiate data scrambling (c_init) for PUSCH.
- txConfig - this indicates whether the device should use codebook based or non-codebook based transmission. Corresponds to L1 parameter “ulTxConfig”.
- dmrs-UplinkForPUSCH-MappingTypeA - this indicates the DMRS configuration for PUSCH transmissions using PUSCH mapping type A (chosen dynamically via PUSCH-TimeDomainResourceAllocation).

- dmrs-UplinkForPUSCH-MappingTypeB - this indicates the DMRS configuration for PUSCH transmissions using PUSCH mapping type B (chosen dynamically via PUSCH-TimeDomainResourceAllocation).
- pusch-PowerControl - this includes various parameters that influence the power.
- frequencyHopping - this indicates if frequency hopping is enabled, as well as the offset configuration, namely “Mode 1” or “Mode 2“.
- frequencyHoppingOffsetLists - this provides a set of frequency hopping offsets used when frequency hopping.
- resourceAllocation - this indicates the type of resource allocation. Includes: Type 0 (bitmap), Type 1 (Start and Stop RBs) or Dynamic Switch.
- pusch-AllocationList - this is the list of time domain allocations for timing of UL assignment to UL data. If configured, the values provided override the values received in corresponding PUSCH-ConfigCommon.
- pusch-AggregationFactor - this is the number of repetitions for data.
- mcs-Table - this indicates which MCS (Modulation and Coding Scheme) table the device should use for PUSCH without transform precoder. Options include 64QAM table or 256QAM table.
- mcs-TableTransformPrecoder - this indicates 256QAM table, however when the field is absent the device uses the 64QAM table.
- transformPrecoder - this enables/disables the transform precoder for the PUSCH.
- codebookSubset - this identifies the Uplink Codebook Subset.
- maxRank - this identifies the max UL Rank and relates also to precoding.
- rbg-Size - this enables selection of “config 1” or “config 2” for RBG (Resource Block Group) size for PUSCH. When the field is absent the device uses “config 1”.
- uci-OnPUSCH - this can include the selection and configuration of dynamic and semi-static beta-offset, i.e. related to power control.
- vrb-ToPRB-Interleaver - this defines the interleaving and is configurable between 2 or 4 PRBs.

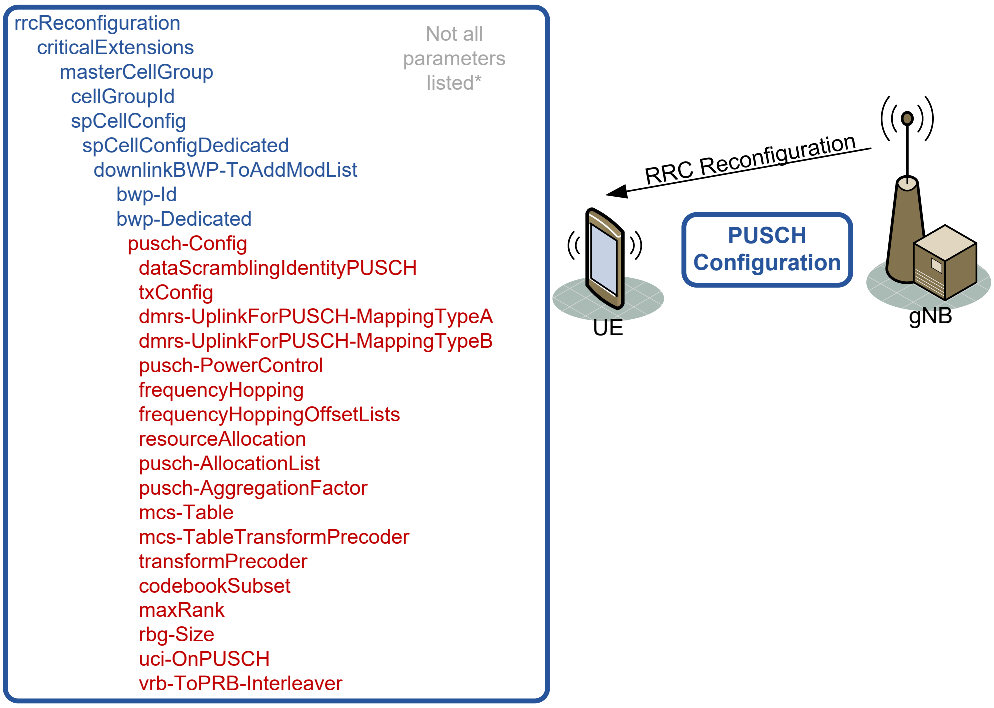


Figure 6-14 NR PUSCH Configuration Setup (Dedicated)

6.3 PUSCH DMRS

The PUSCH DMRS operates with a similar configuration to that of the PDSCH DMRS. As such, it has various types and configuration options. Figure 5-28 illustrates the concept of front loaded DMRS, as well as the difference between Type A (which can be positioned in symbol 2 or 3) and Type B (at the start of the PUSCH resource allocation).

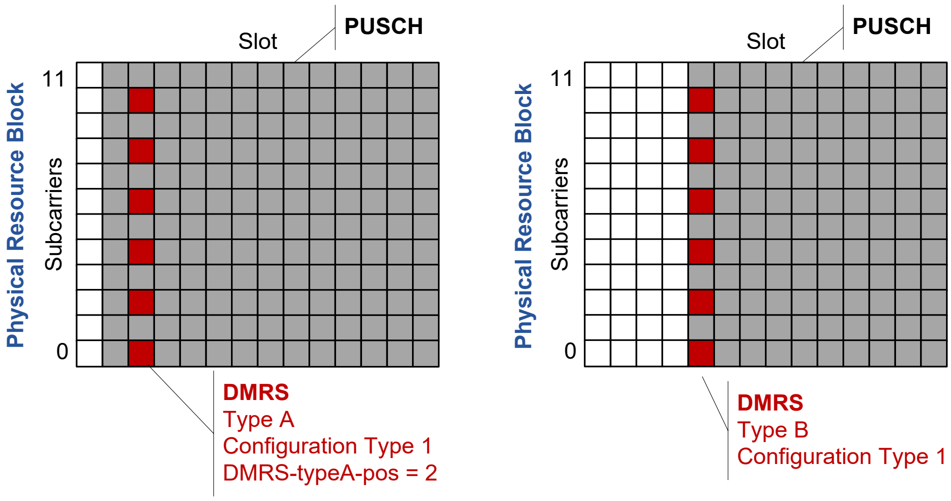


Figure 6-15 DMRS Type A vs Type B

In addition, like the PDSCH DMRS, the concepts of Configuration Type 1 and Type 2 exist, as well as the options for extended and additional DMRS locations.

6.4 NR Physical Uplink Control Channel

The PUCCH main role is to send UCI (Uplink Control Information) from the device. However, note that both the PUCCH or PUSCH can carry UCI. Figure 6-16 illustrates the key aspects of the PUCCH.

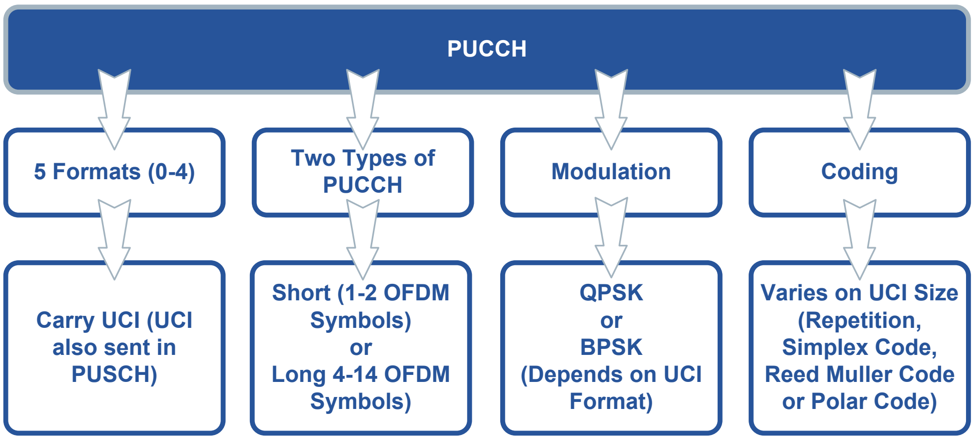


Figure 6-16 Physical Uplink Control Channel

6.4.1 NR PUCCH Formats

The PUCCH supports multiple formats, as illustrated in Figure 6-17. In addition, frequency hopping can also be configured for PUCCH formats.

For small UCI payloads, up to 2 bits, Format 0 or 1 is utilized. In contrast, for large UCI payloads, Formats 2, 3 or 4 are utilized. The difference between these relates to multiplexing (multiple devices) and resource mapping. Typically, a PUCCH with multiplexing requires some form of sequence coding or scrambling.

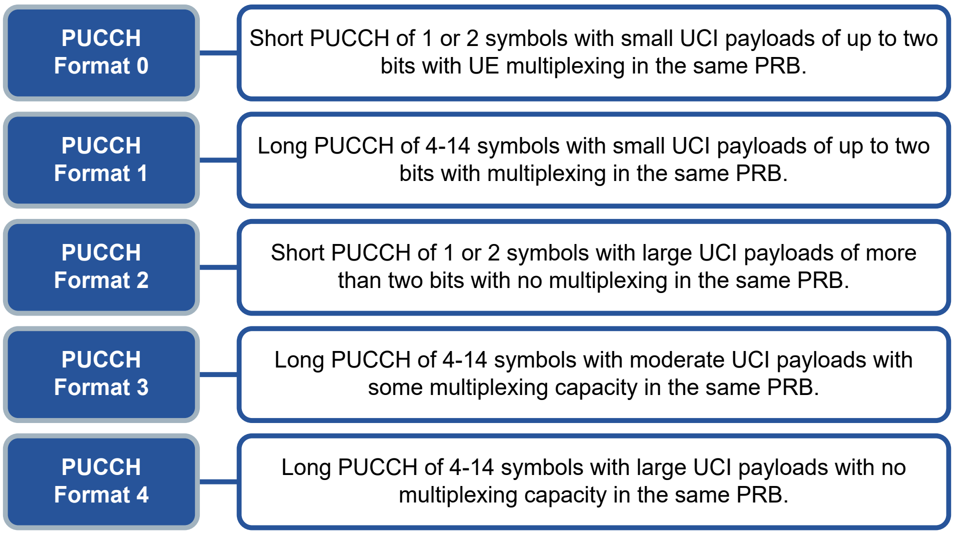


Figure 6-17 NR PUCCH Formats

6.4.2 NR PUCCH Location Example

The actual configuration of the PUCCH is complex since there are so many permutations and parameters. Figure 6-18 illustrates the high-level location parameters which assist in defining a PUCCH location for Format 3. Note that not all formats are configured with the same location parameters, especially when only 1 PRB is utilized.

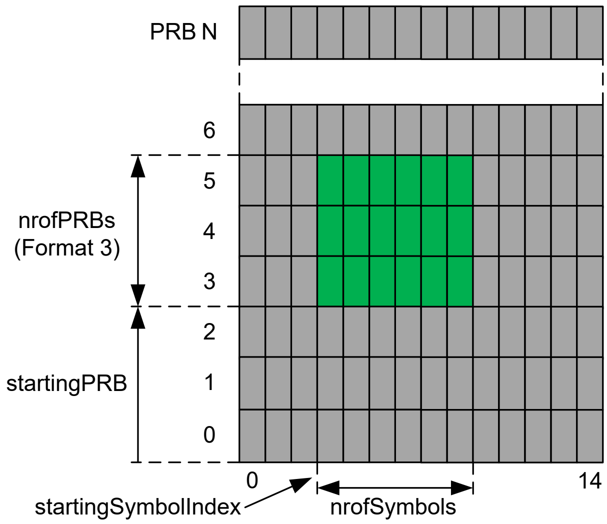


Figure 6-18 PUCCH Location (Format 3)

6.4.3 NR PUCCH Configuration

The actual configuration of the PUCCH includes many parameters, as well as nested parameters and "sets" to allow dynamic configurations. Figure 6-19 illustrates a high-level view of the PUCCH Configuration Setup, highlighting the main parameters. In addition, nested parameters for Format 3 are also highlighted.

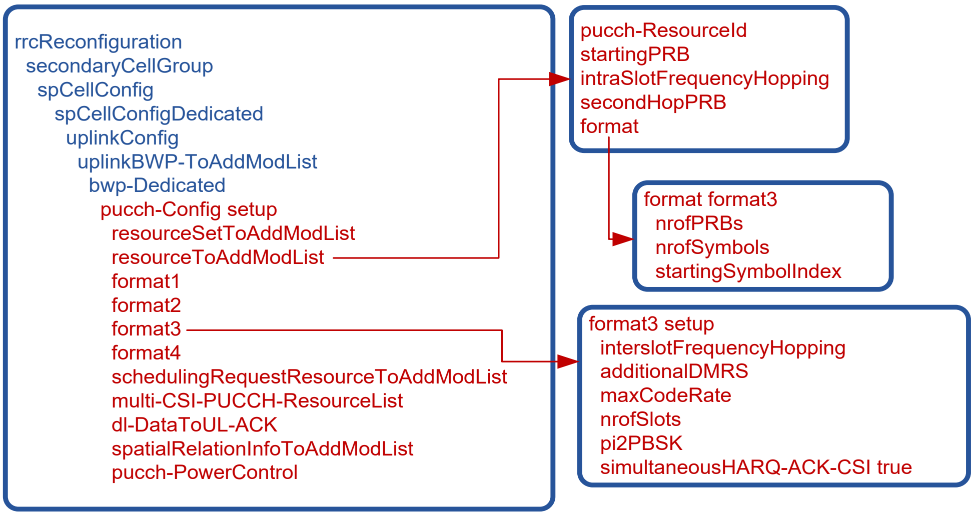


Figure 6-19 PUCCH Configuration Parameters (Format 3)

Key parameters include:

- resourceSetToAddModList - this is the list for adding PUCCH resource sets. Note there is also a separate parameter to release.
- resourceToAddModList - this includes the resources which are utilized by other parts of the configuration.
- format1 to format4 - for each format the appropriate parameters are configured.
- schedulingRequestResourceToAddModList - this include parameters which assist SR (Scheduling Request).
- multi-CSI-PUCCH-ResourceList - this identifies the list of PUCCH Resources Identifiers.

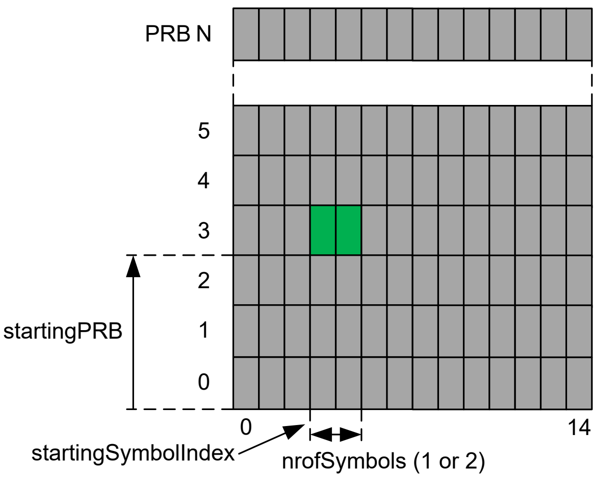
- dl-DataToUL-ACK - this indicates the list of timing for given PDSCH to the UL ACK.
- spatialRelationInfoToAddModList - this provides the configuration of the spatial relation between a reference RS and PUCCH.
- pucch-PowerControl - this include various power control parameters and delta values.

6.4.4 NR PUCCH Format 0 Example

Some PUCCH formats utilize scrambling based on a RNTI. However, as an example Format 0 does not. Instead it utilizes sequence and cyclic shift hopping.

Figure 6-20 illustrates an example of PUCCH Format 0, utilizing 2 symbols. Format 0 can carry up to 2bits (UCI information) which are mapped to a corresponding sequence CS (Cyclic Shift). The device will be configured to be sending 1bit or 2bit HARQ feedback and as such the system knows what to expect.

Since the PUCCH is also utilized to carry SR (Scheduling Request) these, along with HARQ feedback, map to specific cyclic shifts.



HARQ Value	Sequence Cyclic Shift
0	$m_{CS} = 0$
1	$m_{CS} = 6$
00	$m_{CS} = 0$
01	$m_{CS} = 3$
10	$m_{CS} = 6$
11	$m_{CS} = 9$
0 + SR	$m_{CS} = 3$
1 + SR	$m_{CS} = 9$
00 + SR	$m_{CS} = 1$
01 + SR	$m_{CS} = 4$
10 + SR	$m_{CS} = 7$
11 + SR	$m_{CS} = 10$

Figure 6-20 NR PUCCH Format 0 Location and UCI HARQ Example

7 5G Reference Signals

7.1 5G Reference Signals

There are various NR physical signals which are typically identified as synchronization signals or reference signals. The two NR synchronization signals are the PSS (Primary Synchronization Signal) and SSS (Secondary Synchronization Signal), which are sent as part of the SSB (Synchronization Signal Block). In terms of RS (Reference Signals), there are four types, namely DMRS (Demodulation RS), CSI-RS (Channel State Information RS), SRS (Sounding RS) and PTRS (Phase Tracking RS). Figure 7-1 illustrates whether these are utilized in the downlink and/or uplink direction.

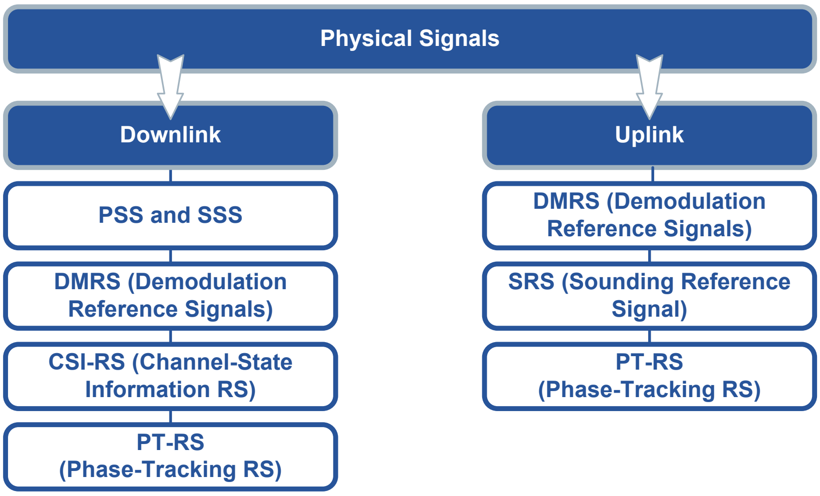


Figure 7-1 NR Reference Signals

7.1.1 PSS and SSS

Detailed Information relating to the PSS/SSS is part of NR Downlink Physical Channels and Signals. In summary, the PSS and SSS, along with the PBCH (Physical Broadcast Channel) and PBCH DMRS, makes up a SSB (Synchronization Signal Block). Each SSB is typically transmitted in a beam. Figure 7-2 illustrates an example with 4 SSB's repeating every 5ms. The PSS and SSS is used to identify timing (symbol), as well as enabling the devices to derive the PCI (Physical Channel Identifier).

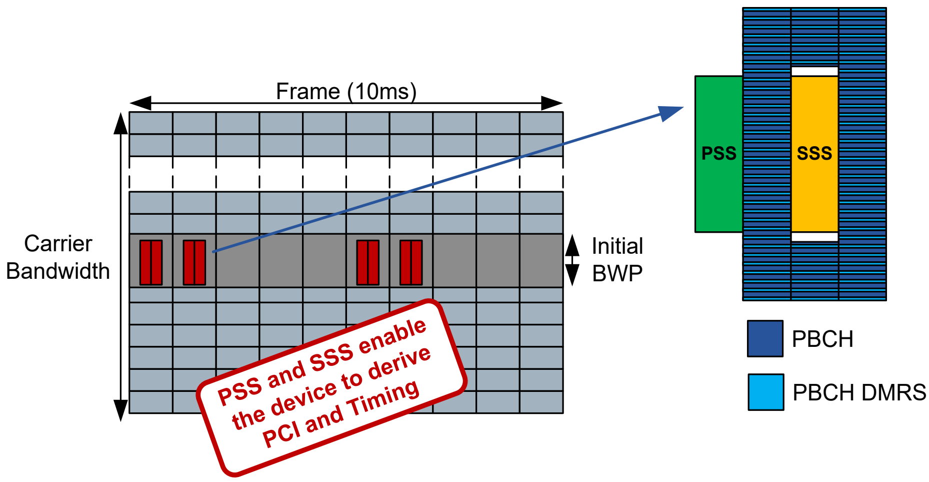


Figure 7-2 PSS and SSS

Note that the SSB also includes DMRS for the PBCH. This is scrambles based on the PCI, as well as the i_{SSB} (Beam Index). In addition, the PBCH DMRS and SSS they are also used for determination of signal measurements.

7.1.2 DMRS

Demodulation Reference signals, as their name suggests, is used to assist in the demodulation of a channel. For 5G there are 4 main types of DMRS, as illustrated in Figure 7-3.

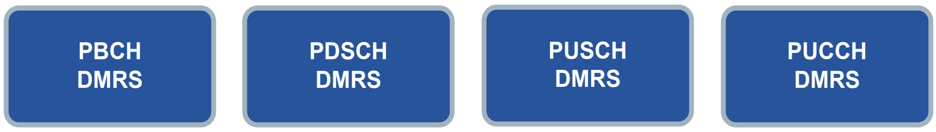


Figure 7-3 5G DMRS

PBCH DMRS

The main function of the PBCH DMRS is to provide a demodulation reference to assist in decoding the PBCH.

The PBCH DMRS also is scrambled based on the PCI, as well as the least significant bits of the i_{SSB} (Beam Index), i.e. it is used as part of Beam Determination. The location of the PBCH DMRS in the SSB is illustrated in Figure 7-2. Note that the exact location is also influenced by a mod4 of the PCI. Finally, the PBCH DMRS and SSS they are also used for determination of signal measurements by the device.

Figure 7-4 PBCH DMRS

PDSCH and PUSCH DMRS

NR PDSCH and PUSCH both utilizes “front-loaded” DMRS symbols, however there are many options and configurations. Detail of the PDSCH DMRS and PUSCH DMRS options are described with in the NR Downlink and Uplink Physical Channel descriptions. A summary of the DMRS flexibility is illustrated in Figure 7-5. These allows for DMRS to be positioned in various locations, such as been optimized for various MIMO (Multiple Input Multiple Output) configurations, as well as for “edge of cell” or fast-moving devices.

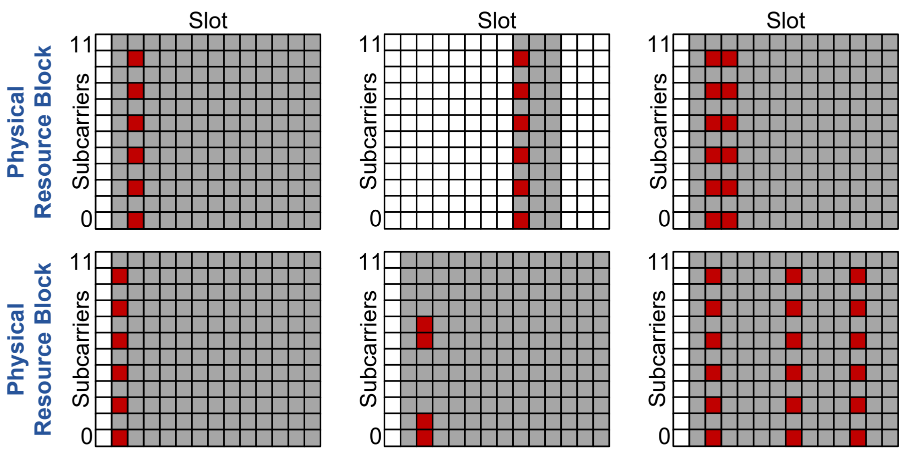


Figure 7-5 Examples of NR DMRS

Scrambling of the PDSCH DMRS and PUSCH DMRS is initialized based on a RNTI values and the PCI.

PUCCH DMRS

DMRS is also including in PUCCH Formats 1, 2, 3 and 4. The DMRS signals are either time multiplexed or frequency multiplexed in to the transmission depending on the format.

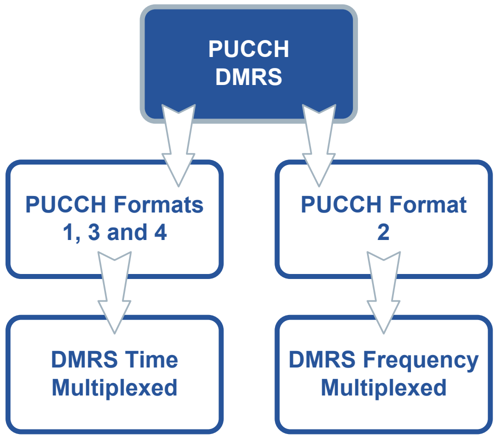


Figure 7-6 PUCCH Demodulation

7.2 Channel State Information Reference Signals

Unlike LTE, 5G NR does not have cell specific reference signals. As such, it needs to configure reference signals that a device can monitor and report on. These are called CSI (Channel State Information) Reference Signals.

7.2.1 CSI-RS Types

The main types of CSI-RS are termed NZP (Non-Zero Power), i.e. the transmit power in a RE (Resource Element). Figure 7-7 illustrates a device with configured NZP-CSI-RS (Non-Zero Power CSI-RS) resources. In addition, the device can also be configured with ZP-CSI-RS (Zero Power CSI-RS). These indicate to the device that the cell is not transmitting on these RE's, which also enables the device to monitor other cells CSI-IM (CSI-RS Interference Management) resources, or simply just the level of noise.

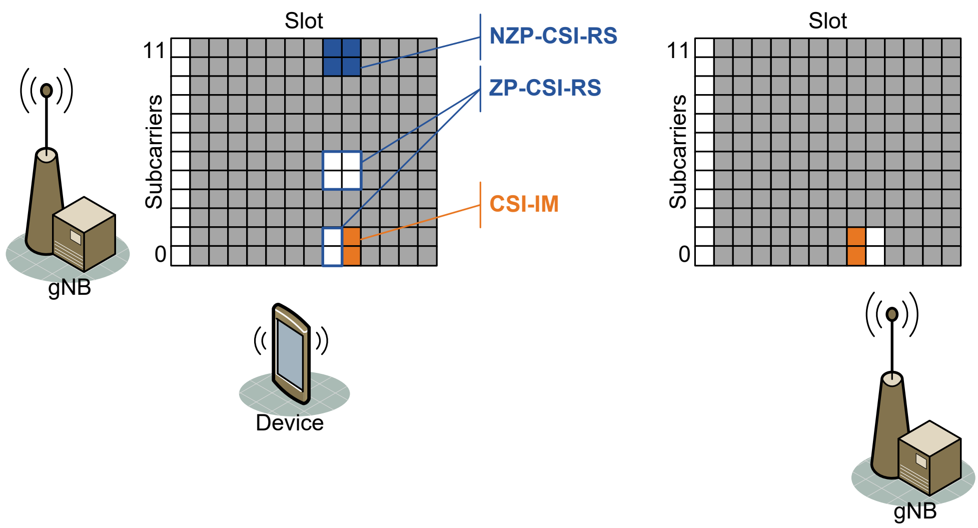


Figure 7-7 CSI-RS Types

7.2.2 CSI-RS Features

The CSI-RS can be utilized for various features, as highlighted in Figure 7-8.

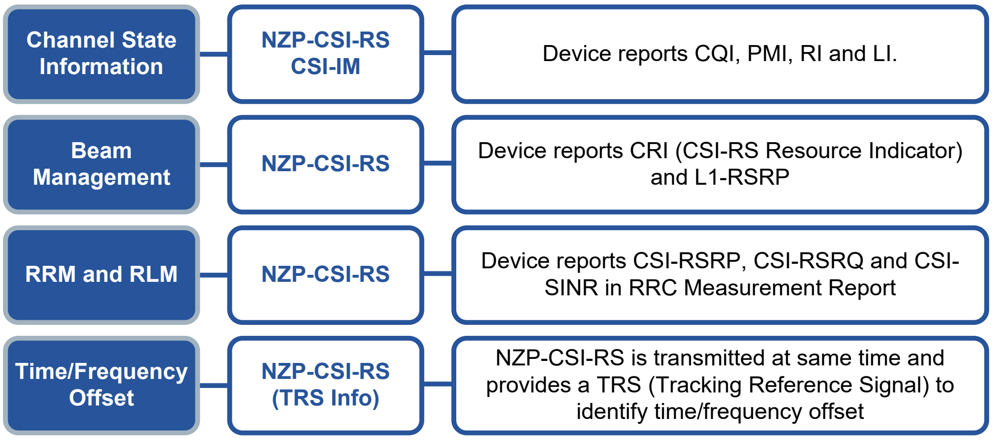


Figure 7-8 CSI-RS Features

Various configuration options exist that enable the CSI-RS to be sent on multiple ports with various scheduling options such as Periodic and Semi Persistent, as well as Aperiodic - whereby the network triggers sending using the DCI. Figure 7-9 summarizes the key aspects of CSI-RS configuration.

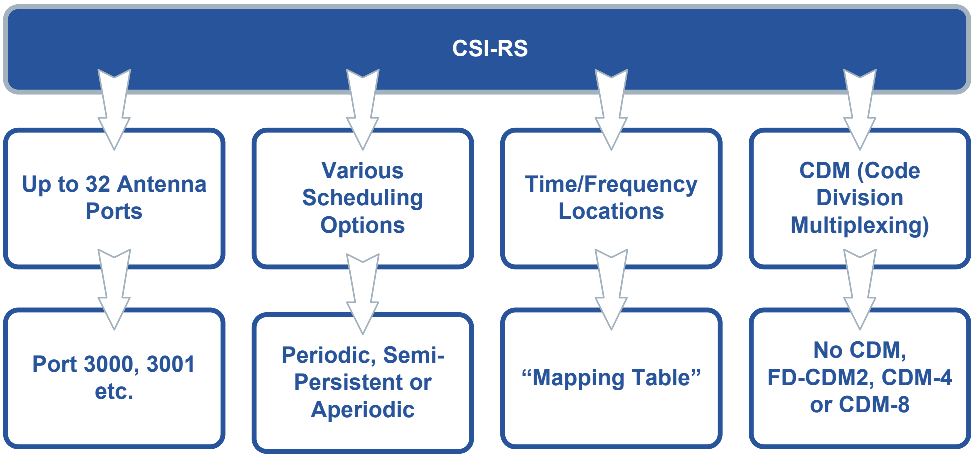


Figure 7-9 Key CSI-RS Aspects

In terms of location, there is a specific time/frequency location table which defines where in the slot the CSI-RS are sent, as well as other aspects such as CDM (Code Division Multiplexing) options.

7.2.3 CSI-RS Locations in a Slot

Figure 7-10 illustrate the various location options (rows) that are available for CSI-RS configuration.

Row	Ports	Density	CDM Type
1	1	3	No CDM
2	1	1, 0.5	No CDM
3	2	1, 0.5	FD-CDM2
4	4	1	FD-CDM2
5	4	1	FD-CDM2
6	8	1	FD-CDM2
7	8	1	FD-CDM2
8	8	1	CDM4 (FD2, TD2)
9	12	1	FD-CDM2
10	12	1	CDM4 (FD2, TD2)
11	16	1, 0.5	FD-CDM2
12	16	1, 0.5	CDM4 (FD2, TD2)
13	24	1, 0.5	FD-CDM2
14	24	1, 0.5	CDM4 (FD2, TD2)
15	24	1, 0.5	CDM8 (FD2, TD4)
16	32	1, 0.5	FD-CDM2
17	32	1, 0.5	CDM4 (FD2, TD2)
18	32	1, 0.5	CDM8 (FD2, TD4)

Figure 7-10 Example of CSI-RS

Row's 1 to 8 are illustrated in Figure 7-11. Note that for CSI Tracking a single port CSI-RS resource with density = 3 is used (row 1). For CSI measurement, rows 2 to 18 patterns can be used and beam management and RRM (Radio Resource Management) measurement row 2 and 3 are utilized.

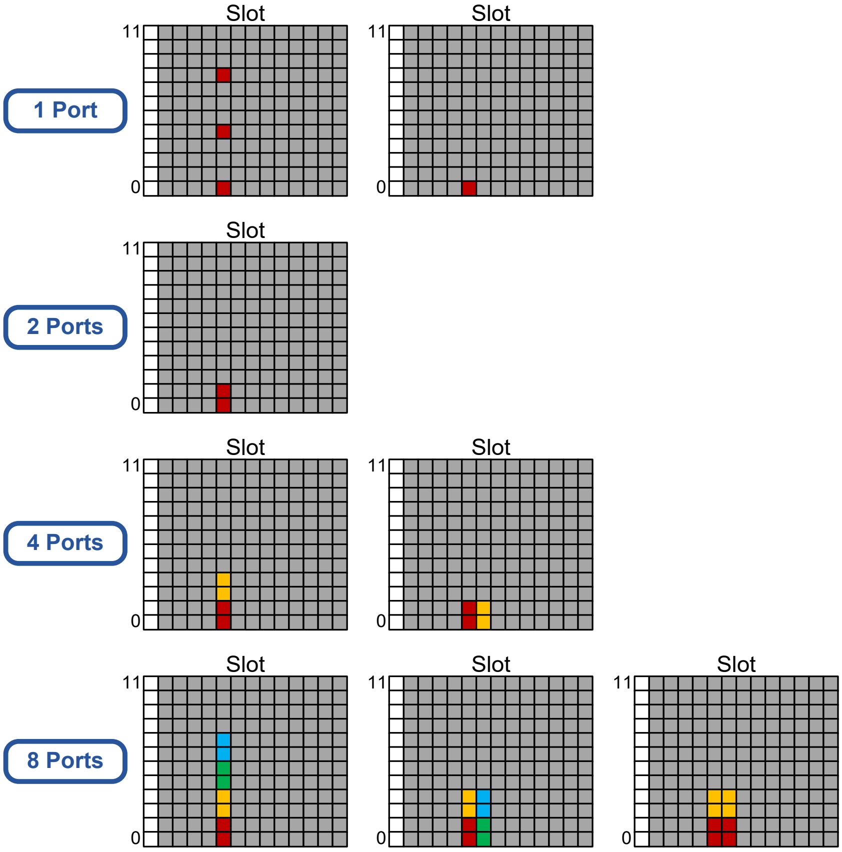


Figure 7-11 Example of CSI-RS (1 to 8 Ports)

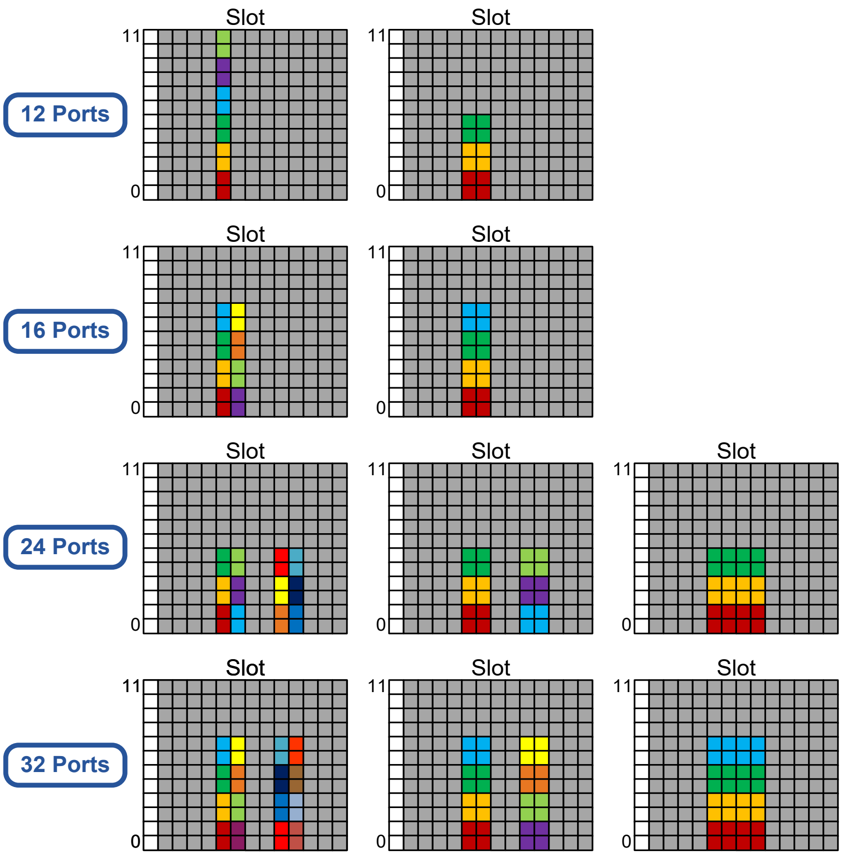


Figure 7-12 Example of CSI-RS (12 to 32 Ports)

The actual position of the CSI-RS in the slot, in terms of subcarrier (frequency domain allocation) and symbol, can be configured.

7.2.4 CSI-IM Patterns

The CSI-IM resource has 2 patterns, as illustrated in Figure 7-13. The location in the slot is defined by subcarrier location and symbol location parameters.

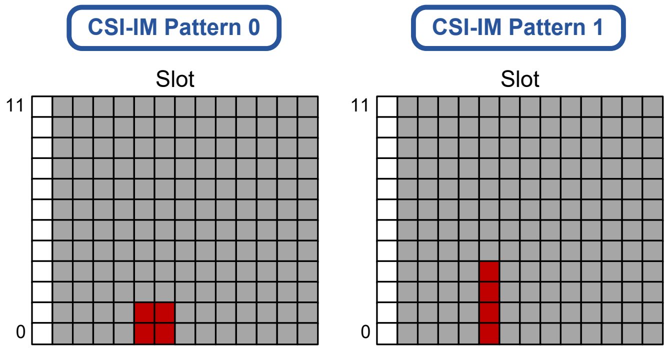
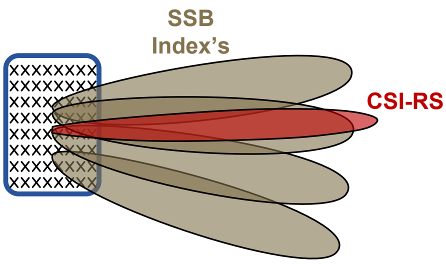


Figure 7-13 CSI-IM Patterns

7.2.5 CSI-RS Configuration

In addition to the SS Blocks, whilst in the RRC_CONNECTED state, the device will be configured to monitor various CSI. Figure 7-14 illustrates the various options for CSI measurement configuration. Up to 64 NZP-CSI-RS Resource Sets can be configured, each linking to one or more NZP-CSI-RS resources.




```
rrcReconfiguration
  secondaryCellGroup
    cellGroupId
    spCellConfig
      spCellConfigDedicated
          csi-MeasConfig
            nzp-CSI-RS-ResourceToAddModList
            nzp-CSI-RS-ResourceSetToAddModList
            csi-IM-ResourceToAddModList
            csi-IM-ResourceSetToAddModList
            csi-SSB-ResourceSetToAddModList
            csi-ResourceConfigToAddModList
            csi-ReportConfigToAddModList
            reportTriggerSize
            aperiodicTriggerStateList
            semiPersistentOnPUSCH-TriggerStateList
```

Figure 7-14 CSI Measurement Configuration

As an example, the measurement configuration for one NZP (Non-Zero Power) CSI-RS resource is shown in Figure 7-15. Note that multiple resources can be configured (added).

```
rrcReconfiguration
  secondaryCellGroup
    cellGroupId
    spCellConfig
      spCellConfigDedicated
        csi-MeasConfig setup
          nzp-CSI-RS-ResourceToAddModList
             nzp-CSI-RS-ResourceId
             resourceMapping
               frequencyDomainAllocation
               nrofPorts
               firstOFDMSymbolInTimeDomain
               cdm-Type
               density
               freqBand
             powerControlOffset
             scramblingID
             periodicityAndOffset
             qcl-InfoPeriodicCSI-RS
          nzp-CSI-RS-ResourceSetToAddModList
```

Figure 7-15 NZP CSI-RS Resource Example

A key parameter is "resourceMapping", which includes:

- frequencyDomainAllocation - this defines the frequency domain allocation within a physical resource block.
- nrofPorts - number of ports (up to 32).
- firstOFDMSymbolInTimeDomain - this identifies the time domain allocation within a PRB.
- cdm-Type - this identifies the specific CDM type, values include: noCDM, FD-CDM2, CDM4-FD2-TD2 or CDM8-FD2-TD4.
- density - this is the density of CSI-RS resource measured in RE / Port / PRB.
- freqBand - this can indicate wideband or partial band CSI-RS.

These parameters enable the NZP-CSI-RS resources to be defined in the frequency and time domain, as well as defining ports and the use of CDM (Code Division Multiplexing) options.

7.2.6 ZP-CSI-RS Configuration

Figure 7-16 illustrates some of the main parameters for CSI-RS configuration inside the PDSCH Configuration. Note that these relate to ZP (Zero Power) Reference signals.

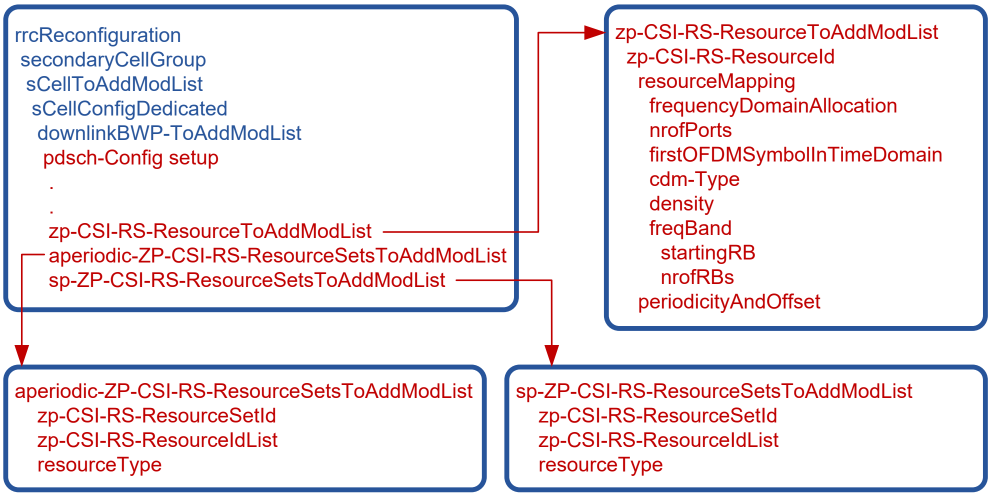


Figure 7-16 Configuring ZP CSI-RS for PDSCH

7.2.7 CSI Timing

CSI-RS resource can be configured as periodic, semi-persistent or aperiodic by the higher layer parameter ResourceType. For periodic and semi-persistent operation, the device assumes that the CSI-RS is transmitted in slots satisfying:

$$\left(N_{slot}^{frame,\mu} n_f + n_{s,f}^{\mu} - T_{offset}\right) \bmod T_{CSI\text{-}RS} = 0$$

Figure 7-17 CSI-RS Transmitted slots for Periodic or Semi-Persistent

Where the periodicity $T_{CSI\text{-}RS}$ (in slots) and slot offset T_{offset} are given by the higher layer parameter CSI-RS-timeConfig. In addition, the device assumes that CSI-RS is transmitted in a candidate slot only if all OFDM symbols of that slot corresponding to the configured CSI-RS resource are classified as "downlink".

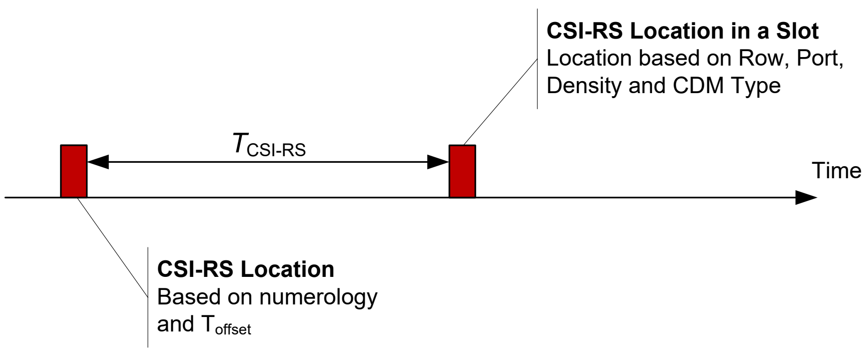


Figure 7-18 CSI-RS Frame Location

7.3 Sounding Reference Signal

The SRS (Sounding Reference Signal) is an uplink sounding signal that provides the gNB with uplink channel quality information which can be used to assist scheduling, beam management or antenna switching.

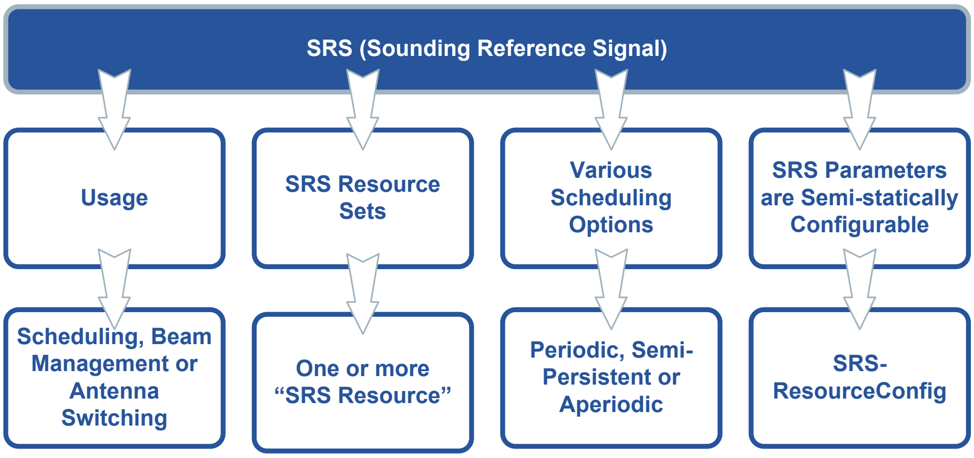


Figure 7-19 Sounding Reference Signal

Figure 7-20 illustrates an example whereby a device has been allocated resources in the uplink. As such, the gNB can use the DMRS to provide channel estimation in this allocation, i.e. a "sub-band". However, the gNB does not know how the device will perform in the other parts of this channel. Such that, if it was to allocate resources in these other bands the conditions may not be "favourable" and additional errors could be introduced. Therefore, by introducing SRS's they provide the network with valuable channel information.

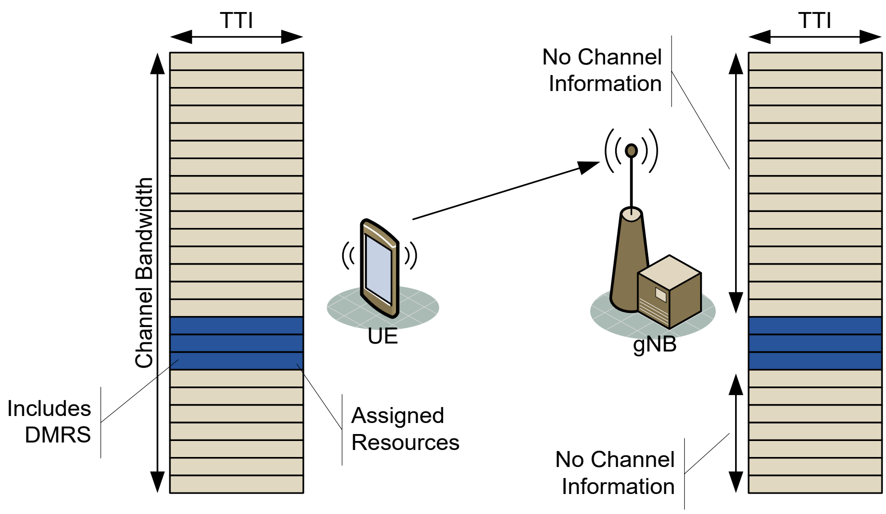


Figure 7-20 Sounding Reference Signal

The configuration of the sounding signal, e.g. bandwidth, duration and periodicity, are given by higher layers. Figure 7-21 illustrates two examples, whereby the gNB has configured SRS over a desired portion of the band.

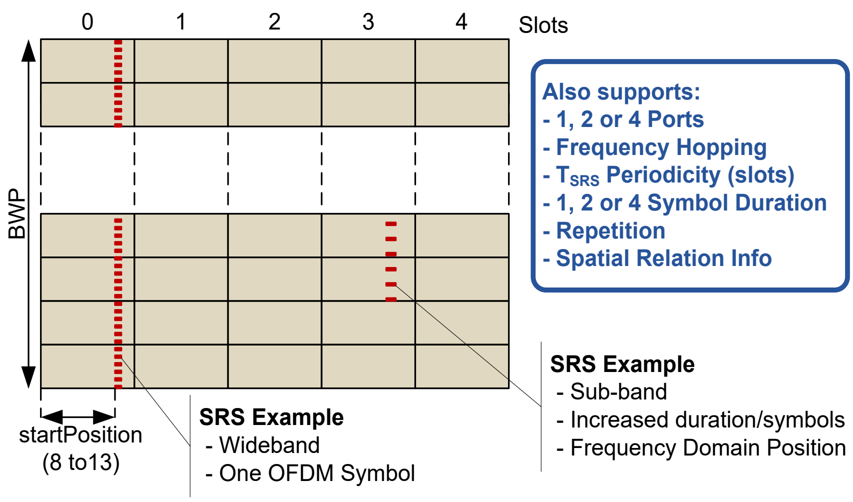


Figure 7-21 SRS Mapping

There are various Sounding Reference Symbol parameters defined. Most are device semi-statically configurable by higher layers.

Figure 7-22 illustrates an example of the SRS configuration parameter (SRS-Config). It consists of two key parameters, namely SRS-ResourceSet and SRS-Resource. The SRS-ResourceSet parameter includes:

- srs-ResourceSetId - this is the ID of this SRS resource set. It is unique in the context of the BWP.
- srs-ResourceIdList - this is a list of srs-ResourceId relating to this set.
- resourceType - this indicates Aperiodic, Semi-Persistent or Periodic. For Aperiodic, the aperiodicSRS-ResourceTrigger parameter defines a “code point” for the DCI message.
- Usage - this indicates if the SRS resource set is used for beam management vs. used for either codebook based or non-codebook based transmission.

The SRS-Resource parameter includes:

- srs-ResourceId - this identifies the SRS Resource.
- nrofSRS-Ports - this can indicate 1, 2 or 4 ports.
- ptrs-PortIndex - this is for non-codebook based UL MIMO and only applicable when the corresponding Phase Tracking Reference Signal is set.
- transmissionComb - this parameter is part of the SRS configuration and influences the position and quantity of the RE’s used.
- resourceMapping - this details the location and includes 3 parameters, namely: startPosition, nrofSymbols and repetitionFactor.
- freqDomainPosition - this parameter influences the location, however is linked to the frequency hopping parameter.
- freqDomainShift - this parameter influences the location.
- freqHopping - this includes a set of parameters which influence frequency hopping.
- groupOrSequenceHopping - this identifies whether none, group or sequence hopping is configured.
- resourceType - this indicates the time domain behaviour of SRS resource configuration, i.e. whether it is Aperiodic, Semi-Persistent, or Periodic.

- sequenceId - this parameter is used to initialize pseudo random group and sequence hopping.
- spatialRelationInfo - this configuration relates to the spatial relation between a reference RS and the target SRS, i.e. it relates to either a ssb-Index, csi-RS-Index or SRS.

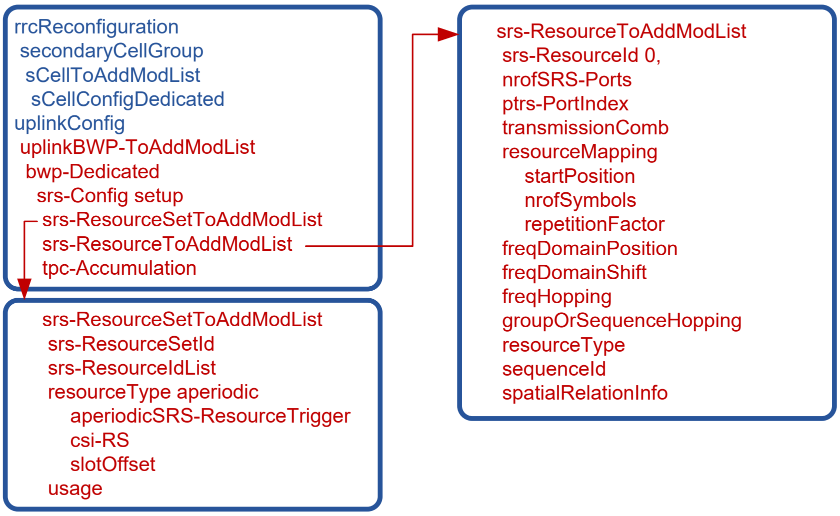


Figure 7-22 SRS Configuration Example

7.4 Phase Tracking Reference Signal

Since 5G supports mmWave there is a problem with “Phase Noise”, also known as CPE (Common Phase Error). This is where the CPE shifts the MCS (Modulation and Coding Scheme) by a common off-set. As such, higher order MCSs, where the constellation points are close, are affected. The PTRS (Phase Tracking RS) is designed to mitigate this.

Utilizing a greater PTRS density (quantity) improves the performance, however increases the overhead, i.e. reduces the data rate.

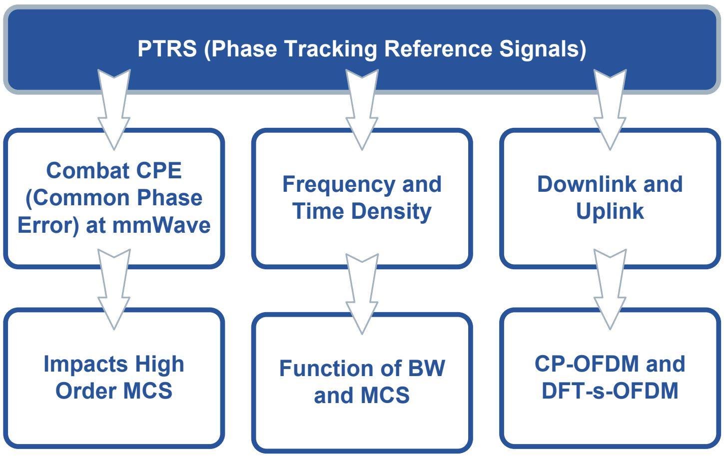


Figure 7-23 Phase Tracking Reference Signal

Figure 7-24 illustrate an example of the PTRS location. Note that there are many parameters which define location and density. For example, in the time domain the PTRS can be in every OFDM symbol, every second OFDM symbol, and every fourth OFDM symbol.

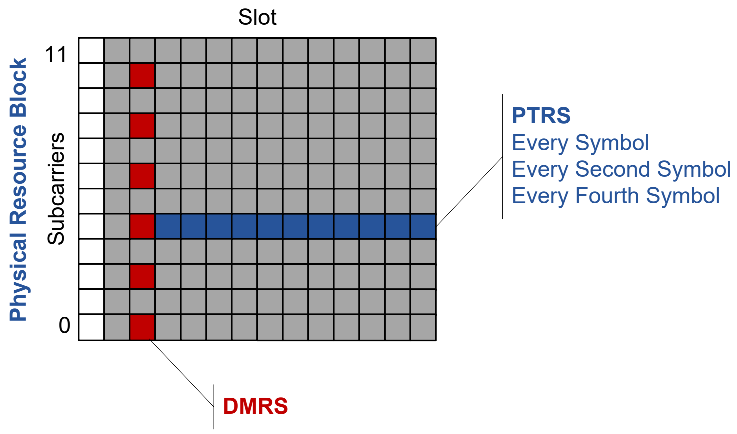


Figure 7-24 Example of PTRS Location

The configuration of the PTRS is illustrated in Figure 7-25. This example shows the phaseTrackingRS parameter as part of the DMRS Mapping Type A parameters. Note that it is also available as part of DMRS Mapping Type B.

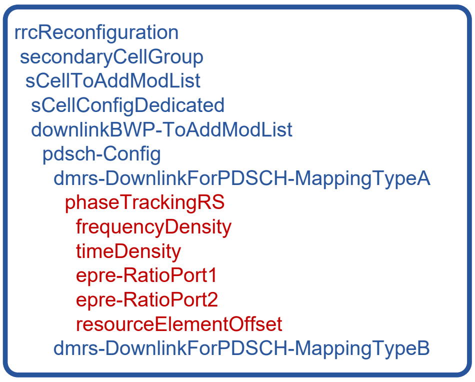


Figure 7-25 Downlink PTRS Configuration Parameters

Key parameters in the PTRS-DownlinkConfig include:

- frequencyDensity - this configures the presence and frequency density of DL PTRS as a function of Bandwidth.
- timeDensity - this configures the presence and time density of DL PTRS as a function of MCS.
- epre-RatioPort1 - EPRE (Energy Per Resource Element) ratio between PTRS and PDSCH.
- epre-RatioPort2 - EPRE ratio between PTRS and PDSCH.
- resourceElementOffset - this indicates the subcarrier offset for DL PTRS.

Figure 7-26 illustrates the uplink PTRS configuration. There are 2 versions depending on whether CP-OFDM or DFT-s-OFDM is configured.

```
rrcReconfiguration
 secondaryCellGroup
  sCellToAddModList
   sCellConfigDedicated
    uplinkConfig
      uplinkBWP-ToAddModList
        bwp-Dedicated
          pusch-Config
            txConfig
            dmrs-UplinkForPUSCH-MappingTypeA
              phaseTrackingRS
                modeSpecificParameters cp-OFDM
                  frequencyDensity
                  timeDensity
                maxNrofPorts
                resourceElementOffset
                ptrs-Power
```

```
rrcReconfiguration
 secondaryCellGroup
  sCellToAddModList
   sCellConfigDedicated
    uplinkConfig
      uplinkBWP-ToAddModList
        bwp-Dedicated
          pusch-Config
            txConfig
            dmrs-UplinkForPUSCH-MappingTypeA
              phaseTrackingRS
                modeSpecificParameters dft-S-OFDM
                        sampleDensity
                        timeDensity
```

Figure 7-26 Uplink PTRS Configuration Parameters

Some parameters in the PTRS-UplinkConfig are the same as the downlink. Additional parameters include:

- maxNrofPorts - the maximum number of UL PTRS ports for CP-OFDM.
- ptrs-Power - this indicates the Uplink PTRS power boosting factor per PTRS port.
- sampleDensity - this indicates the sample density of PTRS for DFT-s-OFDM, pre-DFT, and like CP-OFDM relates to the scheduled BW.
- timeDensity - this identifies the time density, i.e. OFDM symbol level, of PTRS for DFT-s-OFDM.

The device assumes that PTRS is not present when any of these conditions are met:

- The scheduled MCS is from the 64QAM table and is smaller than 10.
- The scheduled MCS is from the 256QAM table and is smaller than 5.
- The number of scheduled RBs is smaller than 3.
- The RNTI equals RA-RNTI, SI-RNTI or P-RNTI, i.e. Random Access, System Information or Paging.

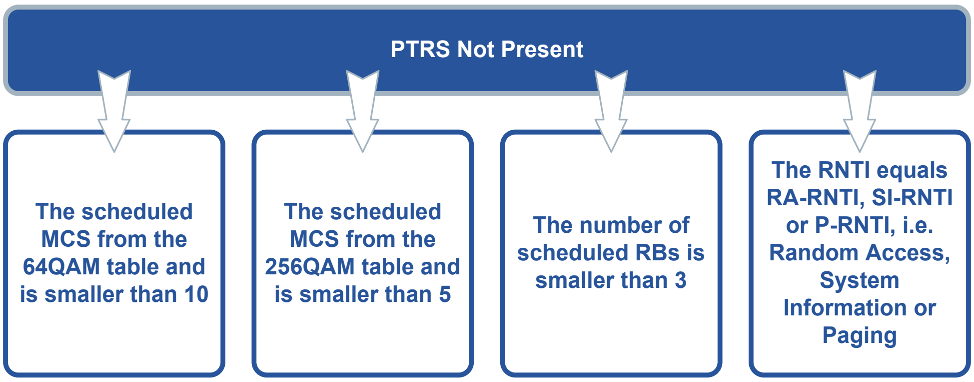


Figure 7-27 PTRS Not Present

8 NR Layer 2 and Layer 3

8.1 NR Radio Resouce Control

NR RRC (Radio Resource Control)[14] is the control protocol between the device and the gNB. 5G Phase 1 RRC ASN.1 (Abstract Syntax Notation - Version 1) for EN-DC (E-UTRA NR Dual Connectivity) operation was completed in March 2018, however the full 5G Phase 1 release wasn't completed till later, as illustrated in Figure 8-1. This means that some of the SA (Standalone) RRC parameters are extensions to the initially defined messages.

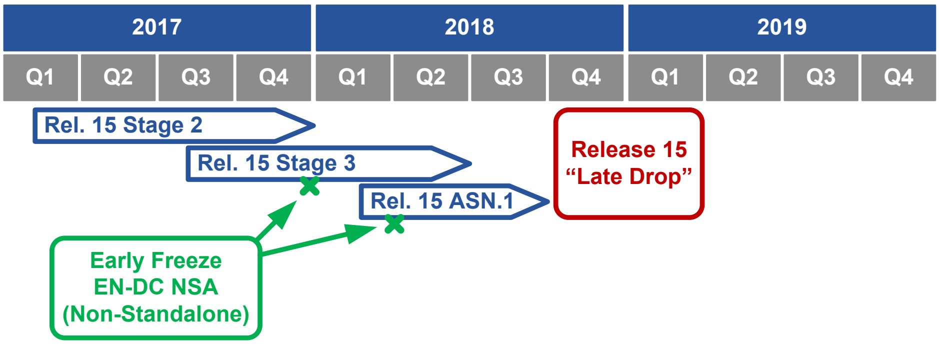


Figure 8-1 NR RRC Timeline

8.1.1 NR RRC States

NR RRC has three defined states:

- NR RRC_Idle - this provides services to support DRX (Discontinuous Reception), broadcast of SI (System Information) to enable access, cell reselection and paging information.
- NR RRC_CONNECTED - in this state the device has AS (Access Stratum) context information stored in the gNB and has an RRC connection.
- NR RRC_INACTIVE - the device is configured with specific DRX parameters and mobility is managed in a RAN-based notification area. For those familiar with UMTS operation, it is like the URA_PCH (UTRAN Registration Area Paging) sub-state concept.

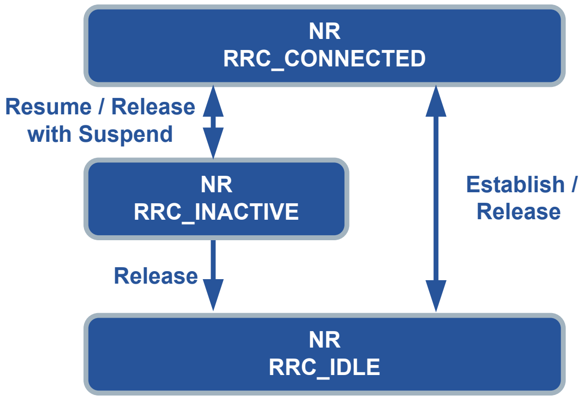


Figure 8-2 NR RRC States

[14] 3GPP TS 38.331 NR RRC (Radio Resource Control) Protocol Specification

8.1.2 RRC Messages

As part of the full 5G Phase 1 release, several new RRC messages have been created, as well as some re-use of existing LTE terminology. Figure 8-3 illustrates the NR RRC messages, along with some relevant grouping.

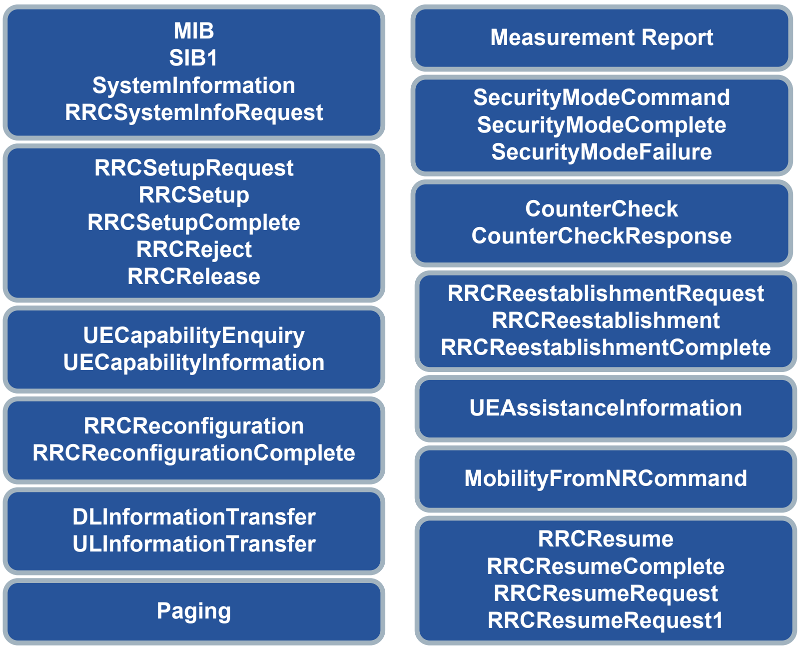


Figure 8-3 NR RRC Messages

8.1.3 RRC Critical and Non-Critical Extensions

Like LTE, NR RRC is also defined using ASN.1 formatting. The mechanism to manage changes/updates in the protocol for specific messages is done using Critical Extensions and Non-Critical Extensions. Figure 8-4 illustrates an example of the NR RRC Reconfiguration message, highlighting the use of a Non-Critical Extension to provide access to parameters which were defined in a latter version of the specification, for example between v15.1 and v15.3 NR RRC. One example is the Master Cell Group parameter, this is in a non-critical extension which is a mandatory for standalone operation.

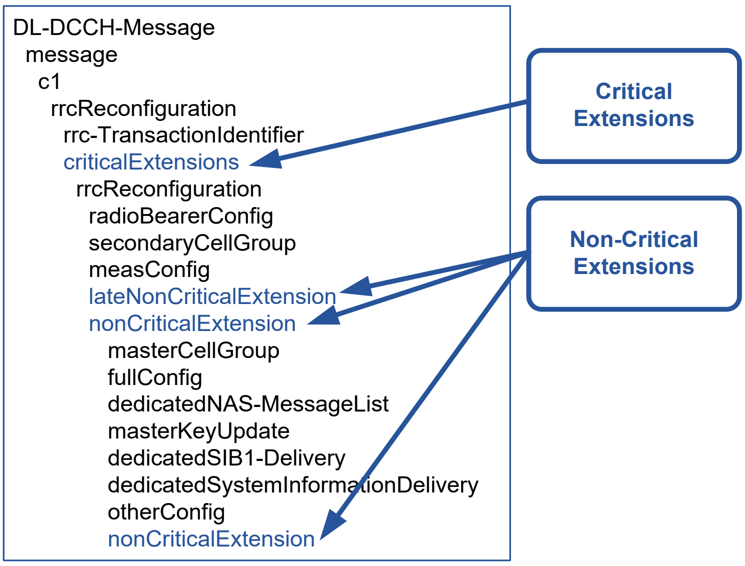


Figure 8-4 Critical and Non-Critical RRC Extensions

8.2 NR Service Data Application Protocol

8.2.1 SDAP in the RAN

SDAP (Service Data Application Protocol) is a new air interface protocol introduced with NR. It will also be utilized on the LTE air interface when operating in NGEN-DC, i.e. a ng-eNB can utilize SDAP when connecting to a 5GC (5G Core). Figure 8-5 illustrates the location of SDAP in the master and secondary RAN nodes, as well as how it relates to the various bearer options.

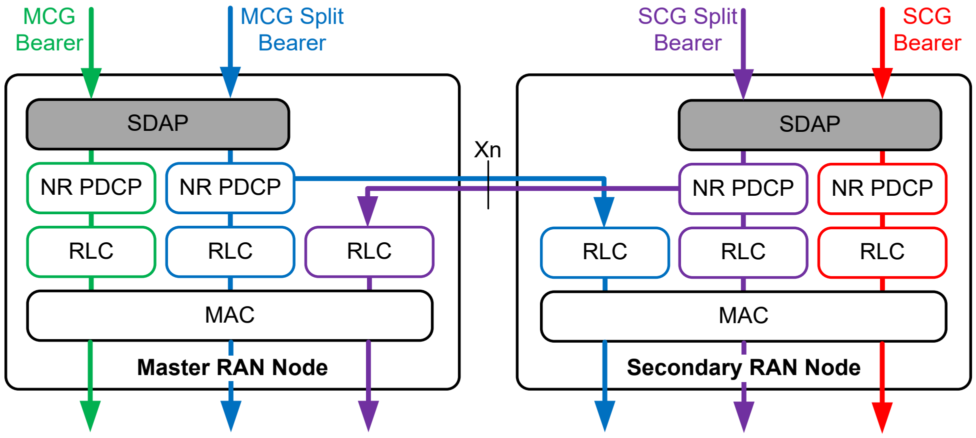


Figure 8-5 NR-DC / MR-DC Split Bearer (NGEN-DC and NE-DC)

8.2.2 SDAP Functions

The main role of SDAP is to transfer UP (User Plane) data. In so doing, it maps one or more QoS Flows to a DRB (Dedicated Radio Bearer) in both the DL (Downlink) and UL (Uplink) directions. Key functions of SDAP are illustrated in Figure 8-6.

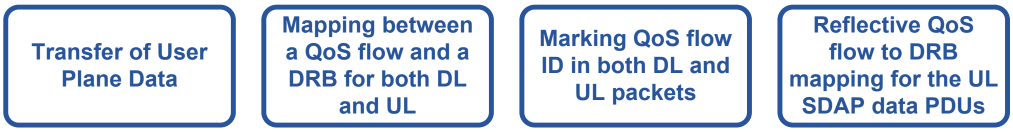


Figure 8-6 SDAP Functions

Figure 8-7 illustrates the functional view of SDAP.

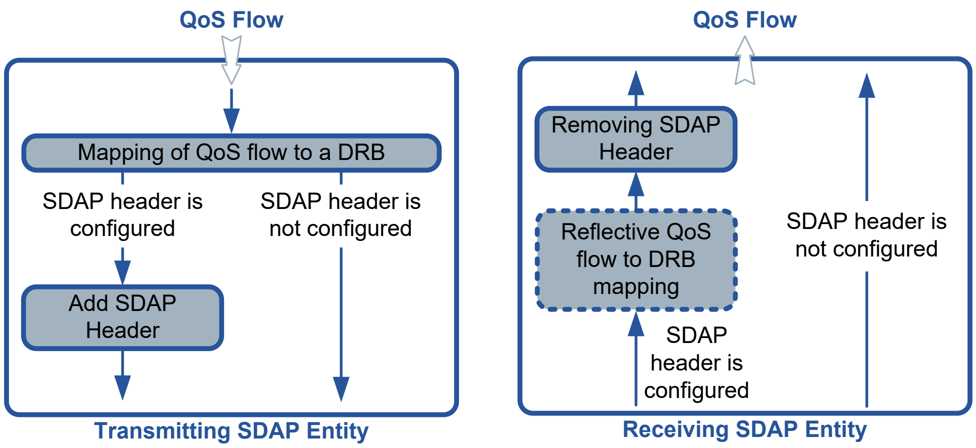


Figure 8-7 SDAP Functional View

The transmitting entity maps the QoS Flow(s) to a DRB. This is initially based on the RRC Reconfiguration; however, it is possible for the downlink SDAP header to indicate a change. Depending on RRC Reconfiguration, SDAP may be configured to include a SDAP header for a DRB that can indicate the QFI (Quality Flow ID). However, if there is a 1 to 1 mapping the header may not be needed.

In the receiving entity, if a SDAP header is included, it will include the QFI of the QoS Flow. In addition, if a downlink SDAP header it can also include the RQI (Reflective QoS Indication) and RDI (Reflective QoS flow to DRB mapping Indication).

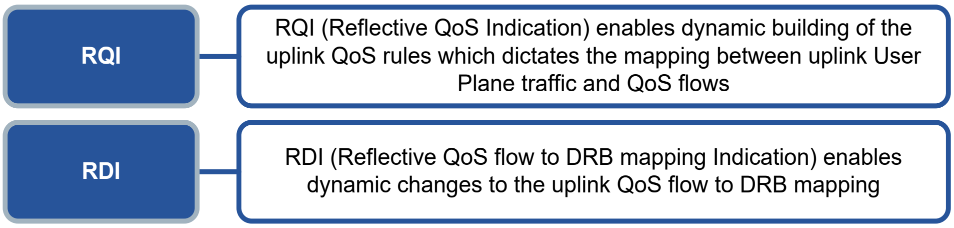


Figure 8-8 RQI and RDI

8.2.3 SDAP Headers

There are various configuration options for SDAP. The simplest configuration illustrated in Figure 8-9, with a 1 to 1 mapping between the QoS Flow and a DRB. As such, there is no need for a SDAP header. The identification of the DRB is performed at the MAC layer, with the receiving entity mapping the DRB directly to the QFI.

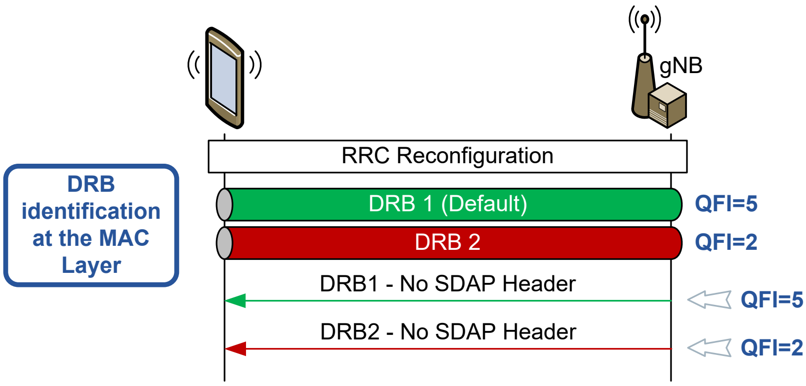


Figure 8-9 SDAP Mapping Example (No Header)

Note that one of the DRBs is defined as the "Default". This is utilized by any flows that have not been configured by RRC to map to a specific DRB.

SDAP Data PDU format without SDAP header

Figure 8-10 illustrates the format when no SDAP header is configured. This can be utilized in both the uplink and downlink.

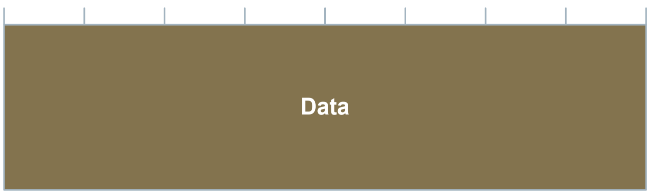


Figure 8-10 SDAP Data PDU format without SDAP header

DL SDAP Data PDU format with SDAP header

The downlink packets may be configured to include a SDAP header, if so the format will be based on Figure 8-11. This includes the QFI, as well as the RDI and RQI bits.

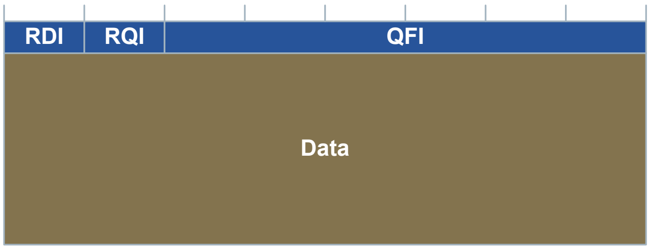


Figure 8-11 DL SDAP Data PDU format with SDAP header

UL SDAP Data PDU format with SDAP header

The uplink SDAP header, if included, will be either a Data PDU (Protocol Data Unit) or a Control PDU. It includes the QFI, as well as a R (Reserved) bit.

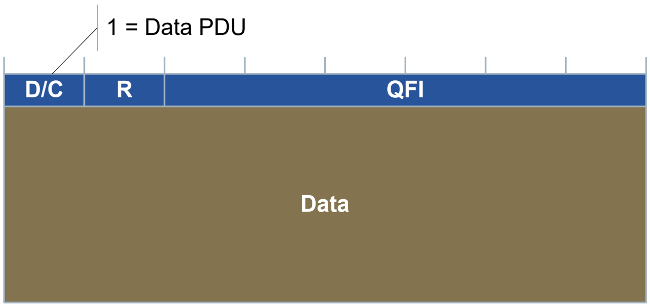


Figure 8-12 UL SDAP Data PDU format with SDAP header

End-Marker Control PDU

The End-Marker is the only defined Control PDU. This is utilized in the uplink to indicated that no more uplink data PDU's for the indicated QFI will be sent on the DRB this is received on.

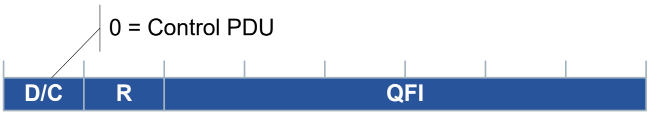


Figure 8-13 End-Marker Control PDU

8.2.4 SDAP Example

Figure 8-14 illustrates an example whereby the device is configured with three DRB's. DRB 1 (Default) and DRB 2 both have an indication to utilize the SDAP header, whereby DRB 3 has not been configured with a SDAP header. Note that the configuration of the SDAP heading in the uplink and downlink is independent. In summary:

- The SDAP header in DRB1 can multiplex QFI=5 and QFI=6.
- The SDAP header is DRB2 can indicate QFI=2. In addition, since the SDAP header is included it enables the use of RQI and RDI.
- There is no SDAP header configured for DRB3. As such, any changes would need to be implemented at RRC.

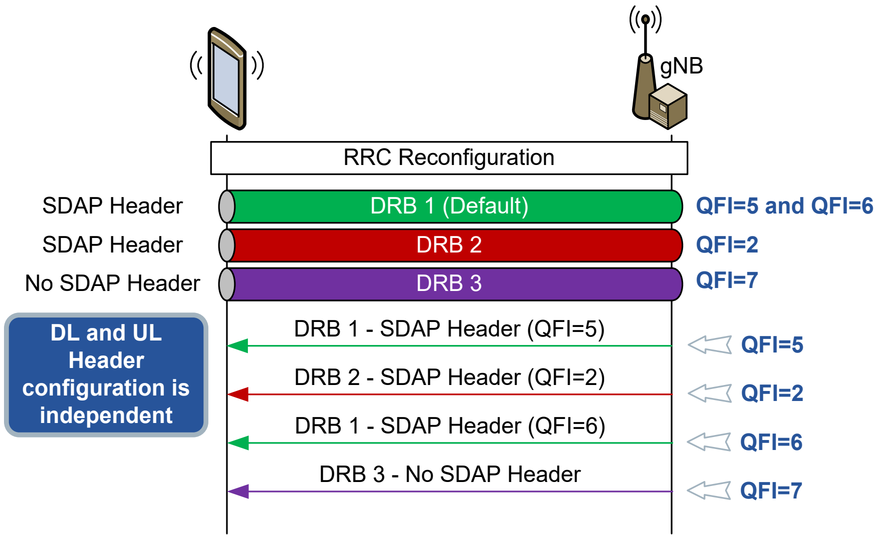


Figure 8-14 SDAP QoS Flow Mapping Example

8.2.5 RDI Indication

The downlink Data PDU with SDAP header can also carry the RDI. As its name suggest it provides "Reflective QoS flow to DRB mapping Indication".

Figure 8-15 illustrates how the RDI can be utilized to move the DRB for QFI=6 uplink data from DRB 1 to DRB 2. Initially, the "stored UL QoS flow to DRB mapping" rule maps QFI=6 to DRB 1 (based on RRC). However, when the device receives a QFI=6 on DRB 2 the RDI is set (RDI=1). This triggers the device to update its stored mapping rule and send an End-Marker Control PDU on DRB 1 indicating no more data from QFI=6 will be sent on it.

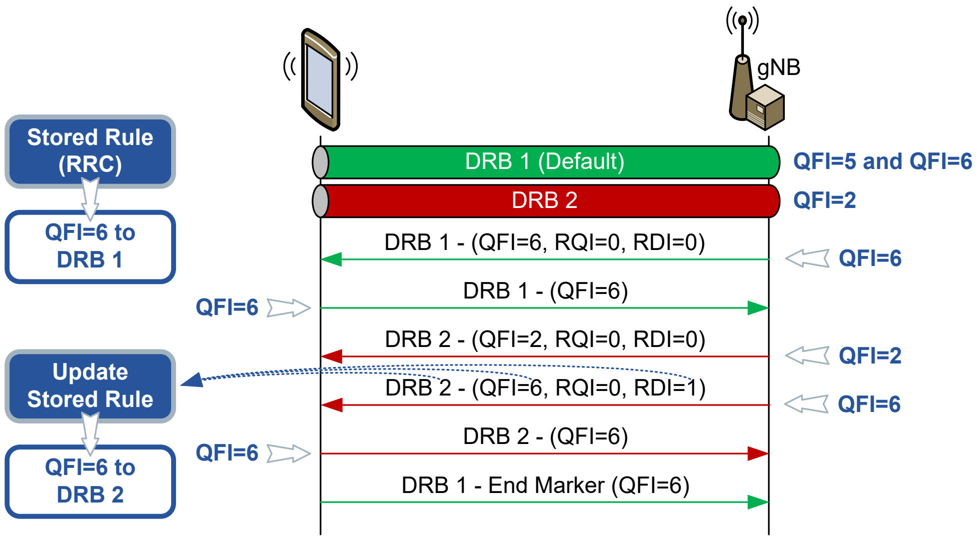


Figure 8-15 RDI Indication

Note that this procedure assumes that the downlink and uplink SDAP headers have been enabled for the DRB's.

8.2.6 RQI Indication

The downlink Data PDU with SDAP header can also carry the RQI. As its name suggest it provides "Reflective QoS Indication". As illustrated in Figure 8-16, this provides a mechanism to update the QoS Rule for a specific QoS Flow.

Initially, the QoS Rule has filters related to the “orange” IP datagram, e.g. source/destination IP addresses, ports etc. The 5GC (5G Core), specifically the UPF (User Plane Function) can trigger the update to the rule by setting the RQI flag in the GTPv1-U (GPRS Tunnelling Protocol version 1 - User Plane) extension header. Specifically, the PDU Session User Plane Protocol extension. The gNB includes the RQI=1 indicator in the downlink SDAP header which indicates to the device that the rule needs updating. As such the NAS (Non Access Stratum) layer is informed and the “blue” IP datagram header is analysed to create an appropriate filter. In so doing, subsequent packets matching the updated QoS Rule will be mapped to QFI=2.

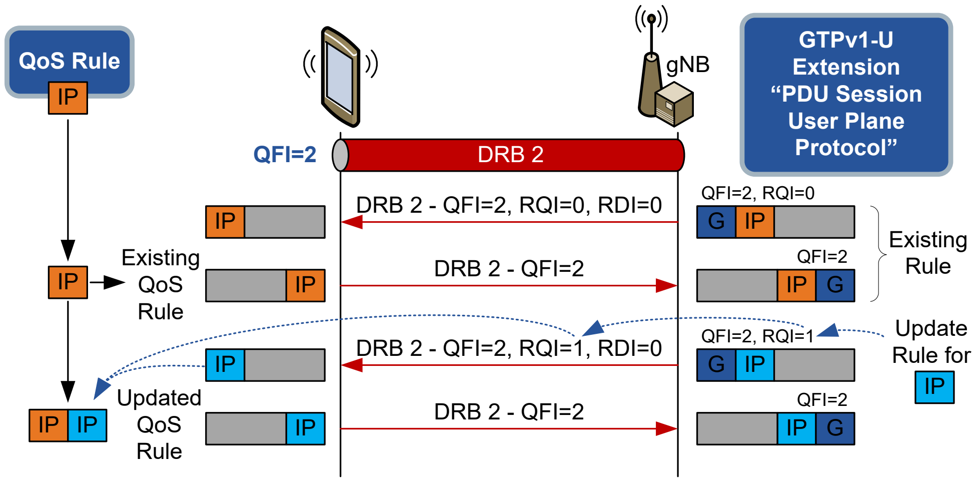


Figure 8-16 RQI Indication

8.3 NR Packet Data Convergence Protocol

The NR PDCP (Packet Data Convergence Protocol) is like E-UTRA PDCP, in that it offers similar services and formats. Figure 8-17 illustrates the location of the NR-PDCP for the various bearer options.

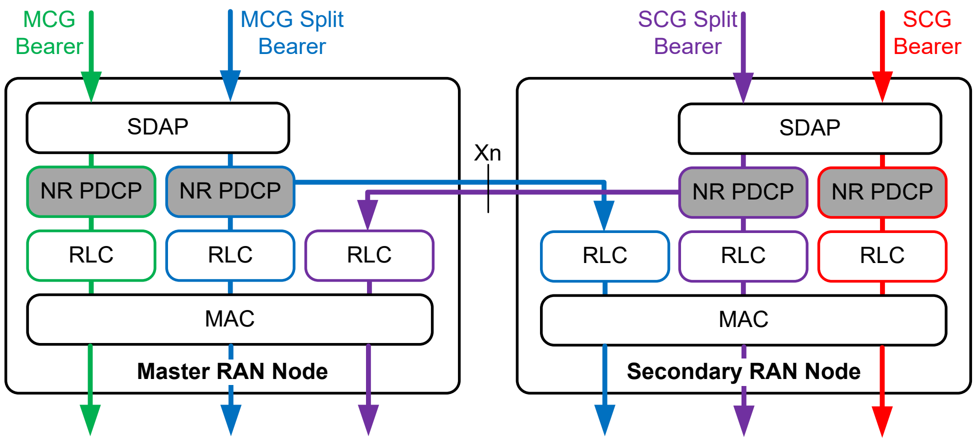


Figure 8-17 NR-DC / MR-DC Split Bearer (NGEN-DC and NE-DC)

8.3.1 PDCP Services

The following services are provided by NR PDCP[15] to the upper layers:

[15] 3GPP TS 38.323 - PDCP (Packet Data Convergence Protocol)

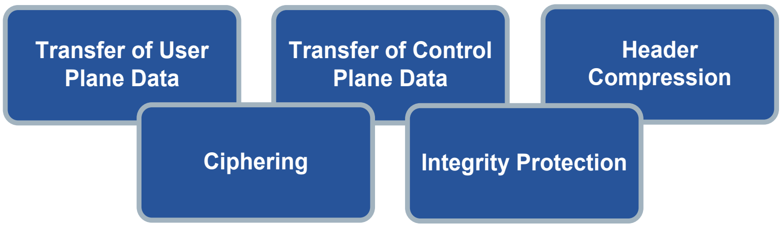


Figure 8-18 PDCP Services to Upper Layers

The maximum supported size of a PDCP SDU (Service Data Unit) is 9000 bytes.

8.3.2 Functions

Figure 8-19 illustrates some of the functions performed in the transmitting and receiving PDCP entity. Packets identified as a PDCP SDU imply that they are from higher layers, e.g. RRC or IP. In contrast, packets not associated to a PDCP SDU are part of PDCP control signalling; typical examples include PDCP Status Report and Header Compression Feedback Information.

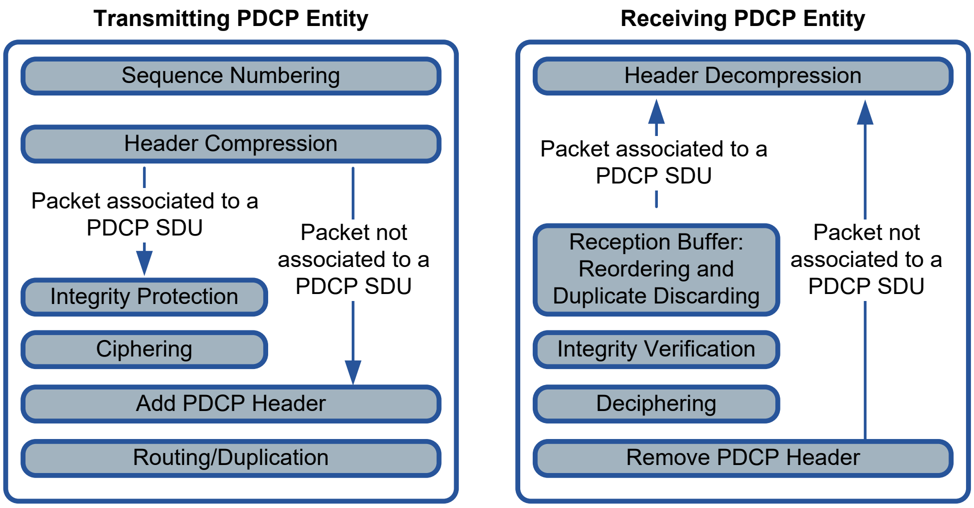


Figure 8-19 PDCP Functions

8.3.3 PDCP Profiles

As part of PDCP implementation, there are several ROHC (Robust Header Compression) profiles used by both compressors and decompressors in the device and RAN. Figure 8-20 identifies the available profiles and associated usage; profile 0x0000 (ROHC uncompressed), RFC 4995 must always be supported when the use of ROHC is configured.

Profile Identifier	Usage	Reference
0x0000	No Compression	RFC 4995
0x0001	RTP/UDP/IP	RFC 3095, RFC 4815
0x0002	UDP/IP	RFC 3095, RFC 4815
0x0003	ESP/IP	RFC 3095, RFC 4815
0x0004	IP	RFC 3843, RFC 4815
0x0006	TCP/IP	RFC 4996
0x0101	RTP/UDP/IP	RFC 5225
0x0102	UDP/IP	RFC 5225
0x0103	ESP/IP	RFC 5225
0x0104	IP	RFC 5225

Figure 8-20 PDCP Profiles

IMS (IP Multimedia Subsystem) capable devices supporting VoIP (Voice over IP) are required to support ROHC profiles 0x0000, 0x0001, 0x0002 and 0x0004.

8.3.4 PDCP Protocol Data Units

The PDCP layer includes data and control PDUs. The PDCP Data PDU conveys:

- Control Plane data with integrity protection (MAC-I).
- User Plane data with optional integrity protection.

In contrast, the PDCP Control PDU carries:

- PDCP Status Reports.
- An interspersed ROHC feedback.

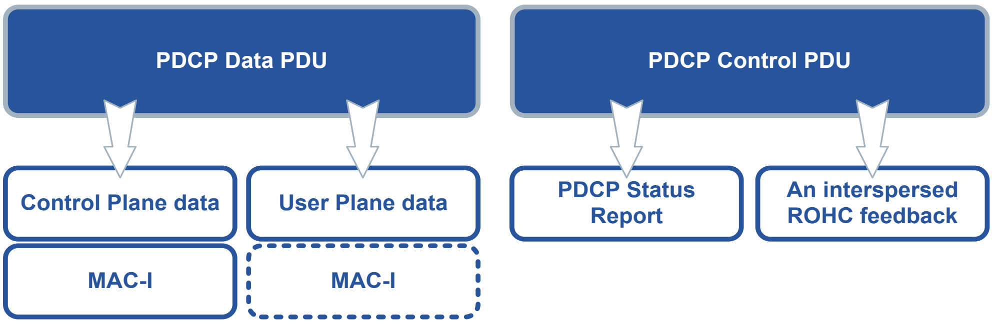


Figure 8-21 PDCP Protocol Data Units

8.3.4.1 PDCP Data PDU - SRBs

Figure 8-22 shows the format of the PDCP data PDU when transferring SRB data. The frame includes a 12bit SN (Sequence Number) and a MAC-I integrity check.

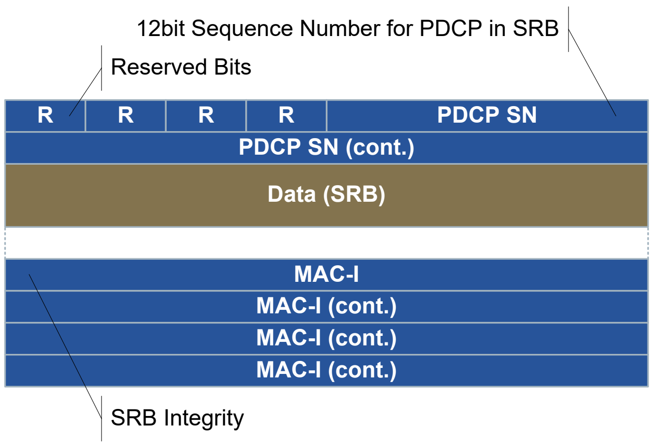


Figure 8-22 PDCP Data PDU for SRBs

8.3.4.2 User Plane PDCP Data PDU - 12bit SN

There are two variants of User Plane PDU defined, providing a long or short sequence number in the header. Figure 8-23 illustrates the short SN PDU, as such it includes a 12bit SN. In addition, the first bit is assigned to a D/C (Data/Control) bit, where 0 = Control PDU and 1 = Data PDU. The 12bit SN format is available to RLC AM (Acknowledged Mode) or UM (Unacknowledged Mode).

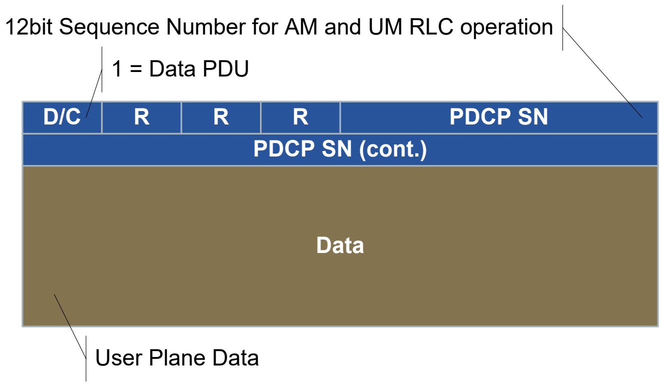


Figure 8-23 User Plane PDCP Data PDU - 12bit SN

8.3.4.3 User Plane PDCP Data PDU - 18bit SN

Figure 8-24 illustrates the PDCP data PDU with a 18bit sequence number. This format is available for RLC AM and RLC UM. It is the responsibility of RRC to configure the “PDCP Configuration” parameter, specifying the SN length, ROHC Profiles, Discard Timer, etc.

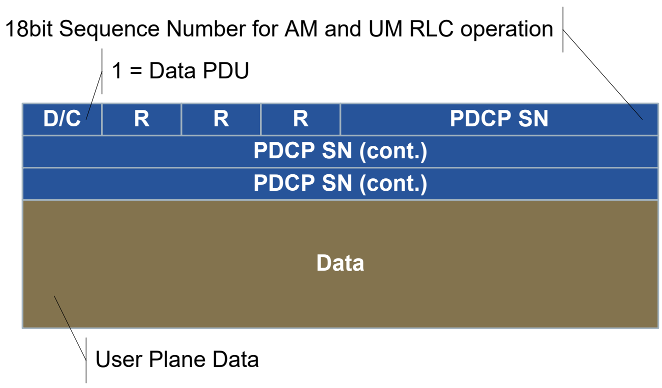


Figure 8-24 User Plane PDCP Data PDU - 18bit SN

8.3.4.4 PDCP Control PDU - Feedback

Figure 8-25 illustrates the control PDU for ROHC feedback. This is sent uncompressed and includes a ROHC feedback packet.

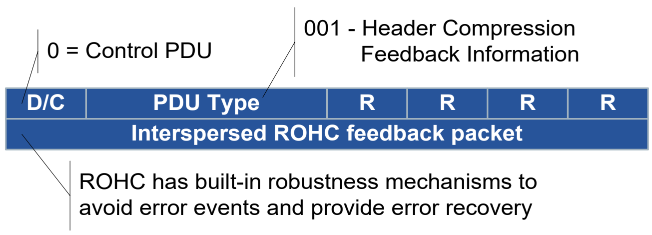


Figure 8-25 PDCP Control PDU - Feedback

8.3.4.5 PDCP Control PDU - Status Report

Figure 8-26 illustrates a PDCP status report using a 12bit SN. It includes the FMC (First Missing Count) as well as an optional bitmap. The bitmap includes 0s and 1s, where a zero indicates a PDCP SDU is missing in the receiver.

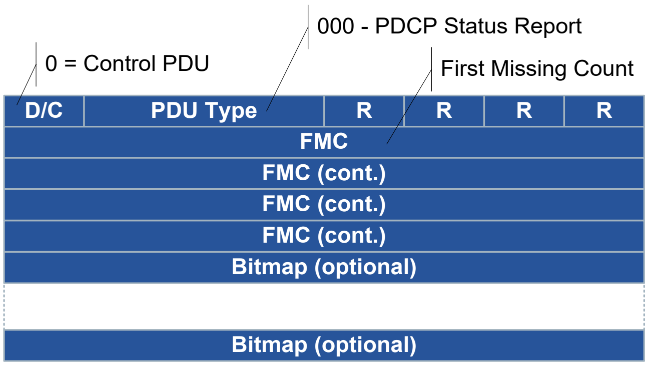


Figure 8-26 PDCP Control PDU - Status Report

8.3.5 PDCP Example

Figure 8-27 illustrates the basic PDCP operation, as well as the utilization of PDCP Status Report messages. Prior to being handed over to the target gNB, the device received PDCP SN (Sequence Number) 1 and 2, as well as sending data with the SN=1.

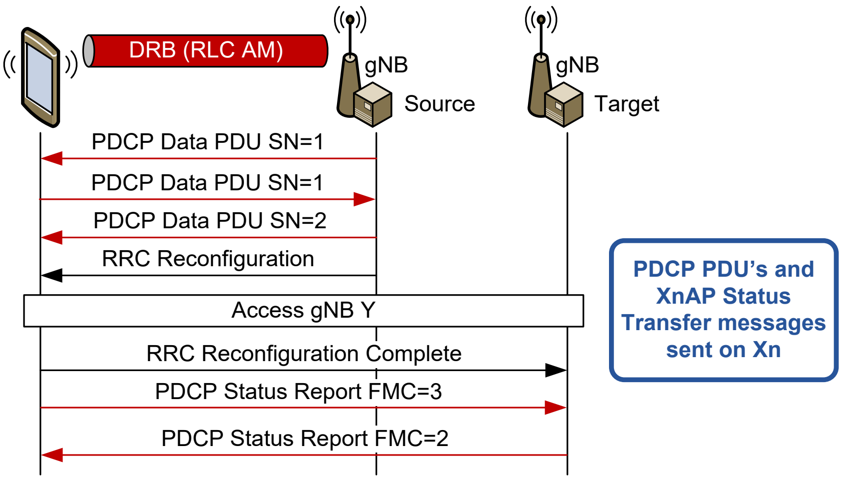


Figure 8-27 PDCP Status Report

Following the successful handover, the device sends a PDCP Status Report in each DRB. This includes the FMC=3, i.e. indicating it has received SN=1 and SN=2 in the downlink. In response, the gNB indicates FMC=2. Note that the source gNB will have utilized a X2AP Status Transfer message to inform the target gNB of the current PDCP count values in the downlink and uplink directions. In addition, the old gNB will forward unsent PDCP packets to the target gNB.

8.4 NR Radio Link Control

The NR RLC (Radio Link Control)[16] protocol exists in the device and the gNB.

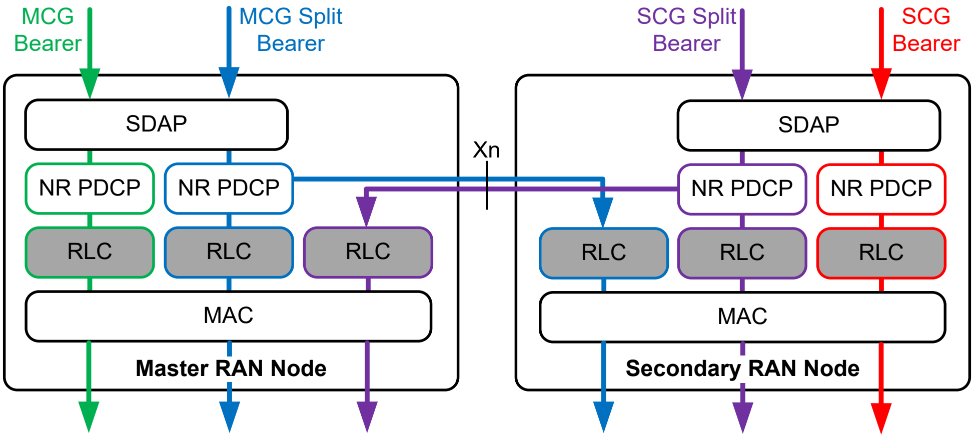


Figure 8-28 NR Radio Link Control

It provides three main information delivery services to the higher layers, TM (Transparent Mode), UM (Unacknowledged Mode) and AM (Acknowledged Mode). In addition, some of these data delivery services offer segmentation and re-assembly and error protection.

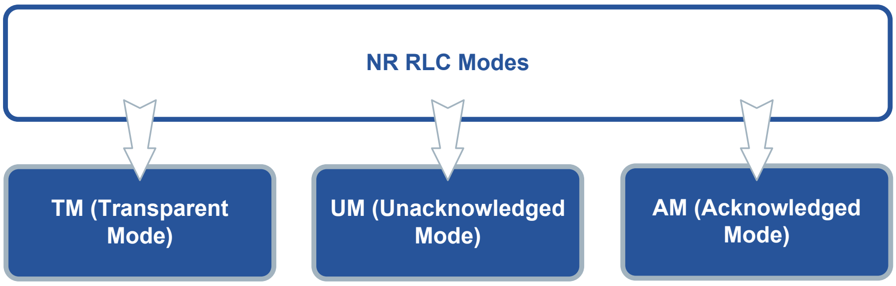


Figure 8-29 Radio Link Control Modes

Figure 8-30 illustrates the different RLC peer entities as identified at the device. It should be noted that the AM entity has one combined transmitting and receiving entity for the delivery of information using the Acknowledged Mode service of RLC.

[16] 3GPP TS 38.322 - RLC (Radio Link Control)

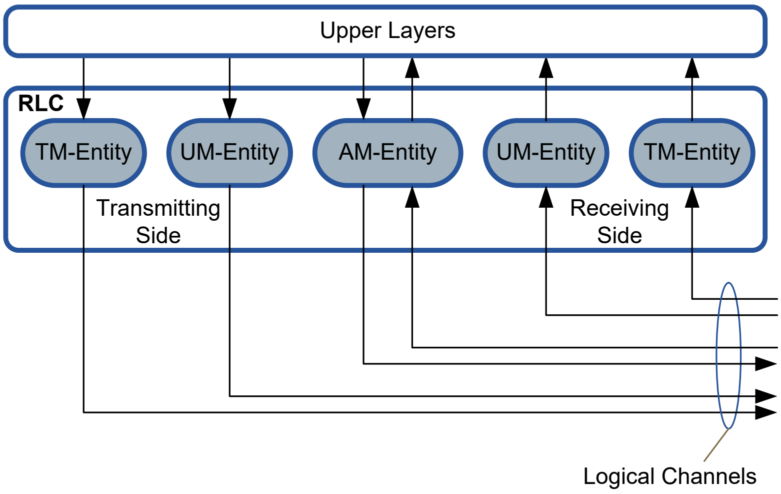


Figure 8-30 RLC Entities

8.4.1 Transparent Mode

TM (Transparent Mode) data is formatted within the TM-Entity of the RLC layer. As the name suggests, it does not add any header information to the higher layer SDU (Service Data Unit). It does however provide a transmission buffer. The TM-RLC mode is used for three logical channels, namely the BCCH (Broadcast Control Channel), PCCH (Paging Control Channel) and Uplink/Downlink CCCH (Common Control Channel). Note that for EN-DC operation the CCCH and PCCH on NR are not required.

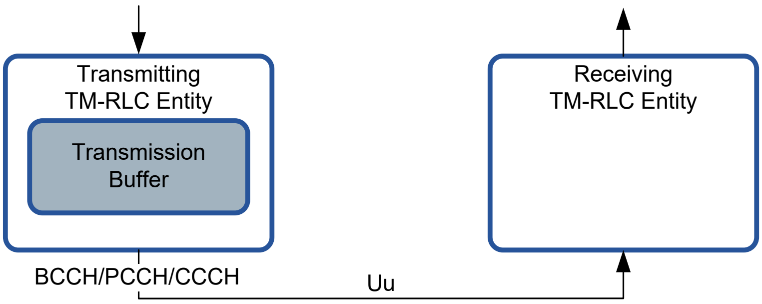


Figure 8-31 Transparent Mode

8.4.2 Unacknowledged Mode

The Unacknowledged Mode functionality allows for the segmentation and reassembly of RLC SDUs. This enables UMD (Unacknowledged Mode Data) PDUs to fit within the total size of RLC PDUs indicated by lower layers at the transmission opportunity notified by the lower layers.

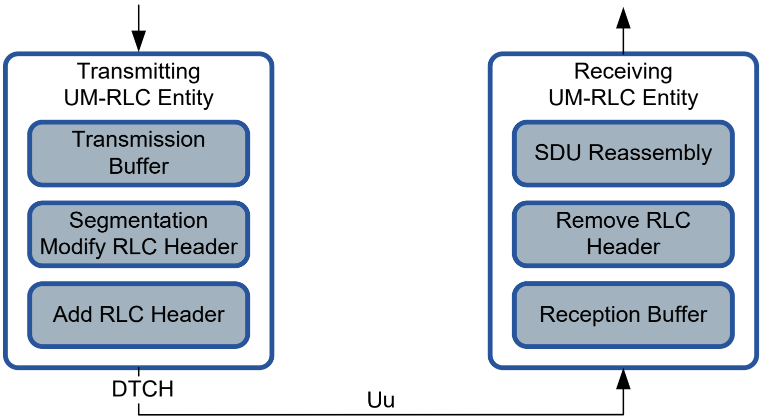


Figure 8-32 Unacknowledged Mode

The UM mode can be utilized for DTCH (Dedicated Traffic Channel) operation.

8.4.3 Acknowledged Mode

The Acknowledged Mode of RLC, as its name suggests, provides functions that are needed to support acknowledged data transfer. These include:

- Segmentation and reassembly.
- Error correction.
- In-sequence delivery of higher layer data.
- Duplicate detection.

Reliability in AM Mode is achieved by selective retransmission. This involves the transmitter sending several AMD (Acknowledged Mode Data) PDUs and then the receiving entity positively acknowledging all or some of them. Figure 8-33 illustrates the AM-RLC entity in the device and gNB.

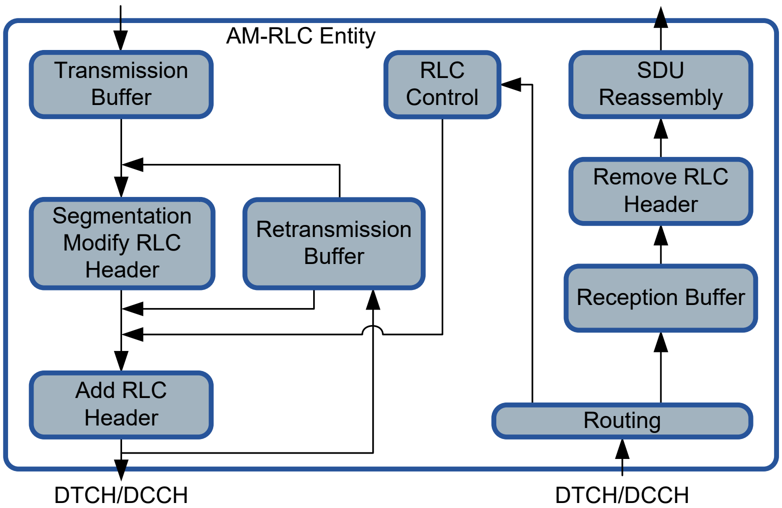


Figure 8-33 Acknowledged Mode

The process begins with the RLC data PDUs being formatted and then being sent from the transmitter buffer. On receipt of several PDUs, the receiving entity will send a status report back to the transmitter. This indicates whether the previous PDUs have been received correctly or not. The sender, based on this information, retransmits the erroneous PDUs. The transmitting side may also include a polling request in the RLC header which forces a status report to be provided from the receiving side.

8.4.4 RLC Protocol Data Units

The RLC protocol defines two main categories of PDU, these are Data and Control. Figure 8-34 identifies the different PDU types that are available.

Data Transfer Mode	PDU Name	Description
Transparent	TMD	Transparent Mode Data
Unacknowledged	UMD	Sequenced Unacknowledged Mode Data
Acknowledged	AMD	Sequenced Acknowledged Mode Data
	STATUS	ACK_SN, NACK_SN, SOstart, SOend, NACK Range and NACK_SN

Figure 8-34 RLC PDU's

8.4.4.1 TMD PDU

The TMD (Transparent Mode Data) PDU carries user data when RLC is operating in Transparent Mode. In this mode, no overhead (i.e. no header) is added.

8.4.4.2 UMD PDU

The UMD (Unacknowledged Mode Data) PDUs are used for unacknowledged data transfer, conveying RLC SDUs. Figure 8-35 illustrates the three main header types.

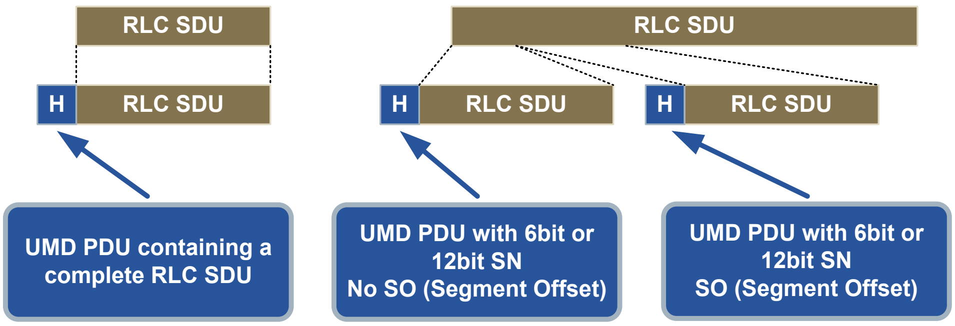


Figure 8-35 UMD PDU Header Options

For segmented RLC SDUs there is the option of using 6bit SN (Sequence Number) or 12bit SN. With the first segment not requiring a SO (Segment Offset).

The RLC specification details the different PDU formats. Figure 8-36 illustrates examples without a SO (Segment Offset). Note that a 6bit SN header also exists.

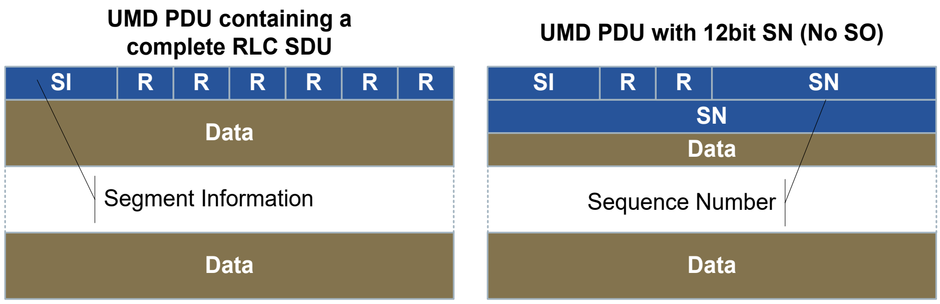


Figure 8-36 Example of UMD PDUs Without SO

Figure 8-37 illustrates an example of the Segment Offset when utilizing the 12bit SN, again a 6bit SN version also exists. The SO field indicates the position of the RLC SDU segment in bytes within the original RLC SDU.

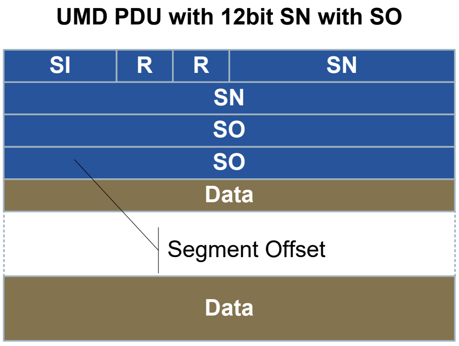


Figure 8-37 Example of UMD PDU with 12bit SN and SO

The SI (Segment Information) field has four possible values and is used for various permutations of segmentation. The different permutations are illustrated in Figure 8-38.

Value	Description
00	Data field contains all bytes of an RLC SDU
01	Data field contains the first segment of an RLC SDU
10	Data field contains the last segment of an RLC SDU
11	Data field contains neither the first nor last segment of an RLC SDU

Figure 8-38 SI (Segment Information) Field

8.4.4.3 AMD PDU

The AMD (Acknowledged Mode Data) PDU is used for acknowledged mode data transfer. Like UMD PDU's, formats exist with and without the SO. Figure 8-39 illustrates an example of the 12bit AMD PDU format with SO. Note that there is also a 18bit version.

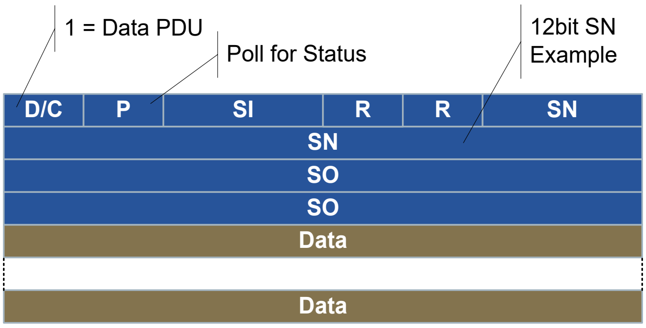


Figure 8-39 AMD PDU - 12bit with SO

Each AMD PDU also includes a P (Polling) flag, allowing the device or gNB to request a Status PDU.

8.4.4.4 Status PDU

An AM RLC entity sends Status PDUs to its peer AM RLC entity to provide positive and/or negative acknowledgements of RLC PDUs (or portions of them). It is the responsibility of RRC to configure whether the status prohibit function is to be used for an AM RLC entity, i.e. a timer to prevent the receiver from sending Status PDUs.

Triggers to initiate STATUS reporting include:

- Polling from its peer AM RLC entity.
- Detection of reception failure of an RLC data PDU.

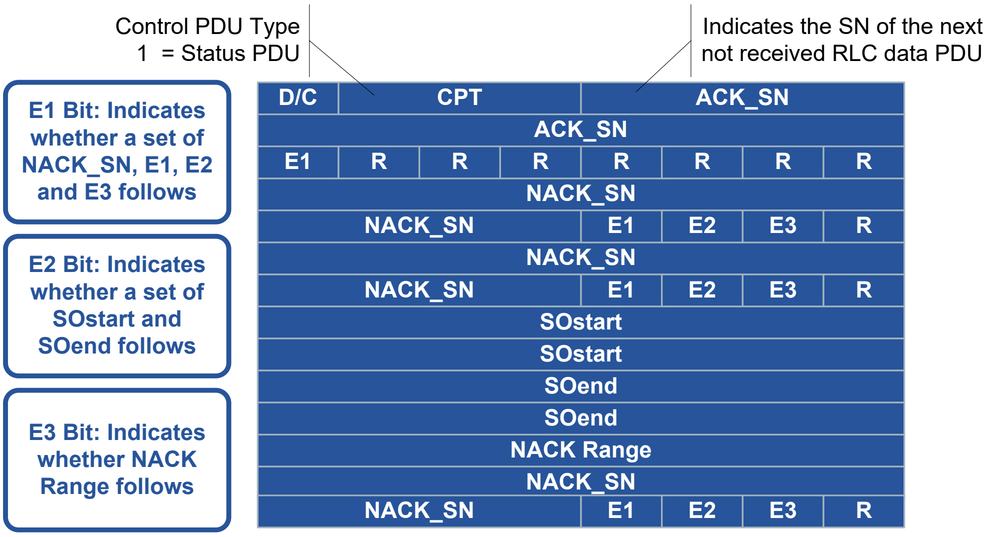


Figure 8-40 Status PDU

Other parameter in the Status PDU include:

- NACK_SN (Negative Acknowledgement SN) Field - this indicates the SN of the RLC SDU (or RLC SDU segment) that has been detected as lost at the receiving side of the AM RLC entity.
- SOstart field and SOend field - these indicate the portion of the RLC SDU with SN = NACK_SN (the NACK_SN for which the SOstart/SOend related to) that has been detected as lost at the receiving side of the AM RLC entity.
- NACK Range - this is the number of consecutively lost RLC SDUs starting from and including NACK_SN.

8.5 NR Medium Access Control

8.5.1 MAC Services and Functions

MAC (Medium Access Control) provides the interface between the NR protocols and the NR Physical Layer.

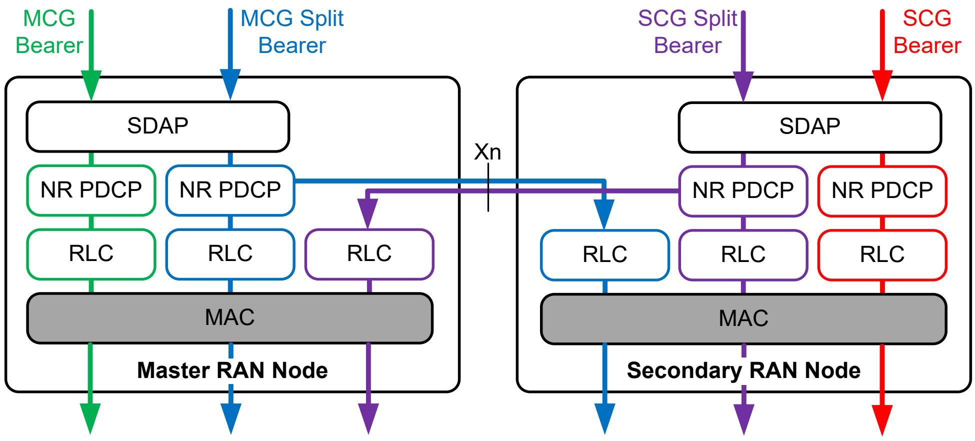


Figure 8-41 NR MAC

8.5.1.1 Services Provided to the Upper Layers

The MAC sublayer provides the following services to the upper layers:

Figure 8-42 Services Provided to Upper Layers

8.5.1.2 Services Expected from Physical Layer

The physical layer provides the following services to MAC:

- Data transfer services.
- Signalling of HARQ feedback.
- Signalling of Scheduling Request.
- Measurements, e.g. CQI (Channel Quality Indicator).

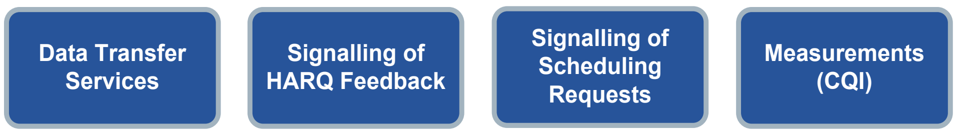


Figure 8-43 Services Expected from Physical Layer

A DL-SCH and UL-SCH may support different numerologies and/or TTI (Transmission Time Interval) duration within the MAC entity.

Access to the data transfer services is through the use of transport channels. The characteristics of a transport channel are defined by its transport format (or format set), specifying the physical layer processing to be applied to the transport channel in question, such as channel coding and interleaving, and any service-specific rate matching as needed.

8.5.1.3 MAC Sublayer Functions

The MAC sublayer supports the following functions:

MAC Function	Downlink	Uplink
Mapping between Logical Channels and Transport Channels	X	X
Multiplexing		X
Demultiplexing	X	
Scheduling Information Reporting		X
Error Correction through HARQ	X	X
Logical Channel Prioritisation		X

Figure 8-44 MAC Sublayer Functions

8.5.2 MAC Control Elements

A key part of MAC operation relates to passing control information, with each identified as a CE (Control Element). There are many CEs for 5G NR, Figure 8-45 lists the various types.

Buffer Status Report MAC CEs
C-RNTI MAC CE
UE Contention Resolution Identity MAC CE
Timing Advance Command MAC CE
DRX Command MAC CE
Long DRX Command MAC CE
Configured Grant Confirmation MAC CE
Single Entry PHR MAC CE
Multiple Entry PHR MAC CE
SCell Activation/Deactivation MAC CEs
Duplication Activation/Deactivation MAC CE
SP CSI-RS / CSI-IM Resource Set Activation/Deactivation MAC CE
Aperiodic CSI Trigger State Subselection MAC CE
TCI States Activation/Deactivation for UE-specific PDSCH MAC CE
TCI State Indication for UE-specific PDCCH MAC CE
SP CSI reporting on PUCCH Activation/Deactivation MAC CE
SP SRS Activation/Deactivation MAC CE
PUCCH spatial relation Activation/Deactivation MAC CE
SP ZP CSI-RS Resource Set Activation/Deactivation MAC CE

Figure 8-45 NR MAC Control Elements

Each CE has a defined set of parameters and structure which can be found within the 3GPP MAC specification[17].

8.5.3 NR RNTI Identities

MAC provides the control and traffic logical channels. When MAC uses the PDCCH (Physical Downlink Control Channel) to indicate radio resource allocation, a RNTI (Radio Network Temporary Identifier) is used. However, there are many different RNTIs types in the gNB.

The set of RNTIs defined for 5G NR include:

- P-RNTI (Paging RNTI).
- SI-RNTI (System Information RNTI).
- RA-RNTI (Random Access RNTI).

[17] 3GPP TS 38.321 MAC (Medium Access Control) Protocol Specification

- C-RNTI (Cell RNTI).
- Temporary C-RNTI.
- MCS-C-RNTI (Modulation and Coding Scheme C-RNTI).
- CS-RNTI (Configured Scheduling RNTI).
- TPC-PUCCH-RNTI (Transmit Power Control PUCCH RNTI).
- TPC-PUSCH-RNTI (Transmit Power Control PUSCH RNTI).
- TPC-SRS-RNTI (Transmit Power Control Sounding Reference Symbols RNTI).
- INT-RNTI (Interruption RNTI).
- SFI-RNTI (Slot Format Indication RNTI).
- SP-CSI-RNTI (Semi-Persistent CSI RNTI).

Figure 8-46 summarizes the usage of the RNTIs.

Value	Usage
P-RNTI	Paging and System Information change notification
SI-RNTI	Broadcast of System Information
RA-RNTI	Random Access Response
Temporary C-RNTI	Contention Resolution (when no valid C-RNTI is available)
Temporary C-RNTI	Msg3 transmission
C-RNTI	Dynamically scheduled unicast transmission
C-RNTI	Triggering of PDCCH ordered random access
MCS-C-RNTI	Indicate use of qam64LowSE for grant-based transmissions
CS-RNTI	Configured scheduled unicast transmission
CS-RNTI	Configured scheduled unicast transmission (deactivation)
TPC-PUCCH-RNTI	PUCCH power control
TPC-PUSCH-RNTI	PUSCH power control
TPC-SRS-RNTI	SRS trigger and power control
INT-RNTI	Indication pre-emption in DL
SFI-RNTI	Slot Format Indication on the given cell
SP-CSI-RNTI	Activation of Semi-persistent CSI reporting on PUSCH

Figure 8-46 NR RNTI Usage

The RNTI is a 16bit value, usually represented in hexadecimal format. Figure 8-47 illustrates the allowed and set values. Note that the majority of RNTI are configured in the range 0x0001 to 0xFFEF. Only the P-RNTI and SI-RNTI have fixed values.

Value	RNTI
0000	N/A
0001-FFEF	RA-RNTI, Temporary C-RNTI, C-RNTI, CS-RNTI, MCS-C-RNTI, TPC-PUCCH-RNTI, TPC-PUSCH-RNTI, TPC-SRS-RNTI, INT-RNTI, SFI-RNTI and SP-CSI-RNTI
FFF0–FFFD	Reserved
FFFE	P-RNTI
FFFF	SI-RNTI

Figure 8-47 NR RNTI Values

8.5.4 MAC Headers

There are various MAC headers depending on whether it is being used for shared channel operation or RAR (Random Access Response).

8.5.4.1 MAC PDU for DL-SCH and UL-SCH

Figure 8-48 illustrates the different MAC subheaders which can be used for the DL-SCH and UL-SCH.

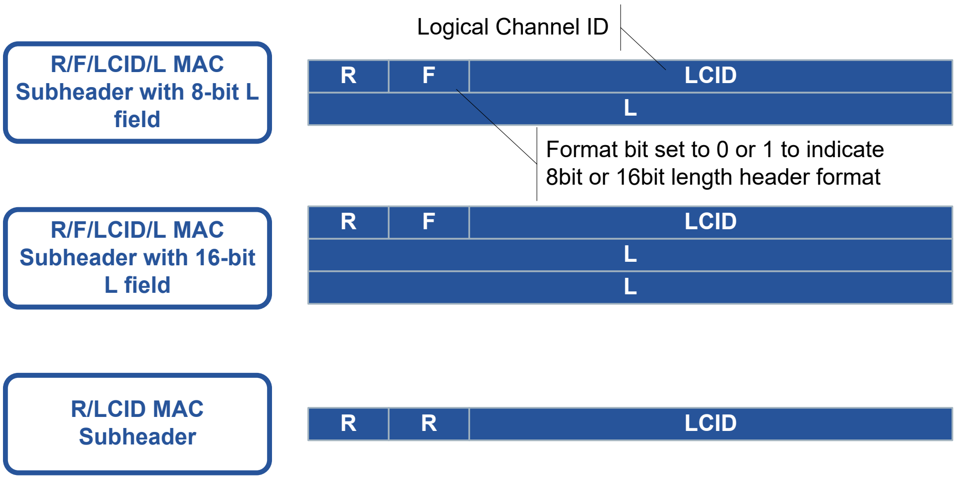


Figure 8-48 MAC Subheaders

Note that the Random Access Response MAC subheader is different.

The main parameter is the LCID (Logical Channel Identity), which is coded differently for the DL-SCH and UL-SCH. Figure 8-49 illustrates the DL-SCH LCID index values.

DL LCID Index	Description
0	CCCH
1-32	Identity of the logical channel
33-46	Reserved
47	Recommended bit rate
48	SP ZP CSI-RS Resource Set Activation/Deactivation
49	PUCCH spatial relation Activation/Deactivation
50	SP SRS Activation/Deactivation
51	SP CSI reporting on PUCCH Activation/Deactivation
52	TCI State Indication for UE-specific PDCCH
53	TCI States Activation/Deactivation for UE specific PDSCH
54	Aperiodic CSI Trigger State Subselection
55	SP CSI-RS / CSI-IM Resource Set Activation/Deactivation
56	Duplication Activation/Deactivation
57	SCell Activation/Deactivation (4 octet)
58	SCell Activation/Deactivation (1 octet)
59	Long DRX Command
60	DRX Command
61	Timing Advance Command
62	UE Contention Resolution Identity
63	Padding

Figure 8-49 LCID for DL-SCH

The LCID index for the UL-SCH is illustrates in Figure 8-50.

UL LCID Index	Description
000000	CCCH
1-32	Identity of the logical channel
33-51	Reserved
52	CCCH of size 48bits
53	Recommended Bit Rate
54	Multiple Entry PHR (4 Octet)
55	Configured Grant Confirmation
56	Multiple Entry PHR (1 Octet)
57	Single Entry PHR
58	C-RNTI
59	Short Truncated BSR
60	Long Truncated BSR
61	Short BSR
62	Long BSR
63	Padding

Figure 8-50 Uplink LCID

8.5.4.2 Subheader Mapping

A number of control LCID values reference a fixed length parameter, e.g. timing advance. In this case the header is only one octet.

Figure 8-51 illustrates how multiple sub-headers concatenate to the MAC header, with the MAC payload being a concatenation of the indicated parameters or data.

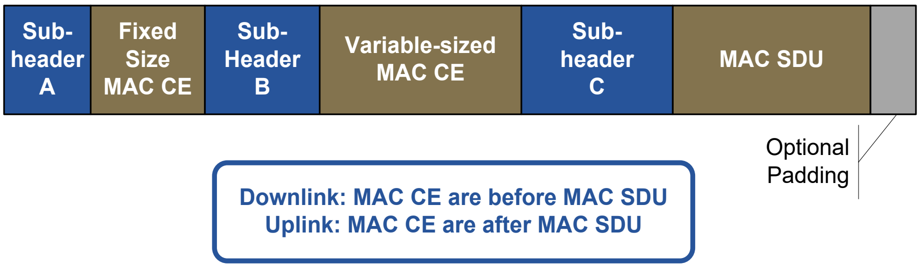


Figure 8-51 Example of Subheader Mapping

A maximum of one MAC PDU can be transmitted per TB (Transport Block) per MAC entity.

9 5G Scheduling

9.1 NR Scheduling

The gNB includes a scheduler at the MAC layer, which utilizes various services from the Physical Layer. It schedules resources for a device based on a variety of factors, some of which are illustrated in Figure 9-1. In so doing, it will inform a device of any resources allocated based on uplink and downlink requirements.

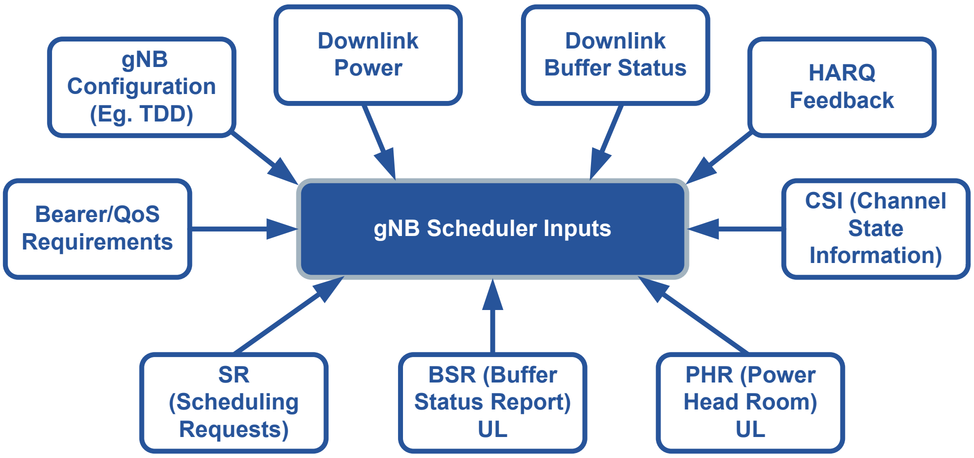


Figure 9-1 Scheduling

Note: Even though the procedures and mechanisms for scheduling devices are standardized, the actual decision on which device is scheduled, as well as the amount of resources to allocate, is vendor specific.

9.1.1 Downlink Control Information

The uplink and downlink resource scheduling is through a combination of RRC configuration and DCI (Downlink Control Information). The DCI is carried in the PDCCH (Physical Downlink Control Channel), specifically in a CORESET (Control Resource Set).

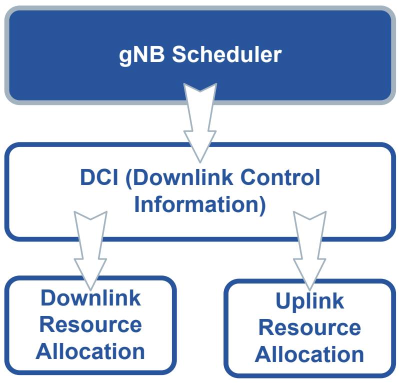


Figure 9-2 Downlink Control Information

There are eight NR DCI formats, as illustrated in Figure 9-3. These are used to schedule resources for the PDSCH (Physical Downlink Shared Channel) and the PUSCH (Physical Uplink Shared Channel), as well as provide configuration changes related to:

- Slot Format.
- Interruptions, i.e. indicated to a device or group of devices that the resource is now not allocated to them (after previously indicating it was).

- PUSCH and PUCCH TPC (Transmit Power Control).
- SRS (Sounding RS) TPC.

DCI formats use a RNTI (Radio Network Temporary Identifier) to indicate which device, or devices, the DCI is intended for. Note that the RNTI is not included as part of the DCI message; instead the RNTI is used to scramble the CRC (Cyclic Redundancy Check) parity bits. The device then performs blind detection of the PDCCH, i.e. the device checks all PDCCH's in a specific search area using the RNTI's it has been allocated (or system RNTI's). As such, when a device de-scrambles the CRC portion, it can be verified. Thus, indicating that both the DCI has no errors and that the DCI is for this device. An error in CRC indicates either an error in the payload, or the DCI is not for this device.

DCI Format	Usage	RNTI
Format 0_0	Scheduling of PUSCH	C-RNTI, CS-RNTI or MCS-C-RNTI
Format 0_1	Scheduling of PUSCH	C-RNTI, CS-RNTI, SP-CSI-RNTI or MCS-C-RNTI
Format 1_0	Scheduling of PDSCH	C-RNTI, CS-RNTI or MCS-C-RNTI
Format 1_1	Scheduling of PDSCH	C-RNTI, CS-RNTI or MCS-C-RNTI
Format 2_0	Notifying a group of the slot format	SFI-RNTI
Format 2_1	Notifying a group about PRB(s) and OFDM symbol(s) with no transmission	INT-RNTI
Format 2_2	Transmission of TPC commands for PUCCH and PUSCH	TPC-PUSCH-RNTI or TPC-PUCCH-RNTI
Format 2_3	Transmission of a group of TPC commands for SRS transmissions by one or more UEs	TPC-SRS-RNTI

Figure 9-3 NR DCI Formats

9.1.2 Search Space

A set of PDCCH candidates for a device to monitor is defined in terms of PDCCH search spaces. There are two categories of search space, namely common search space or UE-specific search space. In addition, various PDCCH search space types also exist, as illustrated in Figure 9-4.

Type	Search Space	RNTI
Type0-PDCCH	Common	SI-RNTI on a Primary Cell
Type0A-PDCCH	Common	SI-RNTI on a Primary Cell
Type1-PDCCH	Common	RA-RNTI or TC-RNTI on a Primary Cell
Type2-PDCCH	Common	P-RNTI on a primary cell
Type3-PDCCH	Common	INT-RNTI, SFI-RNTI, TPC-PUSCH-RNTI, TPC-PUCCH-RNTI, TPC-SRS-RNTI, C-RNTI, CS-RNTI(s) or MCS-C-RNTI
	UE-Specific	C-RNTI, CS-RNTI(s) or MCS-C-RNTI

Figure 9-4 NR PDCCH Search Space

Note that for EN-DC operation not all types are utilized. For example, since no SI (other than the PBCH) or paging messages are required on the PSCell, the device won't be configured to look for Type0, Type0A or Type2.

9.1.3 PDCCH Aggregation Levels

The search spaces consist of CCE (Control Channel Elements) which can have different aggregation levels. The purpose of the aggregation levels is to enable the gNB to provide more error protection.

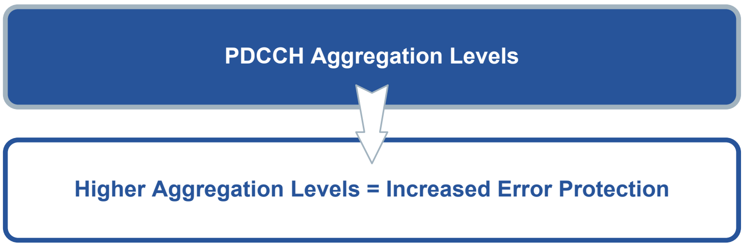


Figure 9-5 PDCCH Aggregation Levels

The common search space(s) and UE-specific search space(s) are configured separately by higher layers (RRC). For common search spaces, typically aggregation levels 4, 8 and 16 are defined. In contrast, for the UE-specific search space the aggregation levels 1, 2, 4, 8 or 16 are used, as illustrated in Figure 9-6.

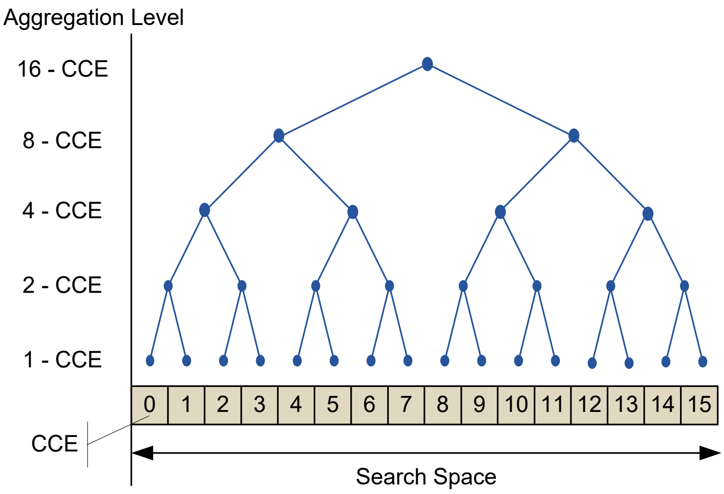


Figure 9-6 Aggregation Levels

Figure 9-5 illustrates an example of the aggregation levels, including few blind detection examples. In so doing, it shows that the device knows at which point different aggregation levels need to be blindly detected.

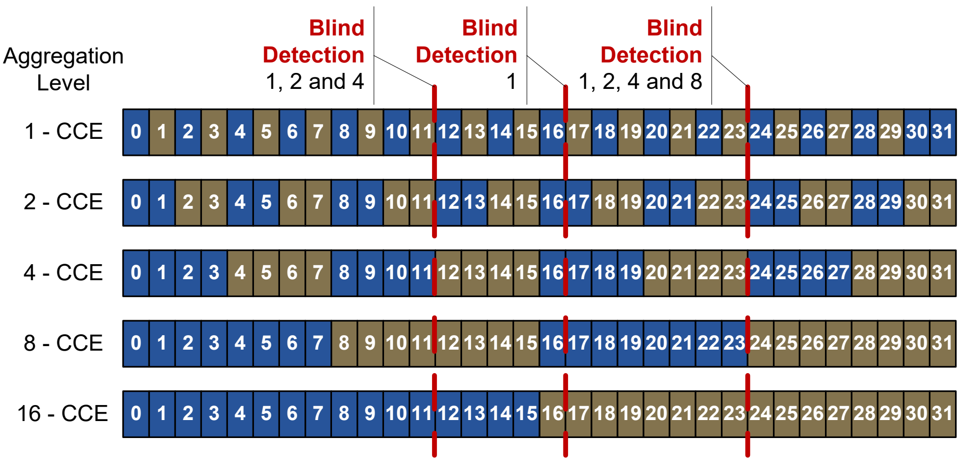


Figure 9-7 UE Specific Search Spaces

9.1.4 Resource Allocation

Resource allocation in 5G relies on providing a device with Frequency Domain Resource Assignment and Time Domain Resource Assignment. The Frequency Domain Resource Assignment is based on Resource Allocation Type, whereas the Time Domain Resource Allocation is based on the Time Domain Allocation List.

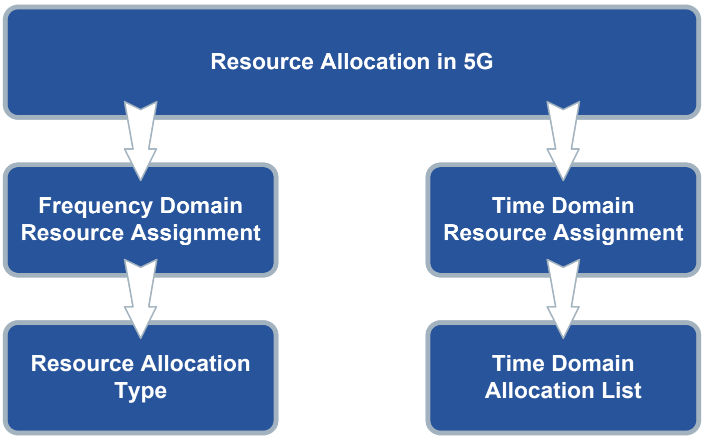


Figure 9-8 Resource Allocation in 5G

9.1.5 Frequency Domain Resource Allocation

The NR Resource Allocation Type defines the resource allocation method in the frequency domain. There are two types defined, namely Type 0 and Type 1. Type 0 is effectively a bitmap, whereas Type 1 uses a RIV (Resource Indication Value) to specify a starting RB, as well as a number of consecutive resource blocks. In addition, the system also enables the device to use Dynamic Switching, i.e. the DCI will indicate which to use.

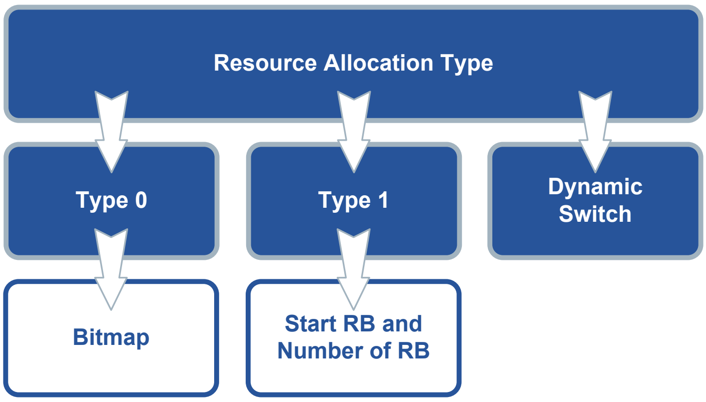
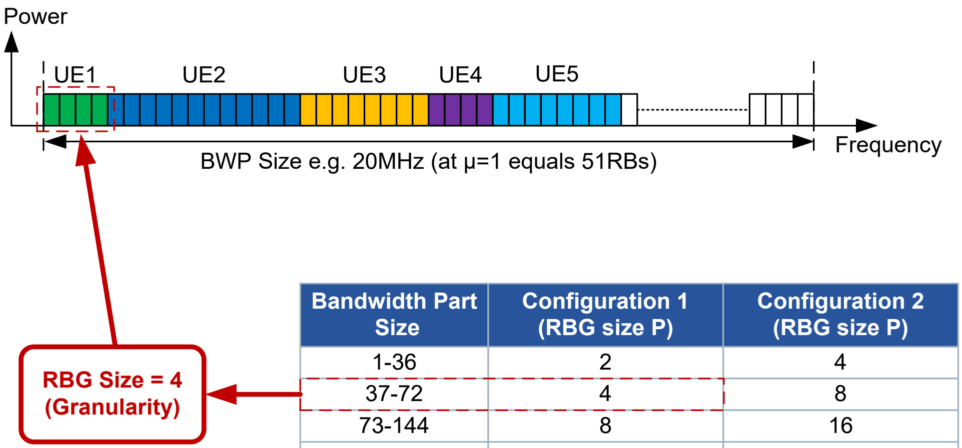


Figure 9-9 NR Resource Allocation Type

9.1.6 Resource Allocation Type 0

This allocation type effectively relies on bundling a number of consecutive Resource Blocks into a RBG (Resource Block Group). As such, the PDSCH and PUSCH are then assigned resources in multiples of RBG.

It is worth nothing that the amount of RB's per RBG varies depending on the BWP (Bandwidth Part) size and Configuration. Figure 9-10 illustrates RBG size "P". Since the BWP may not always be a multiple of the RBG size, there is a calculation to determine the size of the first RBG and the last RBG, i.e. it can be different from “P”. Also, since the allocation is a bitmap, consecutive resources don’t need to be allocated.



Bandwidth Part Size	Configuration 1 (RBG size P)	Configuration 2 (RBG size P)
1-36	2	4
37-72	4	8
73-144	8	16
145-275	16	16

Figure 9-10 Allocation Type 0 - RBG size P

In terms of configuring the device, the Resource Allocation Type is part of the pdsch-config parameter which will be included as part of the downlink BWP configuration.

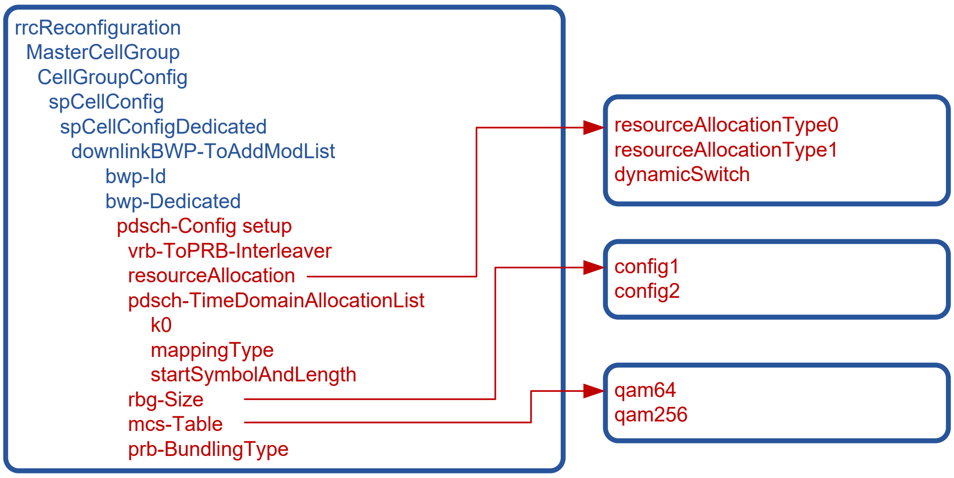


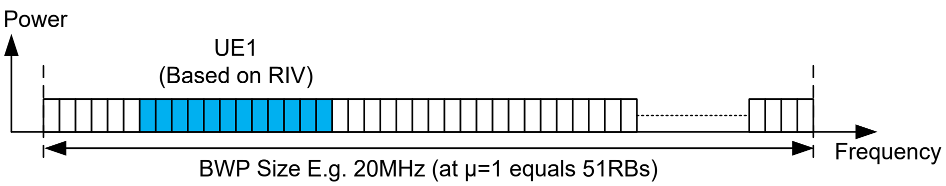
Figure 9-11 PDSCH Resource Allocation Configuration

9.1.7 Resource Allocation Type 1

Resource Allocation Type 1 enables one or more consecutive RB’s to be allocated. This is achieved by providing a RIV (Resource Indication Value) which indicates:

- RB_{start} - this indicates the start of the allocation.
- L_{RBs} - this is the Length, i.e. the number of consecutive RB’s within a BWP.

The RIV is calculated based on the equations in Figure 9-12.



If $(L_{RBs} - 1) \le \lfloor N_{BWP}^{size} / 2 \rfloor$ then

$$RIV = N_{BWP}^{size}(L_{RBs} - 1) + RB_{start}$$

else

$$RIV = N_{BWP}^{size}(N_{BWP}^{size} - L_{RBs} + 1) + (N_{BWP}^{size} - 1 - RB_{start})$$

Figure 9-12 Allocation Type 1

9.1.8 Dynamic Switch

If Dynamic Switching of resource allocation is configured, the MSB (Most Significant Bit) of the DCI Frequency Domain Resource Assignment is used to indicate either Resource Allocation Type 0 or Resource Allocation Type 1.

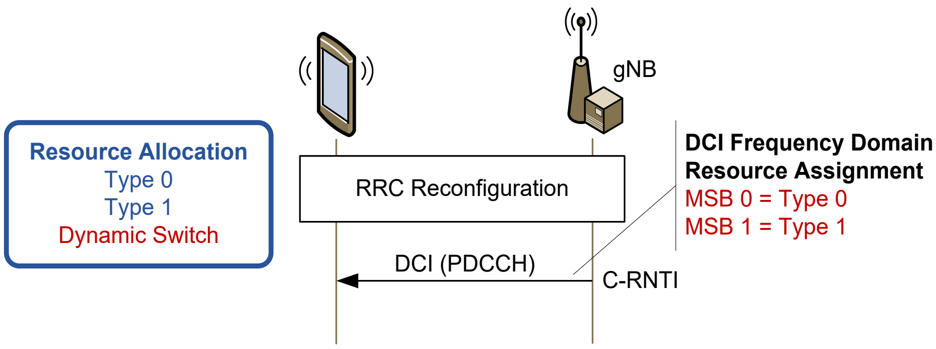


Figure 9-13 Dynamic Switch Resource Assignment

9.1.9 PDSCH and PUSCH Scheduling

The scheduling of the PDSCH and PUSCH relies on the device correctly decoding the DCI and identifying a DCI Format, e.g. Format 1_1 for the PDSCH and Format 0_1 for the PUSCH. Prior to this allocation, the device will have received the NR RRC Reconfiguration message which would have identified key aspects related to one of the BWP on the SpCell.

Figure 9-14 illustrates the scheduling of resources for the uplink and the downlink. Note, this is referred to as "dynamic allocation", since the device receives a DCI, which then triggers downlink or uplink resources.

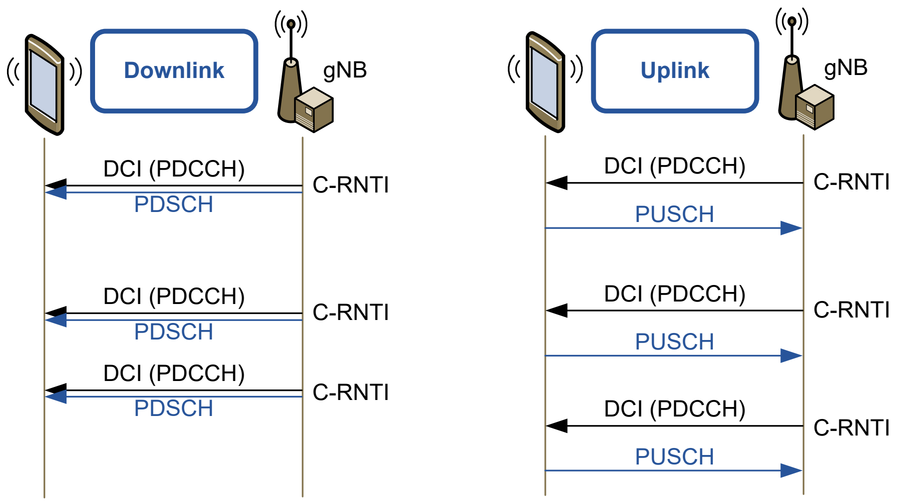


Figure 9-14 Basic PDSCH and PUSCH Scheduling

9.2 NR Downlink Resource Allocation

In the downlink, the gNB can dynamically allocate resources to devices via the C-RNTI on PDCCH(s). As such, a device always monitors the PDCCH(s) in order to find possible assignments when its downlink reception is enabled. If CA (Carrier Aggregation) is configured, the same C-RNTI applies to all serving cells.

The downlink resources are allocated using either the DCI Format 1_0 or Format 1_1, with Format 1_0 having less capability / flexibility. As such, Format 1_0 is used by the system to allocate resources for the RAR (Random Access Response) and “Msg 4”.

To enable a device to utilize Format 1_1, many configuration parameters must first be provided to the device. These are typically included as part of the NR RRC Reconfiguration message.

Included in the DCI Format 1_1 are various parameters related to the feedback expected from the device, i.e. the UCI (Uplink Control Information) it should send, as well as when it should send it.

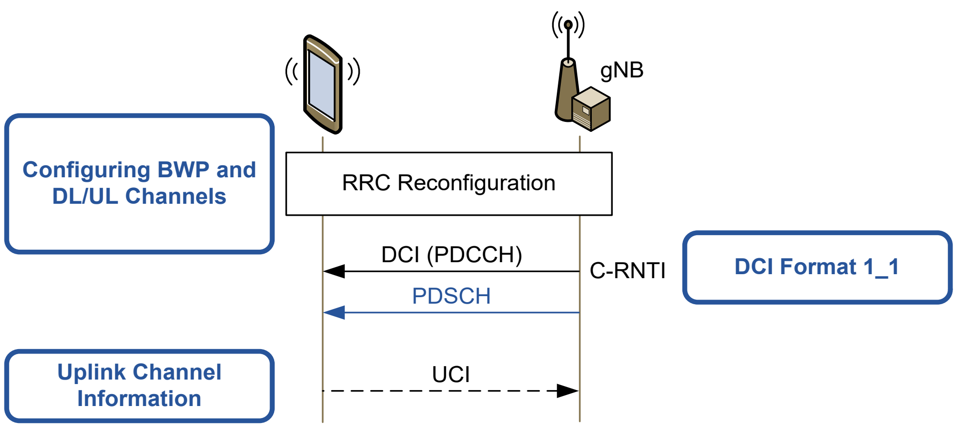


Figure 9-15 DCI Format 1_1

Figure 9-16 includes parameters for DCI Format 1_1. However, the detail of each parameter can be found in 3GPP TS 38.212.

Parameter	Bits
Identifier for DCI Formats	1
Carrier Indicator	0,3
Bandwidth Part Indicator	0,1,2
Frequency Domain Resource Assignment	Variable
Time Domain Resource Assignment	0,1,2,3,4
VRB-to-PRB Mapping	0,1
PRB Bundling Size Indicator	0,1
Rate Matching Indicator	0,1,2
ZP CSI-RS trigger	0,1,2
Modulation and Coding Scheme (TB1)	5
New Data Indicator (TB1)	1
Redundancy Version (TB1)	2
Modulation and Coding Scheme (TB2)	5
New Data Indicator (TB2)	1
Redundancy Version (TB2)	2
HARQ Process Number	4
Downlink Assignment Index	0,2,4
TPC Command for Scheduled PUCCH	2
PUCCH Resource Indicator	3
PDSCH-to-HARQ_Feedback Timing Indicator	0,1,2,3
Antenna Port(s) and Number of Layers	4,5,6
Transmission Configuration Indication	0,3
SRS request	2
CBG Transmission Information	0,2,4,6,8
CBG Flushing Out Information	0,1
DMRS Sequence Initialization	1

Figure 9-16 DCI Format 1_1 Parameters

9.2.1 PDSCH Time Domain Resource Allocation

In addition to allocating resources in the frequency domain, based on Type 0 (RIV) or Type 1 (Bitmap) resource allocation, the device needs to be informed about the time domain. To make the scheduler flexible, a list of time domain allocation parameters can be configured, as illustrated in Figure 9-17. Each configuration includes:

- k0 - this is the slot offset from the PDCCH and ranges from 0 to 32.
- Mapping Type - this relates the DMRS mapping, i.e. Type A (when in symbol 2 or 3) or Types B (at the start of the allocation).
- SLIV (Start and Length Indicator Value) - this number is based on an equation and identifies the start symbol and length.

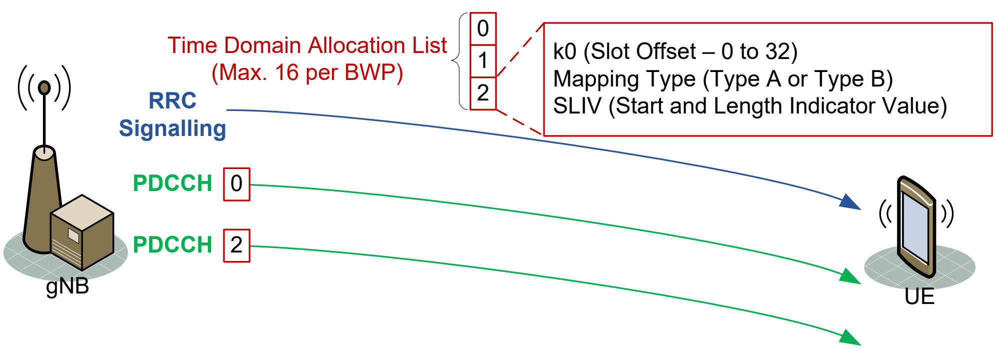


Figure 9-17 Time Domain Resource Allocation

The K_0 parameter forms part of an equation to define the slot. If not present, $K_0 = 0$. In addition, as illustrated in Figure 9-18, the ratio of numerology between the PDSCH and PDCCH is also a factor.

Once the starting slot has been identified (it could be the same slot as the PDCCH), the device then calculates the resource allocation using the SLIV (Start Symbol and Length Indicator Value).

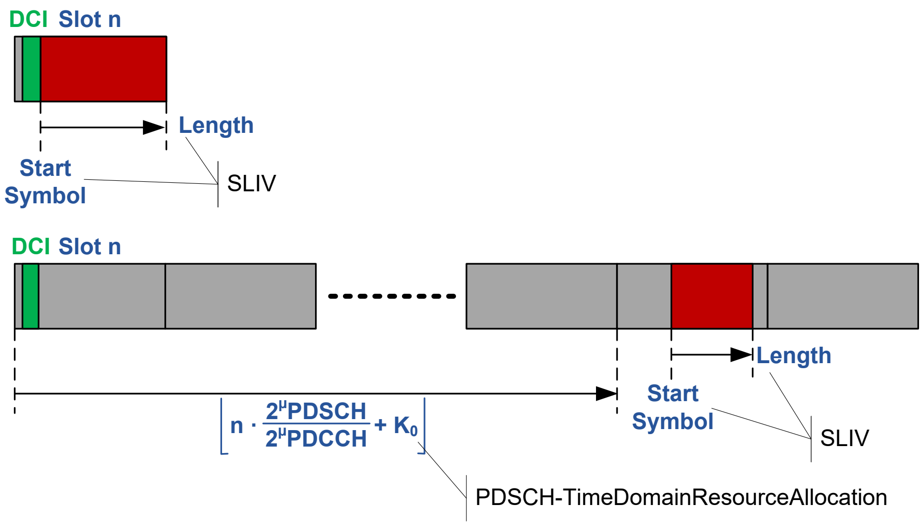


Figure 9-18 PDSCH Time Domain Resource Allocation

The SLIV equation for the downlink is illustrated Figure 9-19. Note that there are two equations to calculate SLIV; the choice depends on the size of L (Length) being allocated.

$(L - 1) \leq 7$ → $SLIV = 14 \cdot (L - 1) + S$

$(L - 1) > 7$ → $SLIV = 14 \cdot (14 - L + 1) + (14 - 1 - S)$

$0 < L \leq 14 - S$

PDSCH Mapping Type	Normal CP			Extended CP		
	S	L	S+L	S	L	S+L
Type A	{0,1,2,3}	{3,…,14}	{3,…,14}	{0,1,2,3}	{3,…,12}	{3,…,12}
Type B	{0,…,12}	{2,4,7}	{2,…,14}	{0,…,10}	{2,4,6}	{2,…,12}

Figure 9-19 PDSCH Start and Length Indicator

It is worth nothing that Type A mapping starts in either symbol 0, 1, 2 or 3 and the length can be anything from 3 symbols to the end of the slot. In contrast, Type B can start in symbols 0 to 12, however it only has three length options. For example, it can have a length of 2, 4, or 7 symbols for Normal CP (Cyclic Prefix).

Figure 9-20 includes part of the SLIV calculated table which identifies the initial permutations, as well as specifying if it is applicable to Mapping Type A or B.

S	L	L-1	SLIV	Valid Mapping Type (Normal CP) PDSCH
0	1	0	0	
	2	1	14	Type B
	3	2	28	Type A
	4	3	42	Type A, Type B
	5	4	56	Type A
	6	5	70	Type A
	7	6	84	Type A, Type B
	8	7	98	Type A
	9	8	97	Type A
	10	9	83	Type A
	11	10	69	Type A
	12	11	55	Type A
	13	12	41	Type A
	14	13	27	Type A
1	1	0	1	
	2	1	15	Type B
	3	2	29	Type A
	4	3	43	Type A, Type B
	5	4	57	Type A
	6	5	71	Type A
	7	6	85	Type A, Type B
	8	7	99	Type A
	9	8	96	Type A
	10	9	82	Type A
	11	10	68	Type A
	12	11	54	Type A
	13	12	40	Type A

Figure 9-20 Part of the SLIV Values for PDSCH (Starting at Symbol 0 or 1)

For Format 1_1, this is either 0, 1, 2, 3, or 4 bits. The size depends on the number of entries in the higher layer parameter pdsch-AllocationList, i.e. the parameter needs to be large enough to indicate which configuration is being used for this allocation. As such, the maximum number of time allocation options is 16.

Figure 9-21 illustrates an example of a NR RRC Reconfiguration message configuring 3 sets (I) of Time Domain Resource Allocation parameters. The number of bits required in the DCI Format 1_1 Time Domain Resource Allocation field would be calculated as $\log_2$ (I).

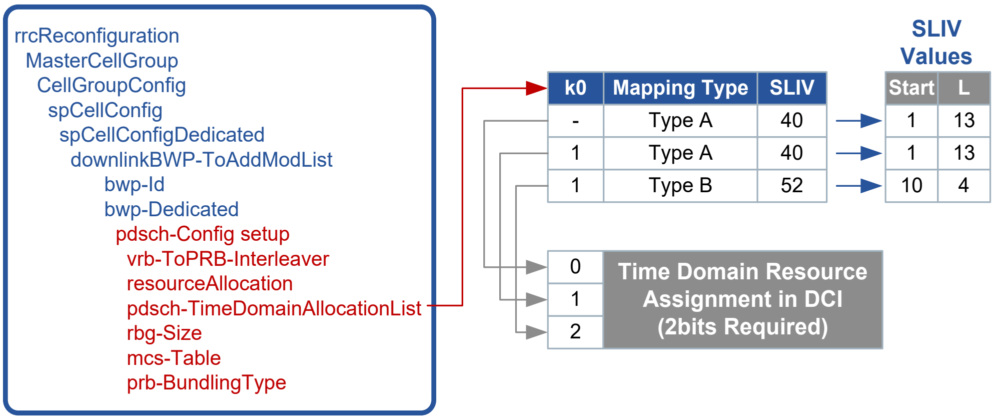


Figure 9-21 Configuring Time Domain Resource Allocation

9.2.2 Table 1 and Table 2 PDSCH/PUSCH MCS

In addition to allocating the frequency and time domain, the device also needs to be informed about the MCS (Modulation and Coding Scheme). As such, the 5bit MCS parameter in the DCI maps to a I_{MCS} (MCS Index)

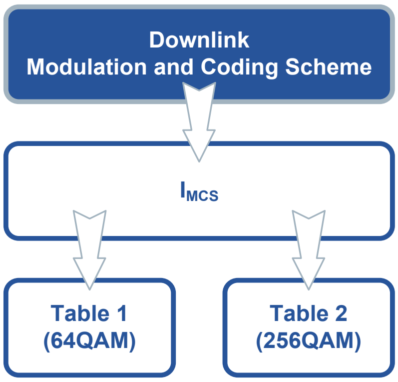


Figure 9-22 MCS for PDSCH

Figure 9-23 illustrates an extract from MCS Table 1 for the PDSCH. The full table is available in 3GPP TS 38.214. Notice that the I_{MCS} value relates to a Q_m (Modulation Order), which is either 2 (QPSK), 4 (16QAM) or 6 (64QAM).

I_{MCS}	Modulation Order (Q_m)	Target code Rate R x [1024]	Spectral Efficiency
0	2	120	0.2344
1	2	157	0.3066
2	2	193	0.3770
3	2	251	0.4902
4	2	308	0.6016
5	2	379	0.7402
⋮	⋮	⋮	⋮
27	6	910	5.3320
28	6	948	5.5547
29	2	Reserved	
30	4	Reserved	
31	6	Reserved	

Figure 9-23 Extract from MCS Table 1 (Max 64QAM)

Figure 9-24 illustrates an extract from MCS Table 2 for the PDSCH, which can indicate Q_m=8. This relates to 256QAM.

I_{MCS}	Modulation Order (Q_m)	Target code Rate R x [1024]	Spectral Efficiency
0	2	120	0.2344
1	2	193	0.3770
2	2	308	0.6016
3	2	449	0.8770
4	2	602	1.1758
5	4	378	1.4766
⋮	⋮	⋮	⋮
27	8	948	7.4063
28	2	Reserved	
29	4	Reserved	
30	6	Reserved	
31	8	Reserved	

Figure 9-24 Extract from MCS Table 2 (Max 256QAM)

9.2.3 Transport Block Size

The TBS (Transport Block Size) determination in NR is quite complicated. In summary, the device first calculates N_{info} (Intermediate Number of Information Bits). This is summarized in Figure 9-25. Once calculated, if $N_{info} \leq 3824$, the TBS table[18] is utilized (with a small calculation). However, if N_{info} is greater than 3824 an equation is utilized to determine the TBS size.

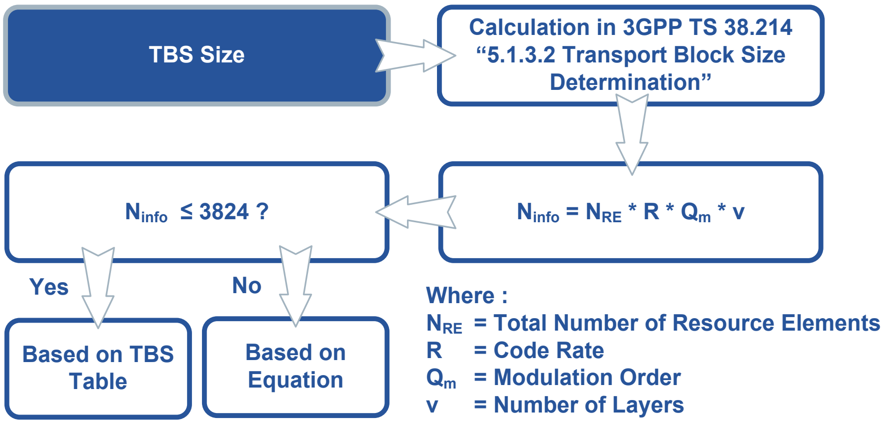


Figure 9-25 TBS Size Calculation

9.2.4 Downlink Configured Scheduling

For the downlink, this is termed SPS (Semi-Persistent Scheduling) and is configured by NR RRC per Serving Cell and per BWP.

The gNB can allocate downlink resources for the initial transmissions to device. RRC defines the periodicity of the configured downlink assignments while PDCCH addresses a CS-RNTI (Configured Scheduling RNTI). This can either signal and activate the configured downlink assignment, or deactivate it. For example, a PDCCH addressed to CS-RNTI indicates that the downlink assignment can be implicitly reused according to the periodicity defined by RRC, until deactivated.

Figure 9-26 illustrates an example of the CS-RNTI location, as well as the sps-Config parameter (including Periodicity values).

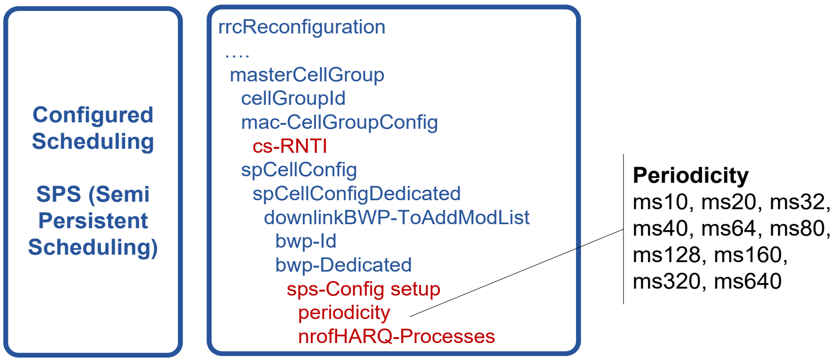


Figure 9-26 Semi-Persistent Scheduling

Figure 9-27 illustrates an example with and without SPS configured.

[18] 3GPP TS 38.214 - Physical Layer Procedures for Data

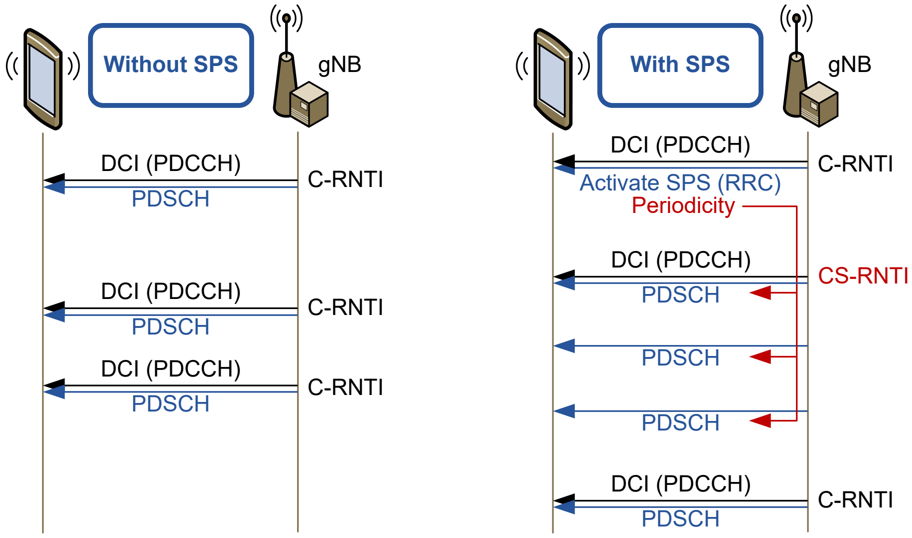


Figure 9-27 PDSCH Configured Scheduling (SPS)

9.2.5 Discontinuous Reception

Like LTE, the NR MAC is also able to configure DRX (Discontinuous Reception) functionality. This controls when a device should monitor the PDCCH for C-RNTI, CS-RNTI, TPC-PUCCH-RNTI, TPC-PUSCH-RNTI and TPC-SRS-RNTI.

In order to configure, RRC defines various parameters including:

- drx-onDurationTimer - this is the duration at the beginning of a DRX Cycle. Value in multiples of 1/32 ms (subMilliSeconds) or in ms (milliSecond). For the latter, ms1 corresponds to 1ms, ms2 corresponds to 2ms, and so on.
- drx-SlotOffset - this is the delay in slots before starting the drx-onDurationTimer. Value in 1/32 ms. Value 0 corresponds to 0ms, value 1 corresponds to 1/32ms, value 2 corresponds to 2/32ms, and so on.
- drx-StartOffset - this is the subframe where the DRX Cycle starts.
- drx-InactivityTimer - this is the duration after the PDCCH occasion in which a PDCCH indicates an initial UL or DL user data transmission for the MAC entity.
- drx-RetransmissionTimerDL (per DL HARQ process) - this is the maximum duration until a DL retransmission is received.
- drx-RetransmissionTimerUL (per UL HARQ process) - this is the maximum duration until a grant for UL retransmission is received.
- drx-LongCycle - this indicates the size of the Long DRX cycle
- drx-ShortCycle - this indicates the size of the Short DRX cycle
- drx-ShortCycleTimer - this indicates the duration a device uses the Short DRX cycle.
- drx-HARQ-RTT-TimerDL (per DL HARQ process) this is the minimum duration before a DL assignment for HARQ retransmission is expected by the MAC entity.
- drx-HARQ-RTT-TimerUL (per UL HARQ process) - this is the minimum duration before a UL HARQ retransmission grant is expected by the MAC entity.

An example of some of these DRX parameters is illustrated in Figure 9-28.

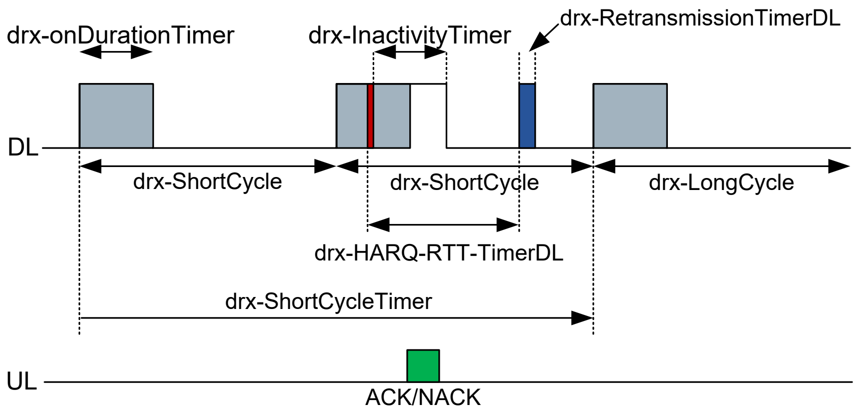


Figure 9-28 Example of DRX Cycle

9.3 NR Uplink Resource Allocation

The gNB, using a combination of RRC signalling and DCI messages, can allocate uplink resources to a device. Like the downlink, there are two main DCI formats, namely Format 0_0 and Format 0_1. It is the latter which provides the greater flexibility, as well as more detail.

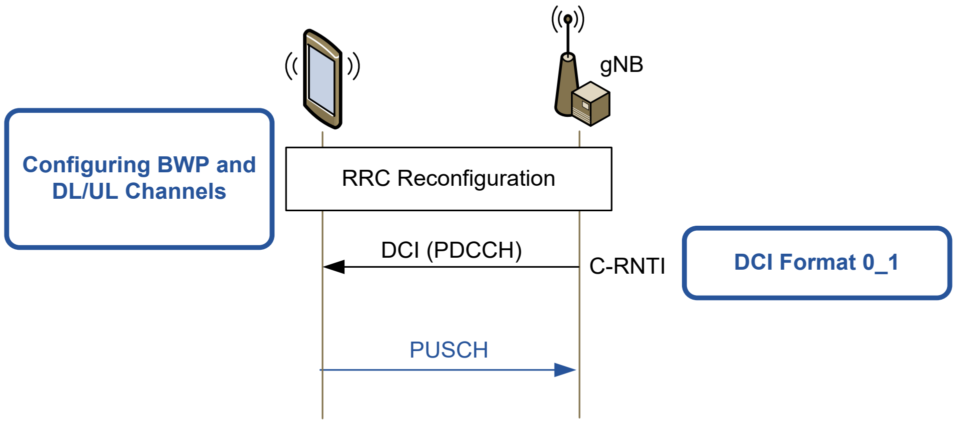


Figure 9-29 Uplink Resource Allocation (Format 0_1)

Figure 9-30 includes parameter listings for various DCI Format 0_1. However, the detail of each parameter can be found in 3GPP TS 38.212.

Parameter	Bits
Identifier for DCI Formats	1
Carrier Indicator	0,3
UL/SUL Indicator	0,1
Bandwidth Part Indicator	0,1,2
Frequency Domain Resource Assignment	Variable
Time Domain Resource Assignment	0,1,2,3,4
Frequency Hopping Flag	0,1
Modulation and Coding Scheme	5
New Data Indicator	1
Redundancy Version	2
HARQ Process Number	4
1st Downlink Assignment Index	1,2
2nd Downlink Assignment Index	0,2
TPC Command for Scheduled PUSCH	2
SRS Resource Indicator	Variable
Precoding Information and Number of Layers	0,1,2,3,4,5,6
Antenna Ports	2,3,4,5
SRS Request	2
CSI Request	0,1,2,3,4,5,6
CBG Transmission Information	0,2,4,6,8
PTRS - DMRS Association	0,2
beta_offset Indicator	0,2
DMRS Sequence Initialization	0,1
UL-SCH indicator	1

Figure 9-30 DCI Format 0_1 Parameters

In terms of the detail, it is worth noting that the NR RRC Reconfiguration message will have configured many PUSCH and PUCCH parameters. These are highlighted in Figure 9-31 and Figure 9-32.

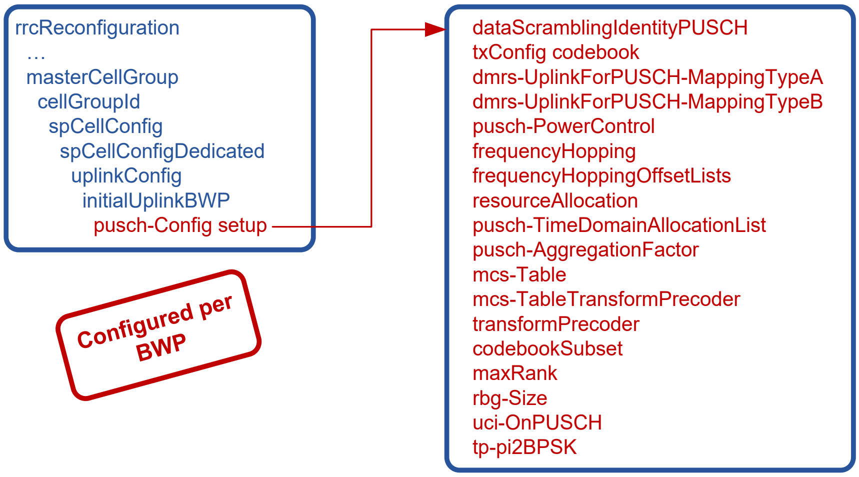


Figure 9-31 Example PUSCH Parameters

```
rrcReconfiguration
 …
 masterCellGroup
  cellGroupId
   spCellConfig
    spCellConfigDedicated
     uplinkConfig
      initialUplinkBWP
       pucch-Config setup
        resourceSetToAddModList
        resourceToAddModList
        format1
        format2
        format3
        format4
        schedulingRequestResourceToAddModList
        multi-CSI-PUCCH-ResourceList
        dl-DataToUL-ACK
        pucch-PowerControl
```

Figure 9-32 Example PUCCH Parameters

9.3.1 PUSCH Time Domain Resource Allocation

Like the PDSCH, the PUSCH has a time domain resource allocation mechanism. This is illustrated in Figure 9-33.

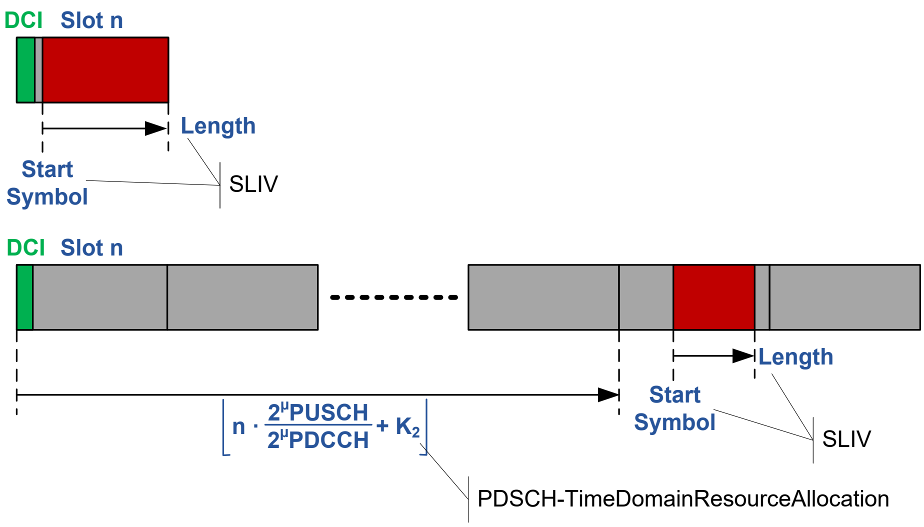
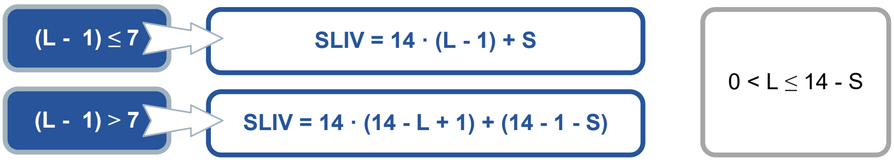


Figure 9-33 PUSCH Time Domain Resource Allocation

The SLIV equation for the uplink is illustrated in Figure 9-34. Note, like the downlink SLIV, there are two equations to calculate SLIV; the choice depends on the size of L (Length).



PUSCH Mapping Type	Normal CP			Extended CP		
	S	L	S+L	S	L	S+L
Type A	0	{4,…,14}	{4,…,14}	0	{4,…,12}	{4,…,12}
Type B	{0,…,13}	{1,…,14}	{1,…,14}	{0,…,12}	{1,…,12}	{1,…,12}

Figure 9-34 PUSCH Start and Length Indicator

In the PUSCH, when using Type A mapping, the allocation always starts on symbol 0 and the length is between 4 and 14 symbols. However, with Type B mapping, it can start on any symbol with a length between 1 and 14 (Normal CP).

Figure 9-35 illustrates the first part of the SLIV mapping based on the equation for the PUSCH. The main difference between the PDSCH and the PUSCH is the fact that Type B mapping can be always configured, whereas Type A is only available when the Start value is 0.

S	L	L-1	SLIV	Valid Mapping Type (Normal CP) PUSCH
0	1	0	0	Type B
	2	1	14	Type B
	3	2	28	Type B
	4	3	42	Type A, Type B
	5	4	56	Type A, Type B
	6	5	70	Type A, Type B
	7	6	84	Type A, Type B
	8	7	98	Type A, Type B
	9	8	97	Type A, Type B
	10	9	83	Type A, Type B
	11	10	69	Type A, Type B
	12	11	55	Type A, Type B
	13	12	41	Type A, Type B
	14	13	27	Type A, Type B
1	1	0	1	Type B
	2	1	15	Type B
	3	2	29	Type B
	4	3	43	Type B
	5	4	57	Type B
	6	5	71	Type B
	7	6	85	Type B
	8	7	99	Type B
	9	8	96	Type B
	10	9	82	Type B
	11	10	68	Type B
	12	11	54	Type B
	13	12	40	Type B

Figure 9-35 Part of the SLIV Values for PDSCH (Starting at Symbol 0 or 1)

9.3.2 PUSCH MCS Index

The MCS Index for the PUSCH can utilize the same tables as defined for the PDSCH (see Figure 9-23 and Figure 9-24). However, if transform precoding is activated there is a specific MCS index table.

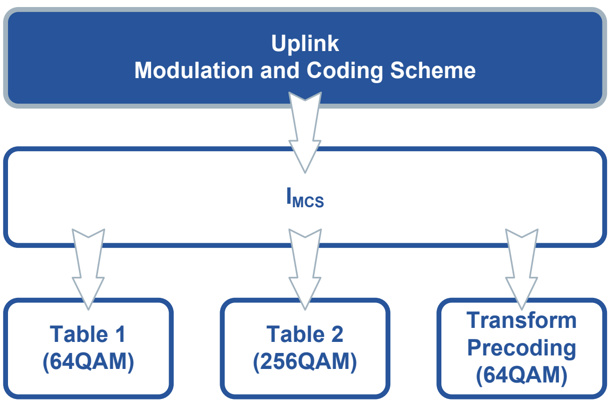


Figure 9-36 PUSCH MCS Index Tables

9.3.3 Uplink Configured Scheduling

In the uplink, the gNB can dynamically allocate resources to devices via the C-RNTI on PDCCH(s). A device always monitors the PDCCH(s) in order to find possible grants for uplink transmission when its downlink reception is enabled (activity governed by DRX when configured). Note that when CA (Carrier Aggregation) is configured, the same C-RNTI applies to all serving cells.

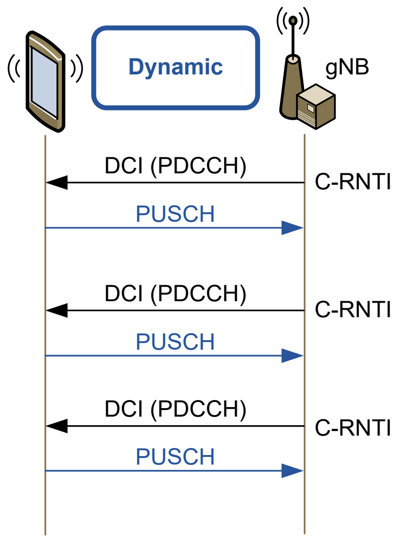


Figure 9-37 PUSCH Scheduling (Dynamic)

There are two types of transmission without dynamic grant:

- Configured Grant Type 1 - this is where RRC directly provides the configured uplink grant (including the periodicity).
- Configured Grant Type 2 - this is where RRC defines the periodicity of the configured uplink grant while PDCCH addressed to CS-RNTI can either signal and activate the configured uplink grant, or deactivate it; i.e. a PDCCH addressed to CS-RNTI indicates that the uplink grant can be implicitly reused according to the periodicity defined by RRC, until deactivated.

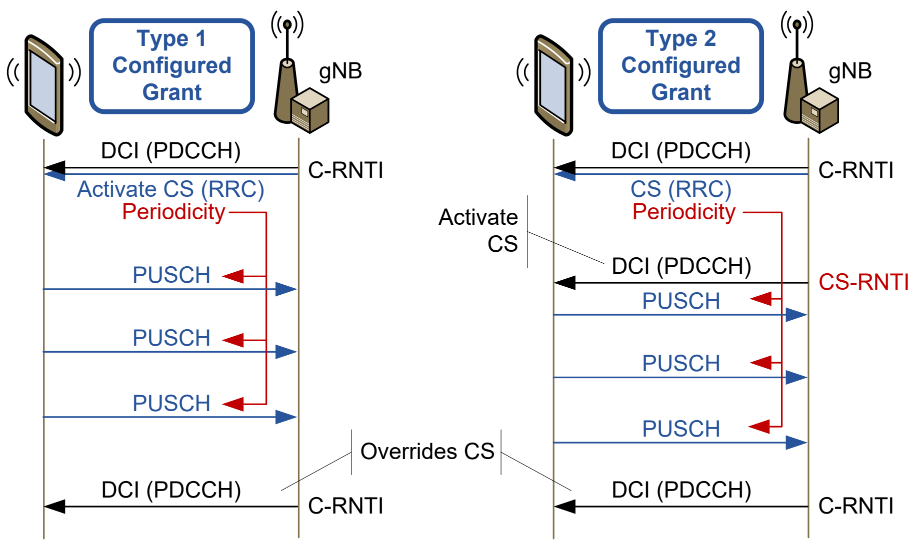


Figure 9-38 PUSCH Scheduling (With CS)

The configuration of Configured Grant is part of the NR RRC Reconfiguration message. An example is illustrated in Figure 9-39. The Periodicity parameter is defined in symbols and varies depending on the numerology.

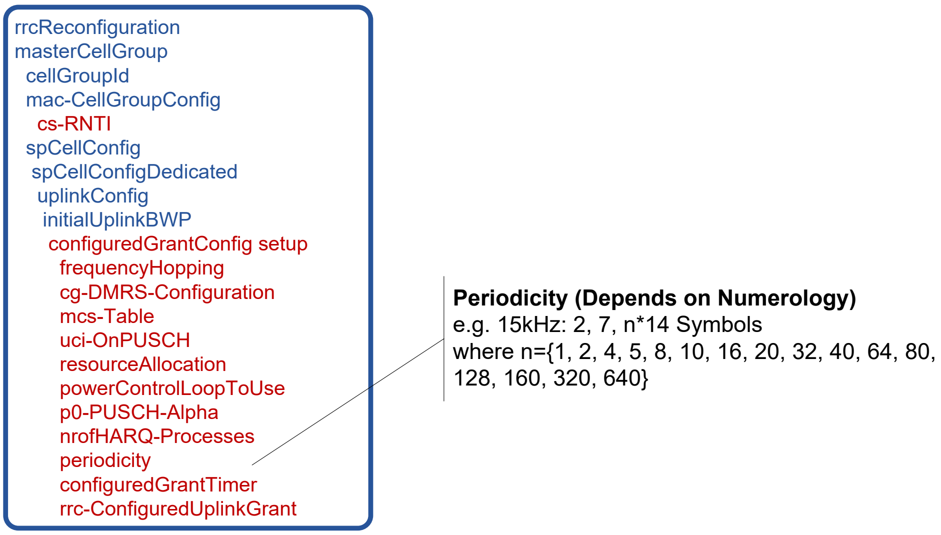


Figure 9-39 Configured Grant

9.4 NR Feedback

The three main types of feedback that assists the gNB scheduler include: BSR (Buffer Status Report), PHR (Power Headroom Report) and UCI (Uplink Control Information).

The UCI can also be broken down into:

- HARQ-ACK.
- SR (Scheduling Request).
- CSI (Channel State Information).

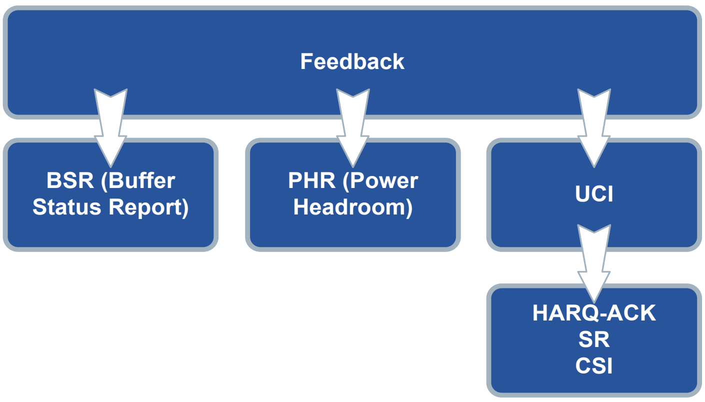


Figure 9-40 NR Uplink Feedback

9.4.1 Buffer Status Reporting

The Buffer Status Reporting procedure provides the gNB with information about the amount of data available for transmission in the UL (Uplink) buffers of the device. The buffers are grouped into LCG (Logical Channel Group) in the UE, with upto 8 LCG's allowed. As data arrives from a RB (Radio Bearer) it will be mapped to a Logical Channel, which in-turn is mapped to a LCG.

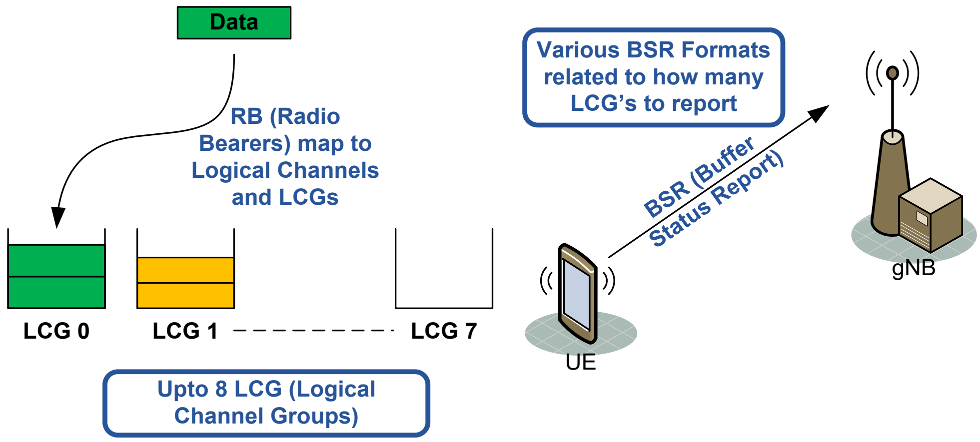


Figure 9-41 Buffer Status Reporting

RRC controls Buffer Status Reporting and triggers a BSR MAC CE (Control Element) if any of the following events occur:

- UL data - when resources are allocated, however either no data is available for that LCG (Logical Channel Group) or the data belongs to a logical channel with higher priority. This is known as Regular BSR.
- Padding bits - UL resources are allocated and the number of padding bits is equal to or larger than the size of the Buffer Status Report MAC control element plus its subheader, in which case the BSR is identified as Padding BSR.
- retxBSR-Timer - when this timer expires and the device has data available for transmission (related to logical channels which belong to a LCG). The is referred to as a Regular BSR.
- periodicBSR-Timer - when this expires the BSR is referred to as Periodic BSR.
-

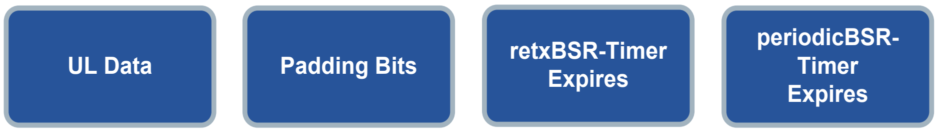


Figure 9-42 BSR Triggers

BSR Types

BSR (Buffer Status Report) consist of either:

- Short BSR - this includes one LCG ID field and corresponding Buffer Size field. Other LCG buffers are empty.
- Short Truncated BSR - this includes one LCG ID field and corresponding Buffer Size field. Other LCG buffers have data.
- Truncated BSR format - this includes one LCG ID field and corresponding Buffer Size field. Other LCG buffers may have data.
- Long BSR format - this includes all four Buffer Size fields, corresponding to LCG IDs (up to 8 supported).

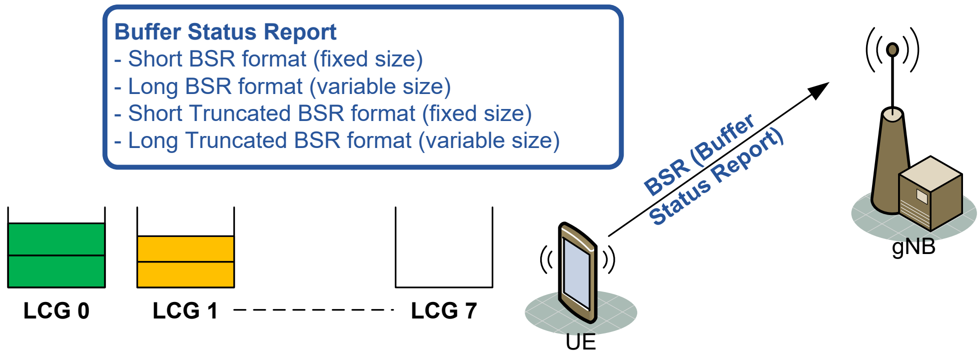


Figure 9-43 Buffer Status Reporting

9.4.2 Power Headroom Reporting

The Power Headroom reporting procedure is used to provide the gNB with information about the difference between the nominal UE maximum power and the estimated power for UL-SCH and PUCCH transmission on SpCell and PUCCH SCell. Figure 9-44 illustrates a simplified representation. The PHR (Power Headroom Report) can then influence who the gNB schedules future resources.

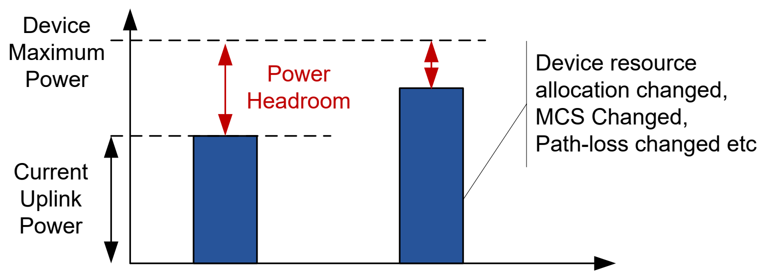


Figure 9-44 Power Headroom Reporting

A PHR (Power Headroom Report) is triggered based on various scenarios, examples include:

- prohibitPHR-Timer expires - it is also sent if the prohibitPHR-Timer timer has expired and the path loss has changed more than dl-PathlossChange dB.
- periodicPHR-Timer expires.
- Activation of a SCell (Secondary Cell) with configured uplink.
- phr-ProhibitTimer expires or has expired - this is related to power backoff and power management.

PHR MAC Control Element

There are two PHR MAC Control Elements, as illustrated in Figure 9-45. One carries a Single Entry PHR and the other the carrier Multiple Entry PHR. The details of which are included in 3GPP TS 38.321.

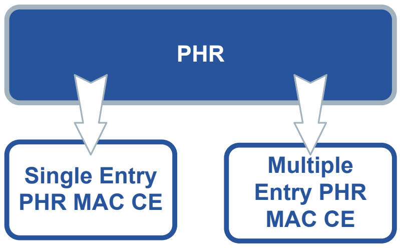


Figure 9-45 PHR MAC Control Elements

9.4.3 HARQ-ACK

Like LTE, NR supports HARQ (Hybrid Automatic Repeat Request). Specifically, it supports Asynchronous IR (Incremental Redundancy) HARQ.

For the downlink, a maximum of 16 HARQ processes per cell is supported by the device. The parameter nrofHARQ-processesForPDSCH can be used to configure the number to use. The uplink also has a maximum of 16 HARQ processes per cell supported, with the parameter nrofHARQ-processesForPUSCH being used to configure the device. Each HARQ process supports 1 TB (Transport Block), however in the downlink it could be 1 or 2 if Spatial Multiplexing is configured.

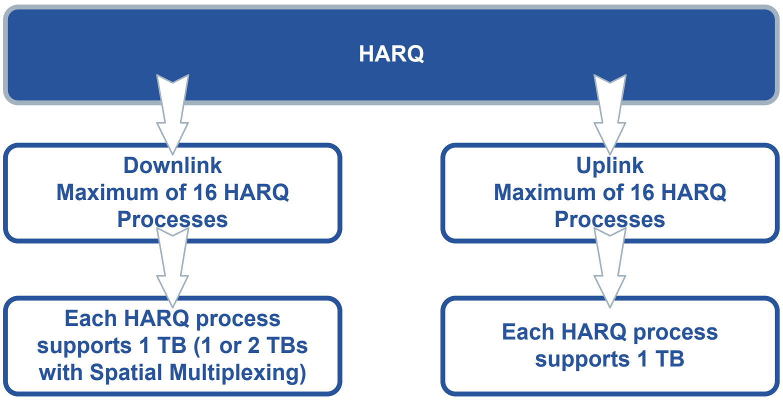


Figure 9-46 NR HARQ

Since NR also supports CBG (Code Block Group) based transmission, it can also be aligned with the HARQ-ACK feedback process.

HARQ-ACK Timing

In addition to configuring the number of processes, the gNB also provides the device with the HARQ-ACK feedback timing either dynamically in the DCI or semi-statically in an RRC configuration. Figure 9-47 illustrates the timing relationship, as well as the RRC configuration parameter dl-DataToUL-ACK.

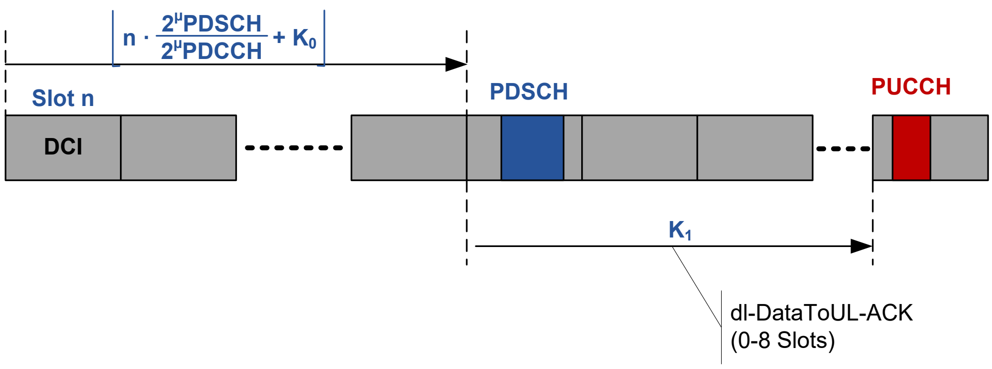


Figure 9-47 HARQ-ACK Timing

9.4.4 Scheduling Request

The SR (Scheduling Request) is used for requesting UL-SCH resources for a new transmission. The device receives a SchedulingRequestConfig parameter which configures dedicated Scheduling Requests, as well as providing a sr-ConfigIndex which links to the MAC logical channel configuration.

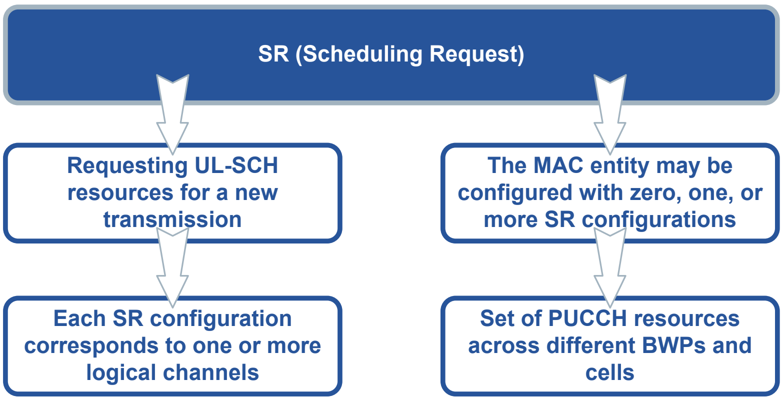


Figure 9-48 Scheduling Request

9.4.5 Channel State Information

The time and frequency resources that can be used by the device to report CSI (Channel State Information) are controlled by the gNB. Figure 9-49 illustrates the various options for CSI.

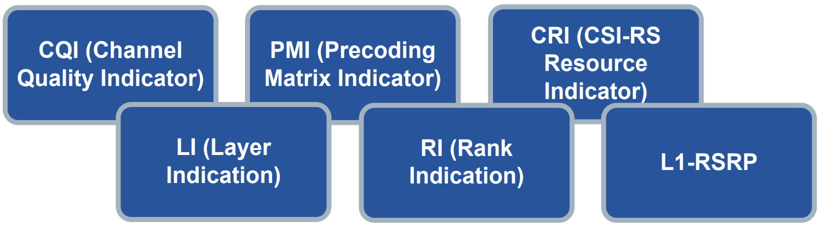


Figure 9-49 Channel State Information

Some of the key terminology associated with CSI framework is illustrated in Figure 9-50. Note that many other terms, as well as configuration options exist.

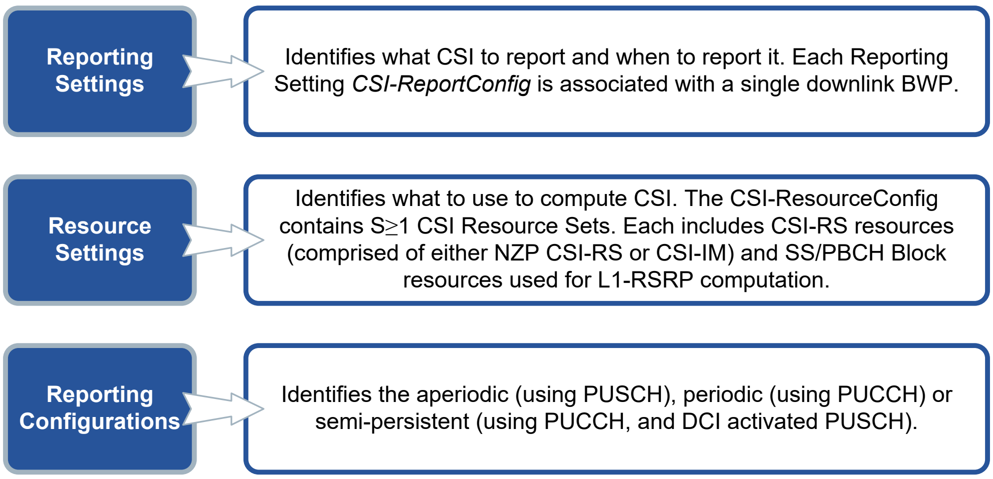


Figure 9-50 CSI Framework

9.4.6 Channel Quality Indicator

Like LTE, NR include CQI indices and their interpretations are given in Figure 9-51. This covers Table 1 (64QAM) and Table 2 (256QAM).

The device derives for each CQI value reported in uplink slot “n” the highest CQI index which satisfies the following condition:

- A single PDSCH transport block with a combination of modulation scheme, target code rate and Transport Block Size corresponding to the CQI index, and occupying a group of downlink physical resource blocks termed the CSI reference resource, could be received with a transport block error probability not exceeding 0.1, or a higher layer configured BLER-target.

CQI Index	Modulation	Code Rate x1024
0	Out of Range	
1	QPSK	78
2	QPSK	120
3	QPSK	193
4	QPSK	308
5	QPSK	449
6	QPSK	602
7	16QAM	378
8	16QAM	490
9	16QAM	616
10	64QAM	466
11	64QAM	567
12	64QAM	666
13	64QAM	772
14	64QAM	873
15	64QAM	948

CQI Index	Modulation	Code Rate x1024
0	Out of Range	
1	QPSK	78
2	QPSK	193
3	QPSK	449
4	16QAM	378
5	16QAM	490
6	16QAM	616
7	16QAM	466
8	16QAM	567
9	16QAM	666
10	64QAM	772
11	64QAM	873
12	256QAM	711
13	256QAM	797
14	256QAM	885
15	256QAM	948

Figure 9-51 NR CQI Table 1 and 2

9.5 Inter-RAN Resource Coordination

In order to better support coexistence, it is possible for the Master RAN Node and Secondary RAN Node to indicate what resources (in terms of PRB’s) they expect to use. This information can then be utilized by both MAC schedulers.

9.5.1 Resource Coordination Signalling

The XnAP (Xn Application Protocol) and X2AP (Xn Application Protocol) both include procedures which can carry coordination information in both directions. As illustrated in Figure 9-52, this illustrates a EN-DC configuration with both DL (Downlink) and UL (Uplink) information.

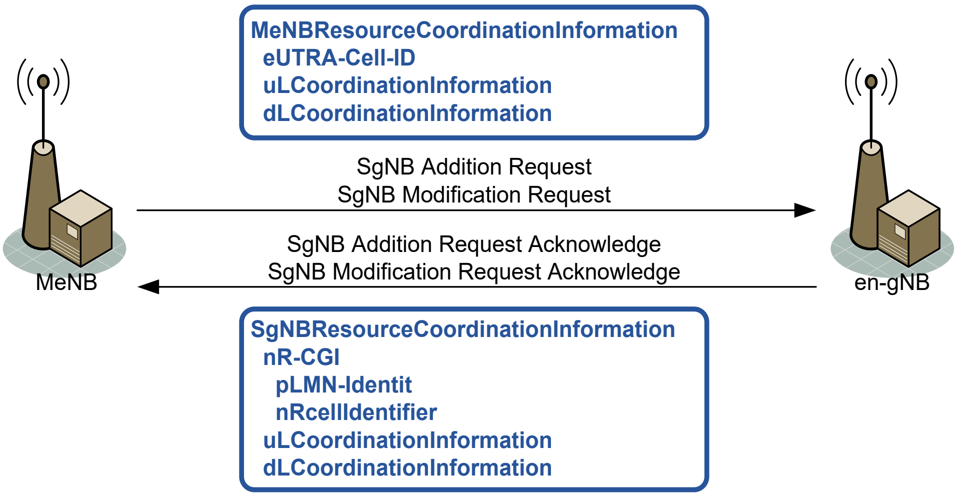


Figure 9-52 EN-DC Resource Coordination

9.5.2 Coordination Resource Bitmap

The representation of the coordination resource bitmap is illustrated in Figure 9-53. It relies on other cell information, specifically the number of resource blocks for the DL/UL, which is provided during the EN-DC X2 Setup or EN-DC X2 Configuration procedure. The length of the coordination information bitmap is in multiples of the N_{RB} indicated. In addition, the bitmap can span multiple subframes, up to a maximum of 40.

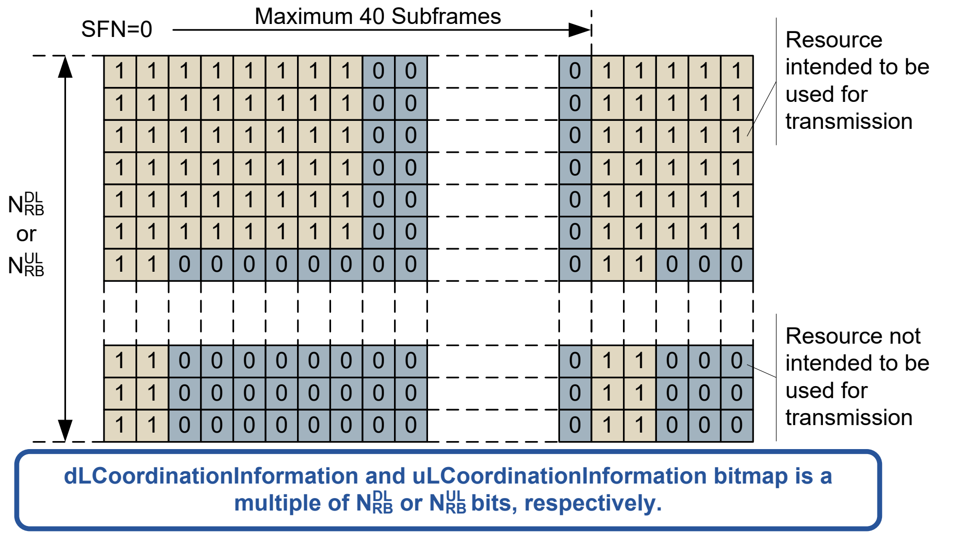


Figure 9-53 Coordination Information Bitmap

10 5G Access Procedures

10.1 5G Initial Access

10.1.1 Network Access Procedure

When a 5G device is switched on, depending on the device capability and stored information, it will attempt to select a suitable network. Figure 10-1 summarizes the key stages.

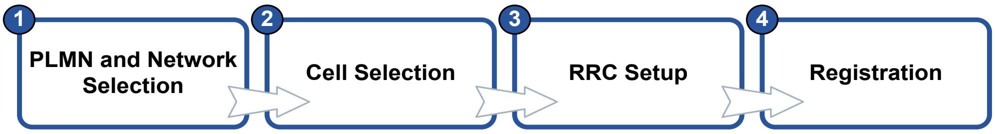


Figure 10-1 Network Access Procedures

10.1.2 PLMN and Access Network Selection

The initial stage involved the device performing PLMN (Public Land Mobile Network) and access technology selection. This will utilize information on the USIM (Universal Subscriber Identity Module), as well as information of the device, as illustrated in Figure 10-2.

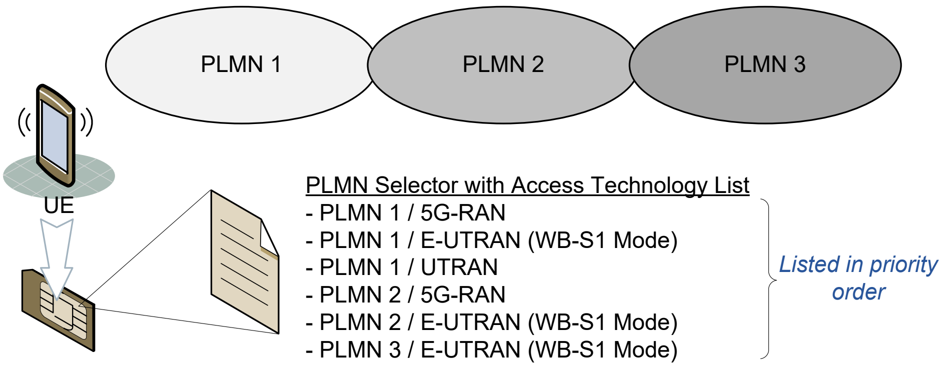


Figure 10-2 PLMN and Access Network Selection

Note that there are various "lists" in the USIM which are able to provide a priority order of both PLMNs and RAT (Radio Access Technology).

10.1.3 Scanning

In order to determine the PLMN identity the device needs to obtain SI (System Information) from a cell. This will involve obtaining the SSB (Synchronization Signal Block) which will be transmitted from the cell based on the GSCN (Global Synchronization Channel Number) raster. Options are illustrated in Figure 10-3. Note that the GSCN has its own numbering scheme, as well as occurring on a NR-ARFCN (NR - Absolute Radio Frequency Channel Number).

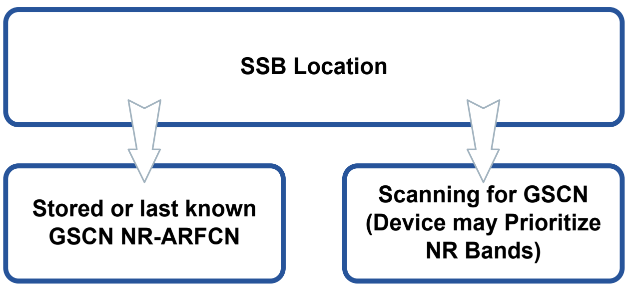
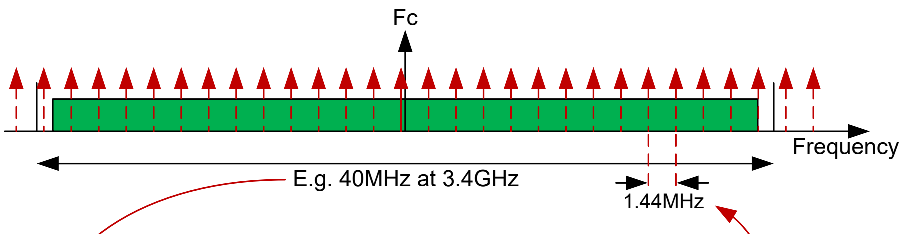


Figure 10-3 SSB Location

10.1.4 GSCN Number and Raster

Figure 10-4 illustrates how the GSCN raster may not be exactly aligned with the service providers channel band. For example, if using a 3.4GHz 5G deployment, the GSCN raster size is 1.44MHz. As such, one or more of these SSB location may be utilized in the band. As such, the centre frequency of the channel (Fc) may not be the same as the centre frequencies for the possible SSB raster locations.



Frequency Range	SSB Frequency Raster	GSCN Range
0 – 3000 MHz	1.20MHz	2 – 7498
3000 – 24250 MHz	1.44MHz	7499 – 22255
24250 – 100000 MHz	17.28MHz	22256 – 26639

Figure 10-4 GSCN Raster

Even though the GSCN has a range of options, the actual operational NR Band dictates the range of GSCN's that can be utilized, as well as the step size, i.e. in some bands not all SSB raster locations are allowed. Figure 10-5 and Figure 10-6 illustrate the applicable channel raster for NR Bands.

NR Band	SS Block SCS	SS Block Pattern	Range of GSCN (First – <Step size> – Last)
n1	15kHz	Case A	5279 – <1> – 5419
n2	15kHz	Case A	4829 – <1> – 4969
n3	15kHz	Case A	4517 – <1> – 4693
n5	15kHz	Case A	2177 – <1> – 2230
	30kHz	Case B	2183 – <1> – 2224
n7	15kHz	Case A	6554 – <1> – 6718
n8	15kHz	Case A	2318 – <1> – 2395
n12	15kHz	Case A	1828 – <1> – 1858
n20	15kHz	Case A	1982 – <1> – 2047
n78	30kHz	Case C	7711 – <1> – 8051
n79	30kHz	Case C	8480 – <16> – 8880

Figure 10-5 Applicable SS Raster per Operating Band (FR1)

NR Band	SS Block SCS	SS Block Pattern	Range of GSCN (First – <Step size> – Last)
n257	120kHz	Case D	22388 – <1> – 22558
	240kHz	Case E	22390 – <2> – 22556
n258	120kHz	Case D	22257 – <1> – 22443
	240kHz	Case E	22258 – <2> – 22442
n260	120kHz	Case D	22995 – <1> – 23166
	240kHz	Case E	22996 – <2> – 23164
n261	120kHz	Case D	22446 – <1> – 22492
	240kHz	Case E	22446 – <2> – 22490

Figure 10-6 Applicable SS Raster per Operating Band (FR2)

10.1.5 SSB Operation

Depending on the deployment the cell will be broadcasting between 1 and 64 SSB (Synchronization Signal Block), each identifiable by an SSB Index. This includes NR synchronization signals and a PBCH (Physical Broadcast Channel). Figure 3-25 illustrates the basic concept of beam sweeping.

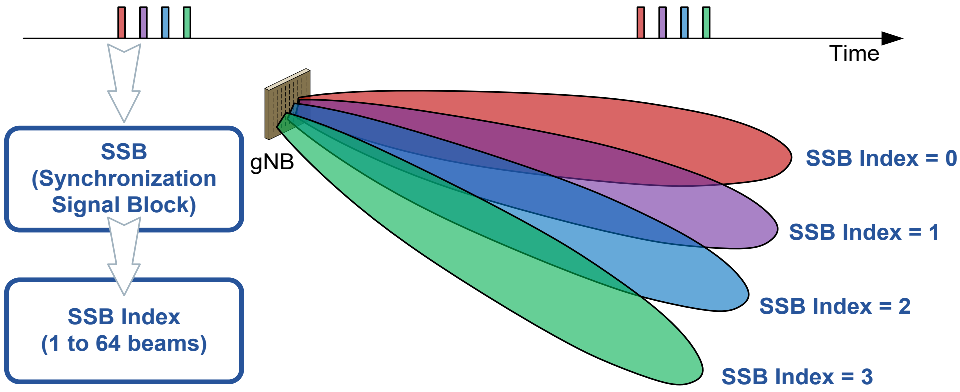


Figure 10-7 Beam Sweeping

The SSB Index is configured to be a maximum (L) of 4, 8 or 64.

Deriving SSB Index

In order for a device to derive the SSB Index it first derives the NR PCI (Physical Cell Identity) from the PSS (Primary Synchronization Signal) and SSS (Secondary Synchronization Signal). This is required since the PCI is used on the cell to initialize the physical layer “scrambling”, as well as the location of the PBCH (Physical Broadcast Channel) and the PBCH DMRS (Demodulation Reference Signal). Both the PBCH DMRS and PBCH are scrambled based on the PCI and the 2 or 3 LSB’s of the SSB Index. As such, a device must utilize blind detection to determine which SSB index/scrambling sequence was utilized.

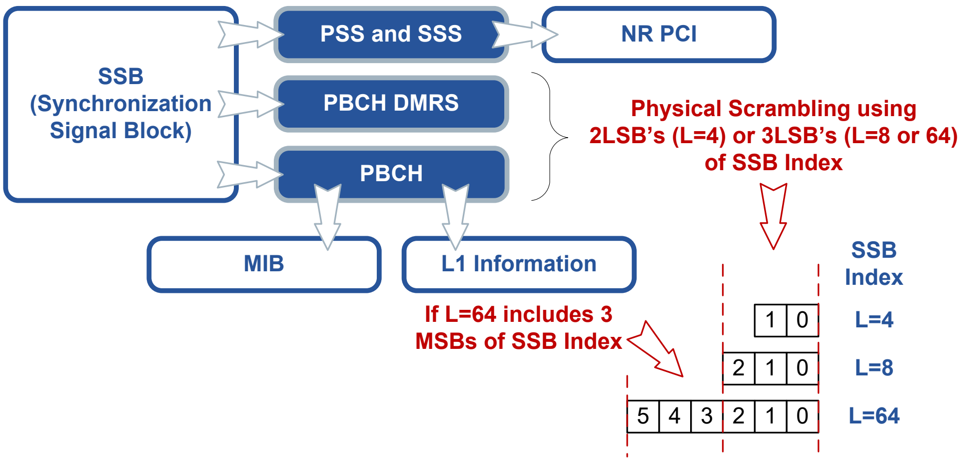


Figure 10-8 Deriving the SSB Index

If the deployment utilizes an SSB Index L=64, i.e. using higher numerologies in higher bands, then a total of 6bits are required for the SSB Index. To facilitate this, the PBCH carries the MIB (Master Information Block) and L1 (Layer 1) Information, with the L1 Information carrying additional frame timing information, as well as the extra 3 MSB’s for the SSB Index.

10.1.6 Downlink Synchronization

Acquiring the SSB enables the device to become downlink synchronized with the cell. Figure 10-9 illustrates the contents of the SSB PBCH and highlights the parameters related to the SFN (System Frame Number). Specifically, the systemFrameNumber parameter is 6bits and represents the MSB's of the SFN. The remaining 4 LSB's required for the SFN are part of the Layer 1 Information. This split in coding enables the MIB to remain unchanged for 160ms, i.e. changing the 4 LSB's in the L1 Information when the SFN changes. In the example, the SSB burst is occurring every 80ms, however it could be sent every 5ms (half a frame). As such, the L1 Information also includes a HRF (Half Radio Frame) bit which can be used in scenarios where the SSB beam sweep is every 5ms, and thus enabling the device to distinguish between the first or second half of the frame.

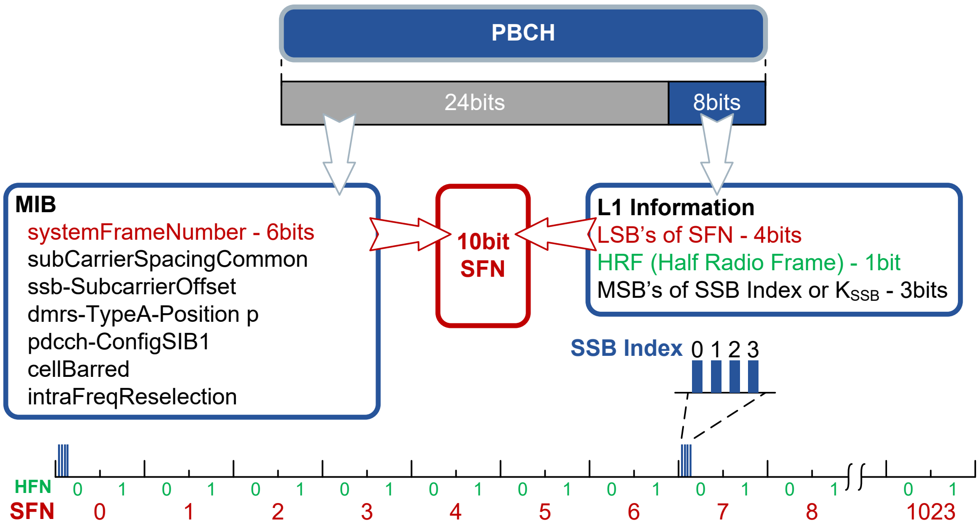


Figure 10-9 NR Downlink Synchronization

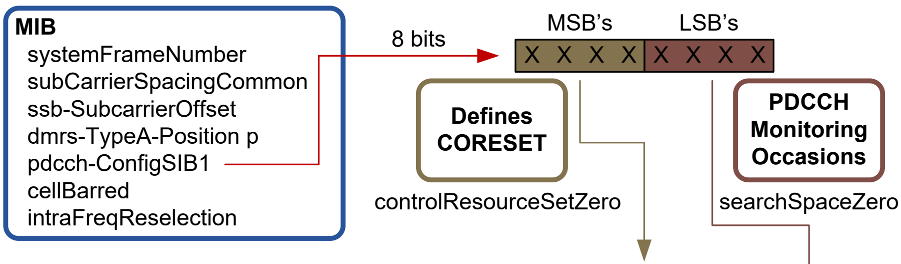
10.2 NR CORESET#0 Acquisition

10.2.1 MIB/SIB1/RMSI

Having received the SSB/PBCH the device can decode the rest of the MIB. One of the key parameters is the PDCCH-ConfigSIB1. This has 8bits which are split to provide two parameters, namely the controlResourceSetZero parameter which defines the CORESET for the Initial BWP (Bandwidth Part) and the searchSpaceZero, defining the PDCCH monitoring occasions. The actual decoding of the bits is based on the system configuration, as illustrated in Figure 10-10.

Based on the combination of SSB SCS (Subcarrier Spacing), PDCCH SCS and the minimum BW (Bandwidth) allowed for the NR band currently being acquired, the device will be able to identify which table from 3GPP 38.213 to utilize (Table 13-1 to 13-10).

The device then applies the controlResourceSetZero index to the appropriate table (13-1 to 13-10 from 3GPP TS 38.213). This identifies the CORESET size, duration and offset. In addition, it identifies the "multiplexing pattern" which combined with the Frequency Range, SSB SCS and PDCCH SCS selects the table (13-11 to 13-15) which will be used to decode the searchSpaceZero index.



SSB SCS (kHz)	PDCCH SCS (kHz)	Minimum BW from NR Band List	Table (38.213)
15	15	5MHz or 10MHz	Table 13-1
15	30	5MHz or 10MHz	Table 13-2
30	15	5MHz or 10MHz	Table 13-3
30	30	5MHz or 10MHz	Table 13-4
30	15	40MHz	Table 13-5
30	30	40MHz	Table 13-6
120	60	n/a	Table 13-7
120	120	n/a	Table 13-8
240	60	n/a	Table 13-9
240	120	n/a	Table 13-10

CORESET Multiplexing Pattern	Frequency Range	SSB SCS (kHz)	PDCCH SCS (kHz)	Table (38.213)
Pattern 1	FR1	n/a	n/a	Table 13-11
Pattern 1	FR2	n/a	n/a	Table 13-12
Pattern 2	n/a	120	60	Table 13-13
Pattern 2	n/a	240	120	Table 13-14
Pattern 3	n/a	120	120	Table 13-15

Figure 10-10 Determining Type0-PDCCH Common Search Space

10.2.2 Example of Mapping

In order to identify the process, the example below can be used.

Example:
FR1
Band n78
pdcch-ConfigSIB1 = 00000000
SSB SCS = 30kHz
PDCCH SCS = 30kHz

Figure 10-11 Example pdcch-ConfigSIB1

Control Resource Set Zero

In this example, the SSB SCS, PDCCH SCS and the band would map to table 13-4 (38.213), as illustrated in Figure 10-12.

Based on the controlResourceSetZero index = 0 (4 MSBs), various CORESET parameters are defined. This includes, pattern = 1, Number of RBs = 24, Number of Symbols = 2 and offset RBs = 0.

Index	SS/PBCH Block and Control Resource Set Multiplexing Pattern	Number of RBs	Number of Symbols	Offset (RBs)
0	1	24	2	0
1	1	24	2	1
2	1	24	2	2
3	1	24	2	3
4	1	24	2	4
5	1	24	3	0
6	1	24	3	1
7	1	24	3	2
8	1	24	3	3
9	1	24	3	4
10	1	48	1	12
11	1	48	1	14
12	1	48	1	16
13	1	48	2	12
14	1	48	2	14
15	1	48	2	16

Figure 10-12 Example of 38.213 Table 13-4

CORESET Offset

There are many permutations related to the SCS used for the SSB and the PDCCH. In addition, the size of CORESET#0 may be 24, 48 or 96 PRBs. Figure 10-13 illustrates one example whereby the SSB and PDCCH are utilizing a 30kHz SCS.

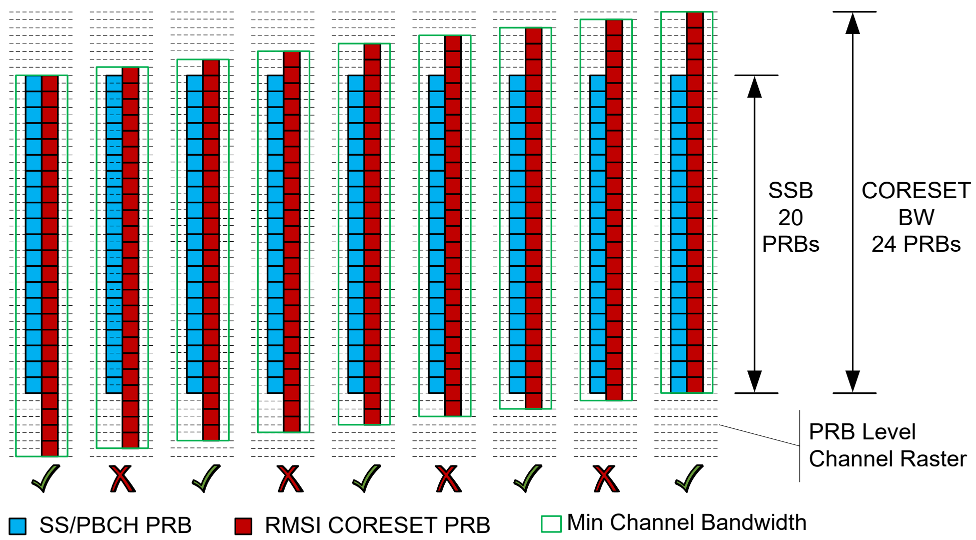


Figure 10-13 Example of RB Offset (3GPP - R1-1721709)

Since the SS/PBCH block is aligned to the GSCN, the PRBs for the SSB and the CORESET may not be actually aligned. The device is informed about the offset using the K_{SSB} parameter which is either in steps of 15kHz (μ=0 or 1) or 60kHz (μ=3 or 4).

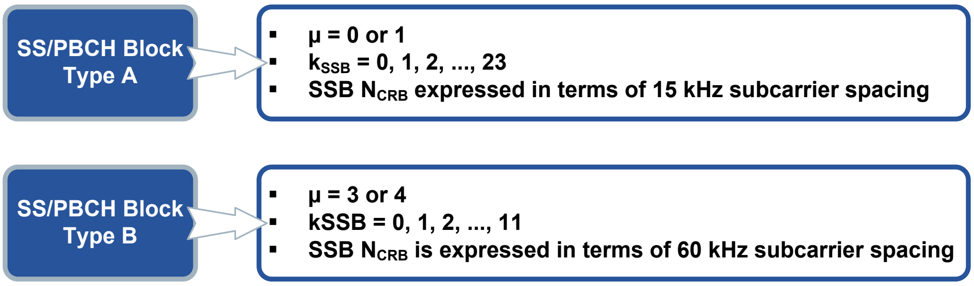


Figure 10-14 SSB Block Type and K_{SSB}

Illustration of CORESET#0 Multiplexing Pattern

Figure 10-15 illustrates an example of the multiplexing patterns used for the RMSI. The pattern is determined based on the deployment scenario and the value of the controlResourceSetZero.

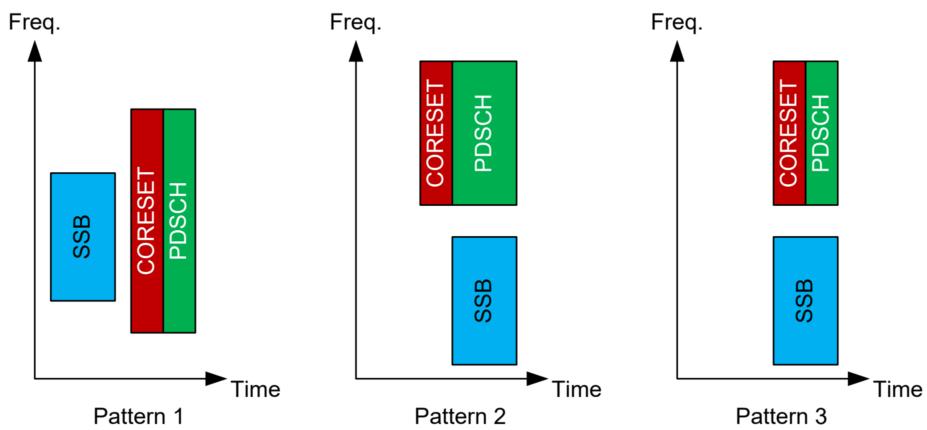


Figure 10-15 Illustration of CORESET#0 Multiplexing Patterns

Pattern 1 enables the CORESET to be located in a different SFN and Slot, whereas Pattern 2 and 3 requires the device to monitor the PDCCH slot equal to the periodicity of SS/PBCH block.

Search Space Zero

Based on Figure 10-10 and the example (Figure 10-11), multiplexing pattern 1 and the use of FR1 (Band n78) is chosen. As such, table 13-11 from 38.213 is selected and is illustrated in Figure 10-16.

Index	*O*	Number of Search Space Sets per Slot	*M*	First Symbol Index
0	0	24	1	0
1	0	24	1/2	{0, if *i* is even}, {$N_{symb}^{CORESET}$, if *i* is odd}
2	2	24	1	0
3	2	24	1/2	{0, if *i* is even}, {$N_{symb}^{CORESET}$, if *i* is odd}
4	5	24	1	0
5	5	24	1/2	{0, if *i* is even}, {$N_{symb}^{CORESET}$, if *i* is odd}
6	7	24	1	0
7	7	24	1/2	{0, if *i* is even}, {$N_{symb}^{CORESET}$, if *i* is odd}
8	0	24	2	0
9	5	24	2	0
10	0	48	1	1
11	0	48	1	2
12	2	48	1	1
13	2	48	1	2
14	5	48	1	1
15	5	48	1	2

Figure 10-16 38.213 (Table 13-11)

Since the searchSpaceZero index = 0, the parameter "*O*" and "*M*" are defined. These can then be used in various equations (illustrated in Figure 10-17) to determine the starting slot and SFN (System Frame Number).

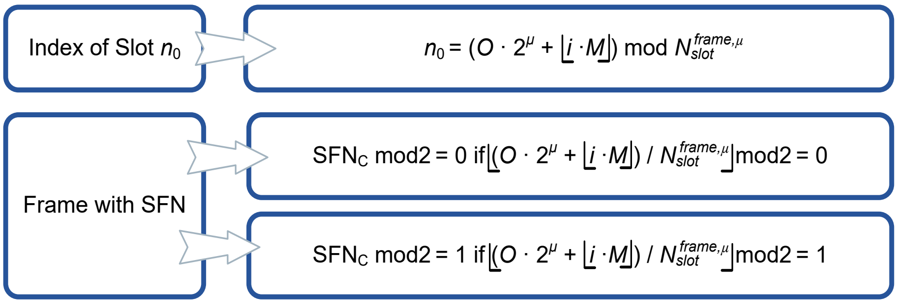


Figure 10-17 Determining Starting Slot - Pattern 1

Note that if pattern 2 or pattern 3 had been selected the monitoring is based on the location of the SS/PBCH block and detailed in 3GPP 38.213 tables "13-13 to 13-15".

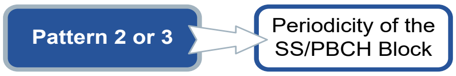


Figure 10-18 Pattern 2 and 3 Timing

10.3 NR System Information and Cell Selection

10.3.1 System Information Block 1

SIB1 is transmitted on the DL-SCH with a periodicity of 160ms and variable transmission repetition periodicity. The default transmission repetition periodicity of SIB1 is 20ms but the actual transmission repetition periodicity is up to network implementation. For SSB and CORESET multiplexing pattern 1, SIB1 repetition transmission period is 20ms. For SSB and CORESET multiplexing pattern 2/3, SIB1 transmission repetition period is the same as the SSB period.

SIB1 includes information regarding the availability and scheduling (e.g. mapping of SIBs to SI message, periodicity, SI-window size) of other SIBs with an indication whether one or more SIBs are only provided on-demand and, in that case, the configuration needed by the device to perform the SI request.

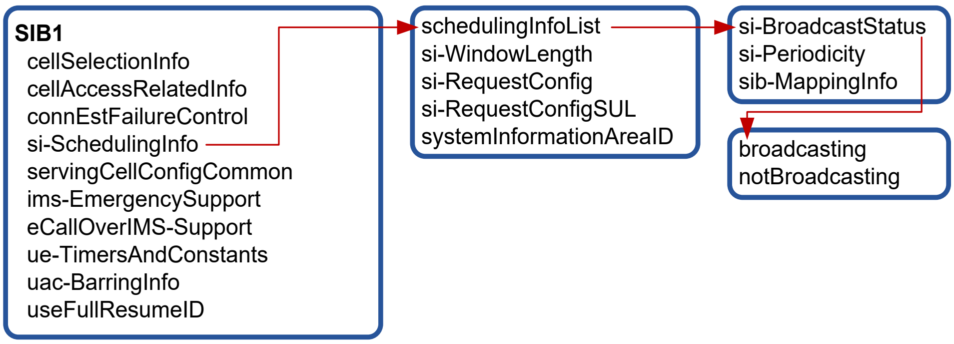


Figure 10-19 NR SIB 1

SIBs other than SIB1 are carried in SI (System Information) messages, which are transmitted on the DL-SCH. Only SIBs having the same periodicity can be mapped to the same SI message. Each SI message is transmitted within periodically occurring time domain windows (referred to as SI-windows with same length for all SI messages). Each SI message is associated with a SI-window and the SI-windows of different SI messages do not overlap. That is, within one SI-window only the corresponding SI message is transmitted. Any SIB except SIB1 can be configured to be cell specific or area specific, using an indication in SIB1. The cell specific SIB is applicable only within a cell that provides the SIB while the area specific SIB is applicable within an area referred to as SI area, which consists of one or several cells and is identified by systemInformationAreaID.

Scheduling SI Messages

The scheduling of other SI messages can be indicated by utilizing DCI Format with the CRC (Cyclic Redundancy Check) scrambled by the SI-RNTI. Figure 10-20 illustrates the key parameters included.

The following information is transmitted by means of the DCI format 1_0 with CRC scrambled by SI-RNTI:
- Frequency domain resource assignment - Variable bits
- Time domain resource assignment - 4 bits
- VRB-to-PRB mapping - 1 bit
- Modulation and coding scheme - 5 bits
- Redundancy version - 2 bits
- System information indicator - 1 bit
- Reserved bits - 15 bits

Figure 10-20 DCI Format 1_0 with CRC scrambled by SI-RNTI

The System Information Indicator bit is used to identify if scheduling SIB1 or a SI message.

10.3.2 System Information Types

NR include its own set on System Information Block types. In addition to the MIB (Master Information Block), SIB 1 to SIB 9 are defined. Figure 10-21, Figure 10-22 and Figure 10-23 identifies the main usages of each.

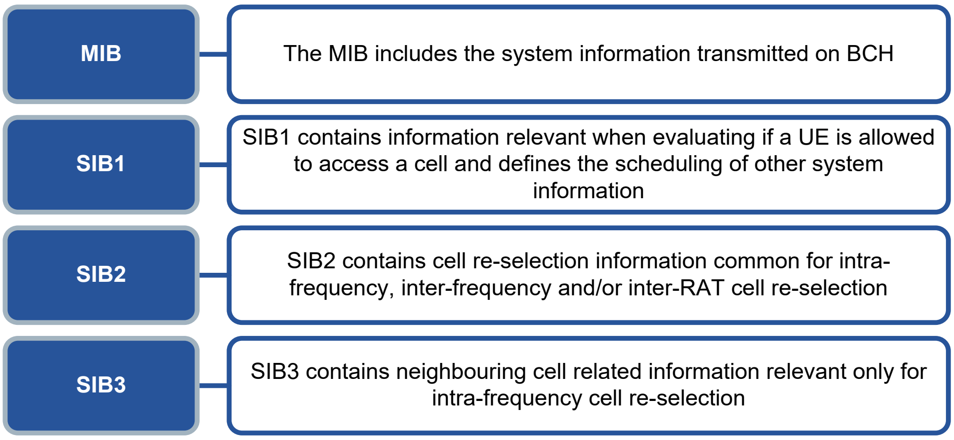


Figure 10-21 NR System Information - Part 1

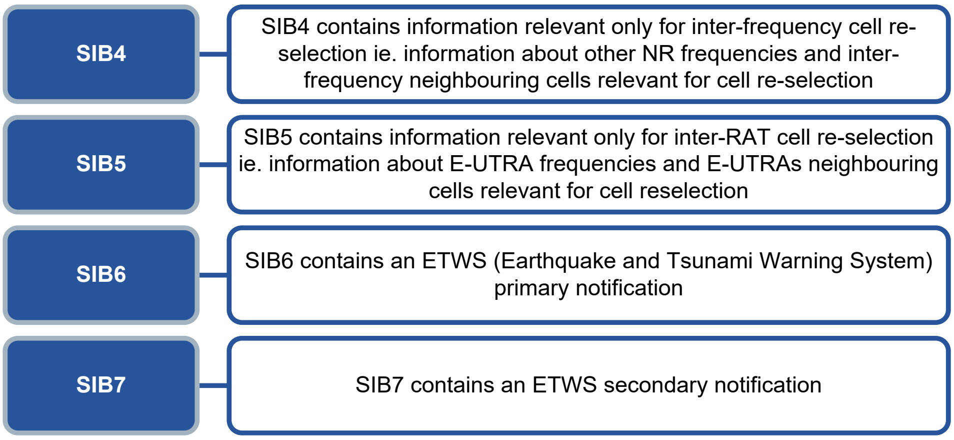


Figure 10-22 NR System Information - Part 2

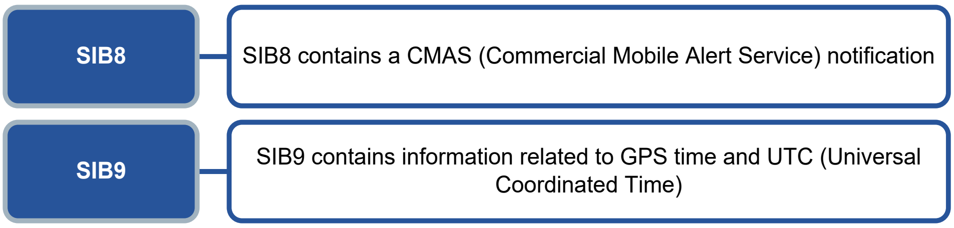


Figure 10-23 NR System Information - Part 3

10.3.3 Cell Selection

Before the device can access the network, it must first select a suitable cell. The selection of a suitable cell is based on radio criteria and information sent from the cell in SIB1. However, depending on the device features and capabilities, eg. support of SUL (Supplementary Uplink) it may be required to receive other system information messages.

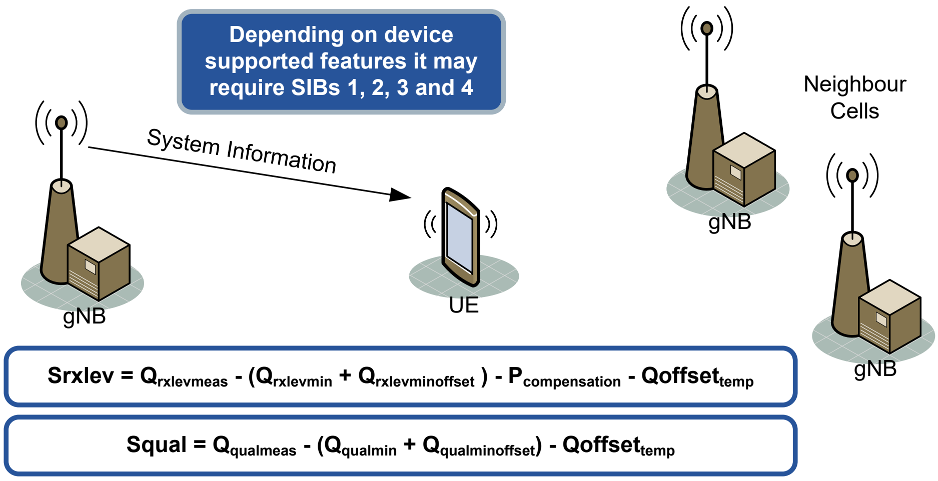


Figure 10-24 NR Cell Selection

The goal of the cell selection process is to camp on a cell with the best S (Selection) value, both in terms of RXLEV (Received Level) and QUAL (Quality). The selection calculations are illustrated in Figure 10-24, with various requirements and offsets provided in the system information messages from that cell.

10.4 NR Random Access

10.4.1 Random Access Triggers

Assuming a device has selected a suitable cell, the RA (Random Access) procedure is typically triggered. It is controlled by MAC (Medium Access Layer) and as such, MAC is responsible for initialization, resource selection and contention resolution.

There are various triggers for performing the random access, as illustrated in Figure 10-25.

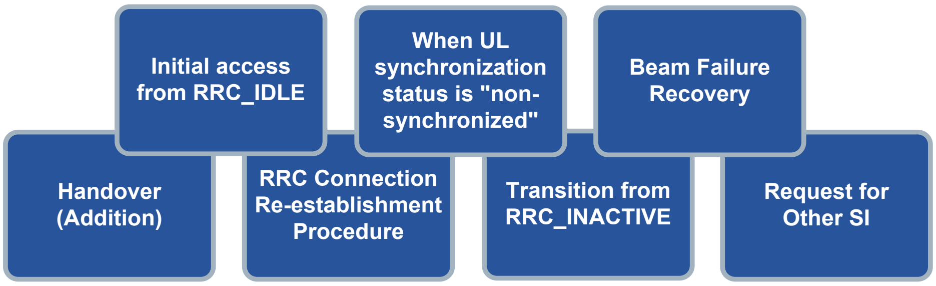


Figure 10-25 NR Random Access Triggers

Furthermore, the Random Access procedure takes two distinct forms, namely CB (Contention Based) and CF (Contention Free).

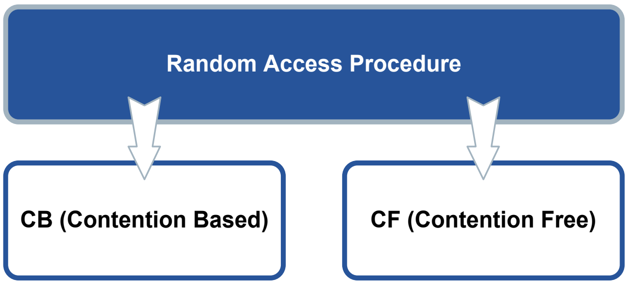


Figure 10-26 Random Access

10.4.2 Contention Based Random Access Procedure

Figure 10-27 illustrates the basic RA procedure.

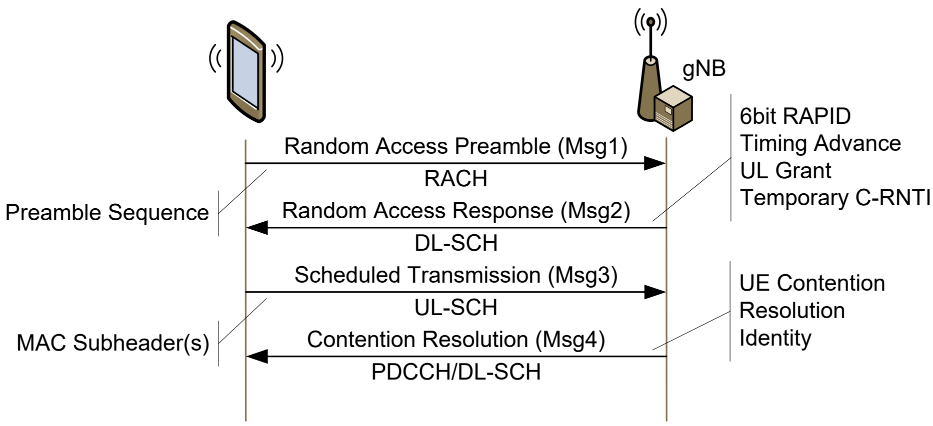


Figure 10-27 Random Access Procedure

For contention based access, there are typically 4 steps/messages:

- Msg1 - the transmission of random access preamble in a PRACH
- Msg2 - this includes the RAPID (Random Access Preamble Identifier), which identifies the preamble index corresponding to the one sent by the device. It also includes the RAR (Random Access Response) message which defines the uplink resources for the device.
- Msg3 - the transmission of the PUSCH, this will typically include the initial RRC messages, namely the RRC Setup Request.
- Msg4 - the PDCCH/PDSCH for contention resolution.

10.4.3 PRACH Preambles

In order to access a NR cell, the device needs to utilize a PRACH preamble sequence/code. Like LTE, NR utilizes a RSI (Root Sequence Index) which enables the device to generate the correct 64 preambles. However, unlike standard LTE, the use of beamforming in NR influences the set of preambles that can be used when a device is access in a specific beam.

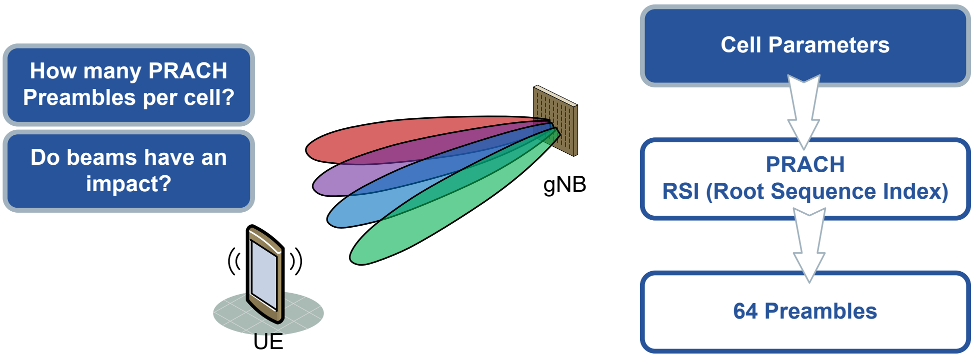


Figure 10-28 PRACH Preambles

10.4.4 RACH Configuration Common

In order to access a NR cell, the device must obtain its RACH parameters. This is included as part of SIB1 rach-ConfigCommon parameter and is illustrated in Figure 10-29.

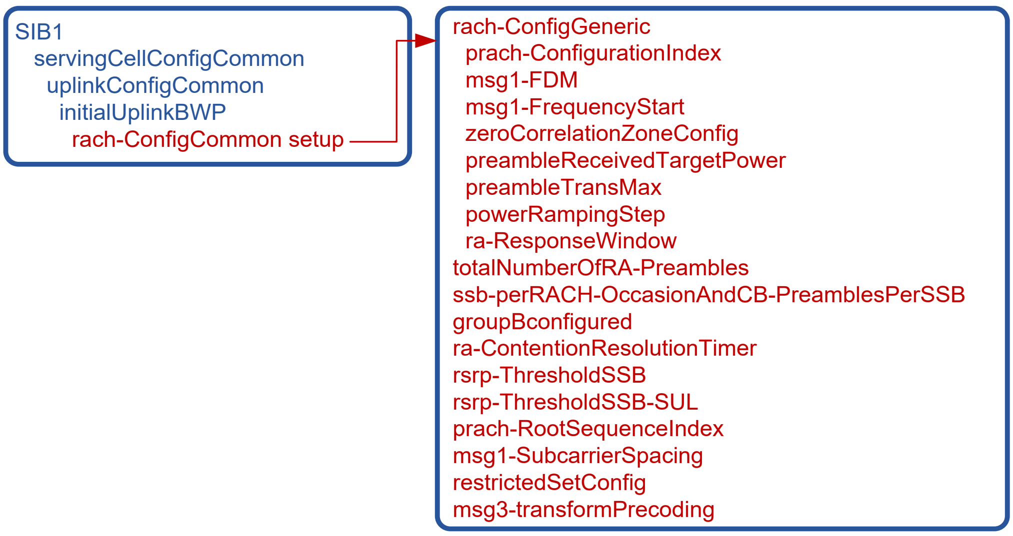


Figure 10-29 NR RACH/PRACH Configuration

The following parameters assist the Random Access procedure:

- rach-ConfigGeneric - this includes:

    - prach-ConfigurationIndex - this defines the available set of PRACH occasions for the transmission of the Random Access Preamble.
    - msg1-FDM - this defines the number of PRACH transmission occasions, using FDM (Frequency Division Multiplexing), in one time instance.
    - msg1-FrequencyStart - this identifies the offset of the lowest PRACH transmission occasion in frequency domain with respect to PRB 0. The value is configured so that the corresponding RACH resource is entirely within the bandwidth of the Uplink BWP (Bandwidth Part).
    - zeroCorrelationZoneConfig - this is linked to the identification of the cyclic shift which is used to generate the 64 preambles.
    - preambleReceivedTargetPower - this is utilized for the initial Random Access Preamble power calculation.
    - preambleTransMax - this defines the maximum number of Random Access Preamble transmissions.
    - powerRampingStep - this the power-ramping factor for stepping up for the next preamble.
    - ra-ResponseWindow - this is the Msg2 (RAR) window length in number of slots.
- totalNumberOfRA-Preambles - if present, this limits the total number of access preambles.
- ssb-perRACH-OccasionAndCB-PreamblesPerSSB - this defines the number of SSBs mapped to each PRACH occasion and the number of Random Access Preambles mapped to each SSB.
- groupBconfigured - this includes various parameters which can define a set of preambles (Group B). This can be used to indicate a larger msg3 and possibly increased pathloss.
- ra-ContentionResolutionTimer - this is the initial value for the contention resolution timer in subframes.
- rsrp-ThresholdSSB - this is the RSRP threshold for the selection of the SSB and corresponding Random Access Preamble and/or PRACH occasion.
- rsrp-ThresholdSSB-SUL - this is similar to the rsrp-ThresholdSSB parameter however linked to the SUL (Supplementary Uplink).
- prach-RootSequenceIndex - this is used as part of the generation of the 64 preambles.
- msg1-SubcarrierSpacing - this identifies the subcarrier spacing of the PRACH.
- restrictedSetConfig - this provides configuration of an unrestricted set or one of two types of restricted sets.
- msg3-transformPrecoding - this indicates to the device whether transform precoding is enabled for Msg3 transmission.

10.4.5 Preamble Options

There are up to 64 preambles per cell which may be grouped into “Group A” and “Group B”, as illustrated in Figure 10-30. Group B preambles relate to the size of Msg3 and the pathloss.

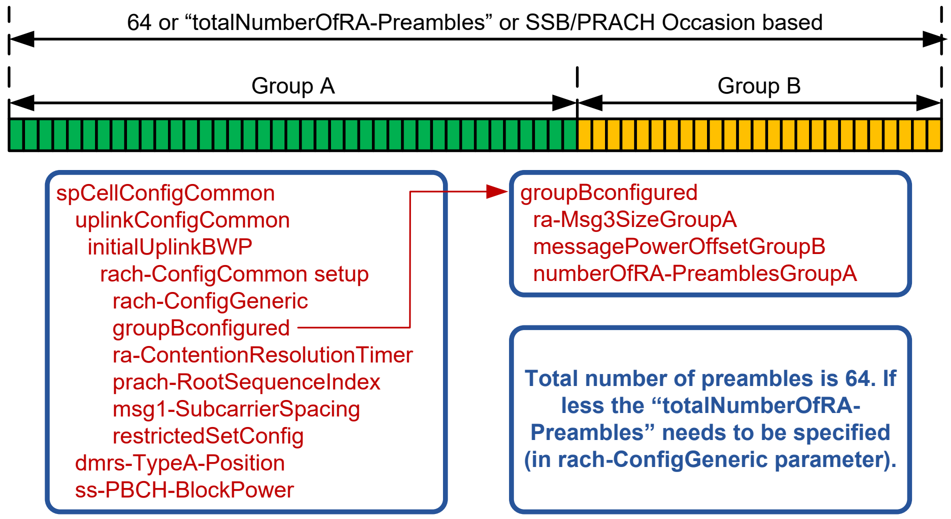


Figure 10-30 Preamble Group Configuration

The groupBconfigured parameter indicates:

- ra-Msg3SizeGroupA - this defines the Transport Blocks size threshold in bits below which the device should use Group A. Values include b56, b144, b208, b256, b282, b480, b640, b800 or b1000.
- messagePowerOffsetGroupB - power offset for Group B preamble selection. Value in dB. Value minus infinity corresponds to infinity. Values include: dB0, dB5, dB8, dB10, dB12, dB15 or dB18.
- numberOfRA-PreamblesGroupA (SpCell only) - this defines the number of Random Access Preambles in Random Access Preamble Group A for each SSB, if Random Access Preambles Group B is configured.

10.4.6 Preambles per SSB per PRACH Occasion

In addition to allocating Group A and Group B preamble sets, the system can configure the ssb-perRACH-OccasionAndCB-PreamblesPerSSB parameter. This defines the number of SSB per RACH occasion, as well as the number of contention based preambles per SSB. As illustrated in Figure 10-31, the total number of preambles per SSB per PRACH occasion can then be calculated.

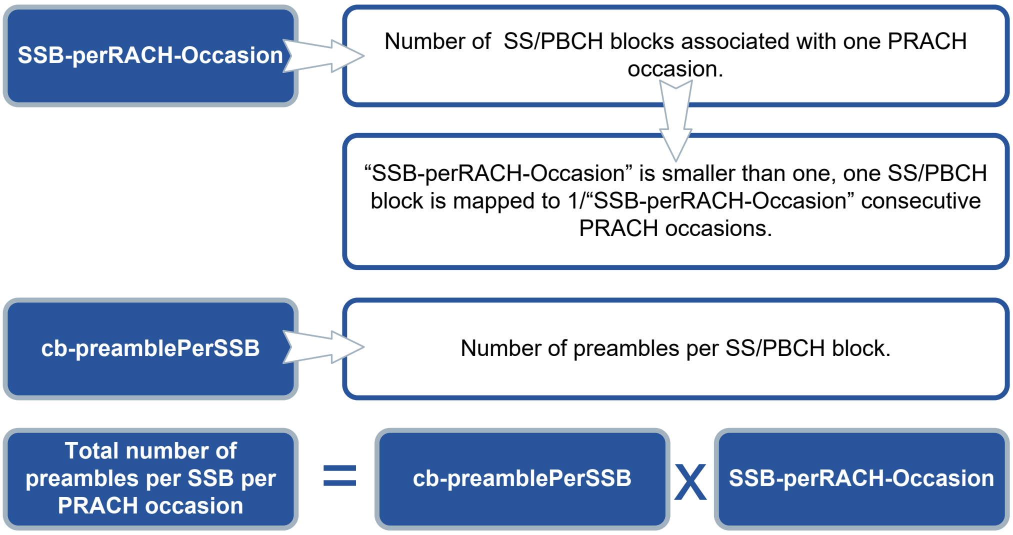


Figure 10-31 Preambles per SSB per PRACH Occasion

Note that If numberOfRA-PreamblesGroupA is equal to the number of Random Access Preambles per SSB configured by ssb-perRACH-

OccasionAndCB-PreamblesPerSSB, there is no Random Access Preambles Group B.

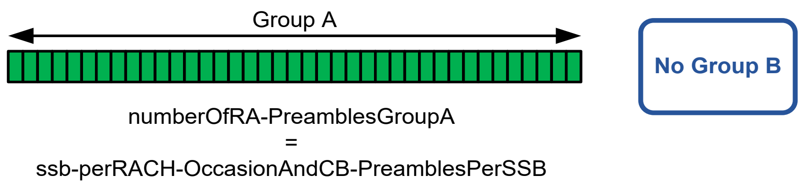


Figure 10-32 No Group B

The Random Access Preambles in Random Access Preamble Group A are the Random Access Preambles from 0 to numberOfRAPreamblesGroupA – 1 (if Random Access Preambles Group B is configured). Otherwise, the Random Access Preambles in Random Access Preamble Group A are the Random Access Preambles from 0 to the number of Random Access Preambles per SSB configured by ssb-perRACH-OccasionAndCBPreamblesPerSSB.

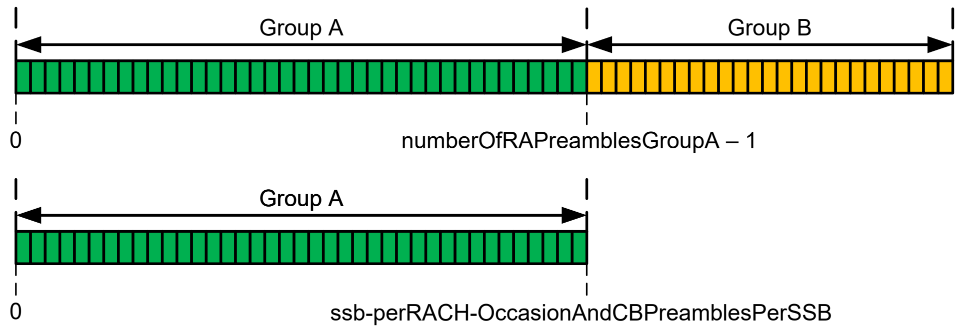


Figure 10-33 Group A Numbering

The Random Access Preambles in Random Access Preamble Group B, if existing, are the Random Access Preambles numberOfRA-PreamblesGroupA to the number of Random Access Preambles per SSB configured by ssb-perRACH-OccasionAndCB-PreamblesPerSSB.

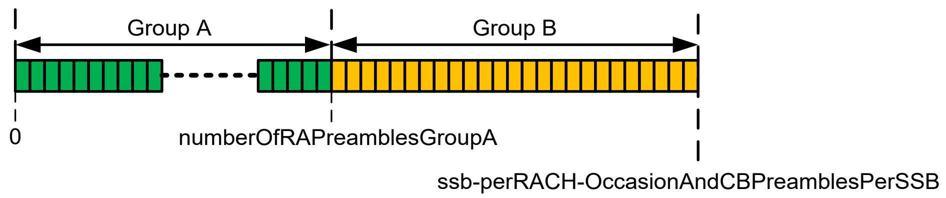


Figure 10-34 Group B Numbering

10.4.7 SS/PBCH Index Mapping to PRACH Occasion

SS/PBCH block indexes are mapped to PRACH occasions in the following order:

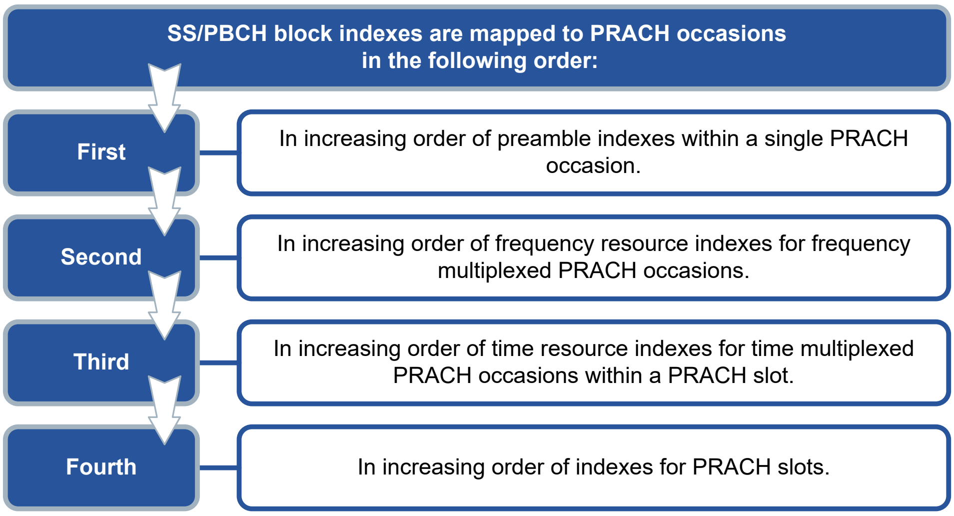


Figure 10-35 SS/PBCH Index Mapping to PRACH Occasion

The period, starting from frame 0, for the mapping of SS/PBCH blocks to PRACH occasions is the smallest of 1, 2 or 4 PRACH configuration periods that are larger than or equal to $\lceil N_{Tx}^{SSB}/N_{PRACH\ Period}^{SSB} \rceil$, where the UE obtains N_{Tx}^{SSB} from higher layer parameter SSB-transmitted-SIB1 and $N_{PRACH\ Period}^{SSB}$ is the number of SS/PBCH blocks that can be mapped to one PRACH configuration period.

10.4.8 Random Access Response Window

Once the device has transmitted the selected preamble from the appropriate group/set, it monitors the PDCCH for Random Access Response(s) identified by the RA-RNTI (Random Access RNTI) in the RAR (Random Access Response) window. This is illustrated in Figure 10-36.

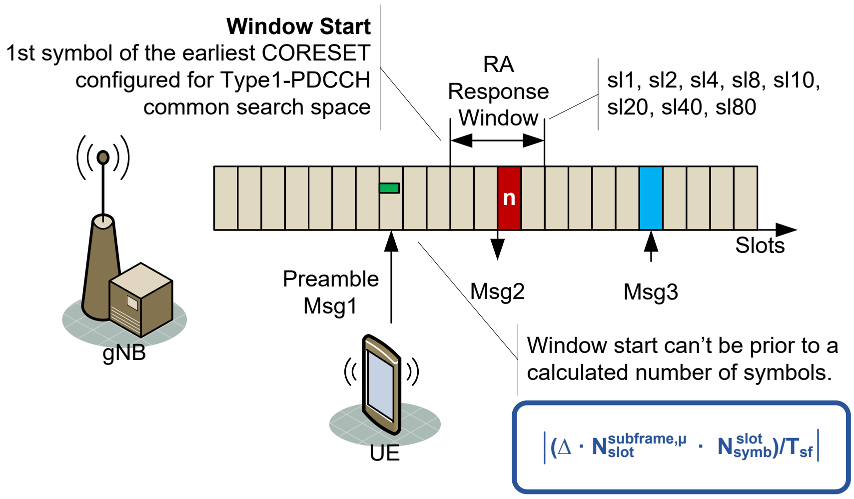


Figure 10-36 Random Access Response Window

10.4.9 Random Access Response Message

On receiving the preamble, the gNB sends a Random Access Response on the DL-SCH. This is addressed to the RA-RNTI and scheduled on the PDCCH (Physical Downlink Control Channel).

The RA-RNTI is slightly different from the other RNTI's since it's calculated by the device based on where/when it accessed the network. It is then used by the device to calculate the correct RAR (Random Access Response) to decode. The RA-RNTI is calculated using the formula shown in Figure 10-37.

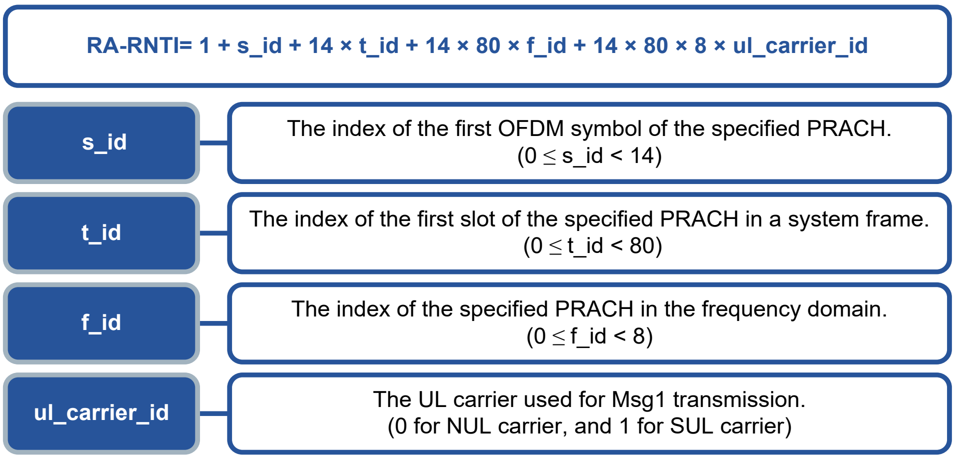


Figure 10-37 RA-RNTI Calculation

It is also used by the physical layer to scramble the CRC of the PDCCH (Physical Downlink Control Channel).

The RAR includes the RAPID (Random Access Preamble Identifier) in a MAC subheader. This corresponds to the preamble heard. The RAR payload is illustrated in Figure 10-38 and includes TA (Timing Advance) information, initial UL grant and assignment of a Temporary C-RNTI.

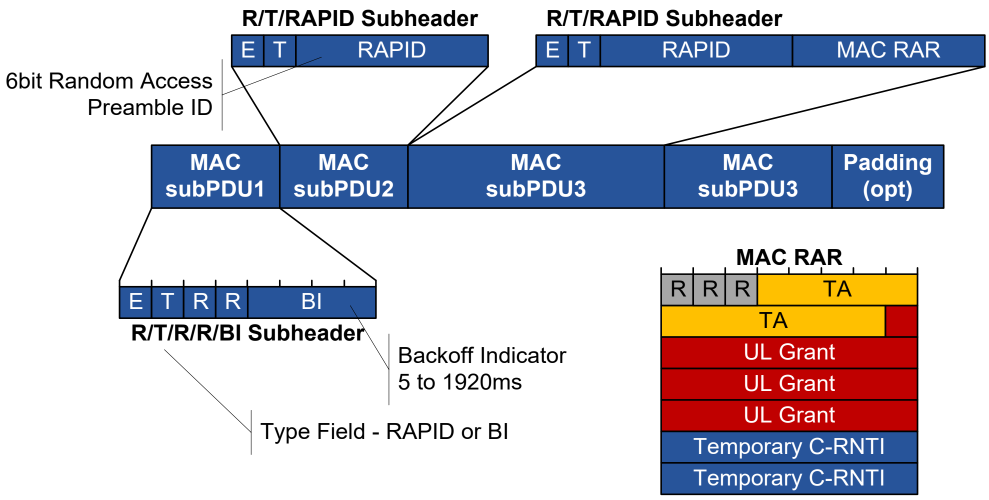


Figure 10-38 Random Access Response Message

The UL grant contains 25bits of information, including:

Frequency Hopping flag - 1bit
Msg3 PUSCH frequency resource allocation - 12bits
Msg3 PUSCH time resource allocation - 4bits
MCS (Modulation and Coding Scheme) - 4bits
TPC command for Msg3 PUSCH - 3bits
CSI request - 1bit

Figure 10-39 UL Grant

Following the scheduled transmission, and since multiple devices may have transmitted in the same opportunity with the same RAPID, MAC performs contention resolution on the downlink. This includes a UE Contention Resolution Identity being sent.

RAR Timing Advance

The RAR includes a 12bit TA (Timing Advance) command, for a TAG (Timing Advance Group), which indicates $T_A = 0, 1, 2, ..., 3846$. Figure 10-40 illustrates how the timing alignment is calculated based on the value in the RAR. It also identifies the Timing advanced steps (in terms of duration), as well as the timing calculation for other cases, which includes a +ve or -ve adjustment.

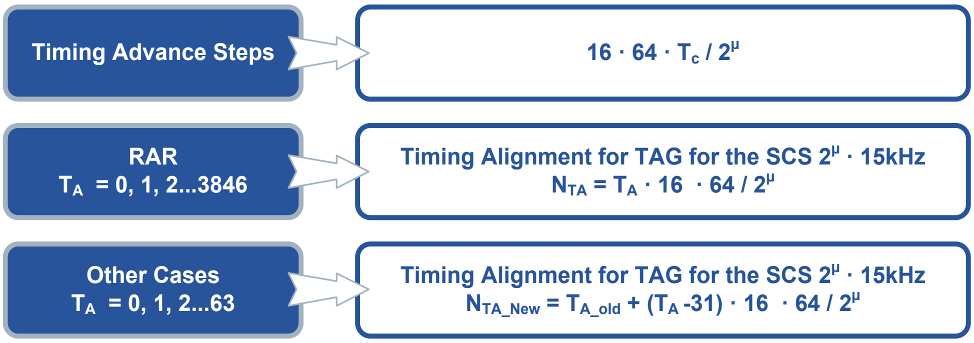


Figure 10-40 Timing Alignment

A TAG containing the SpCell of a MAC entity is referred to as PTAG (Primary Timing Advance Group), whereas the term STAG (Secondary Timing Advance Group) refers to other TAGs.

10.4.10 PRACH Power

Figure 10-41 summarizes the device power calculation whilst on the PRACH (Physical Random Access Channel). In so doing, illustrates the ramping up of power based on the Preamble Power Ramping Step parameter.

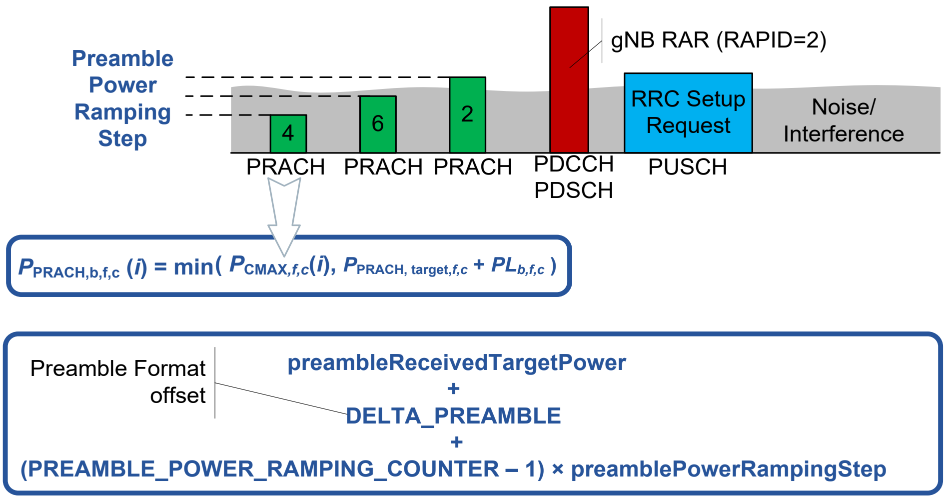


Figure 10-41 PRACH Power Control

10.4.11 Contention Free Random Access Procedure

It is also possible for the gNB to allocate CFRA (Contention Free Random Access) opportunities, i.e. dedicated RACH configuration. Figure 10-42 illustrates an example of the process during NR DC (Dual Connectivity). This includes the SgNB (Secondary gNB) assigning a C-RNTI, as well as dedicated RACH resources, including a ra-PreambleIndex. This information will be passed via the MgNB (Master gNB) towards the device. Using the

RACH configuration parameters, the device can access using the allocated preamble sequence. Assuming it is detected by the SgNB, the successful confirmation can be either a PDCCH addressed to the allocated C-RNTI, or alternatively, a PDCCH based on the RA-RNTI which indicates a RAR carrying the correct RAPID value.

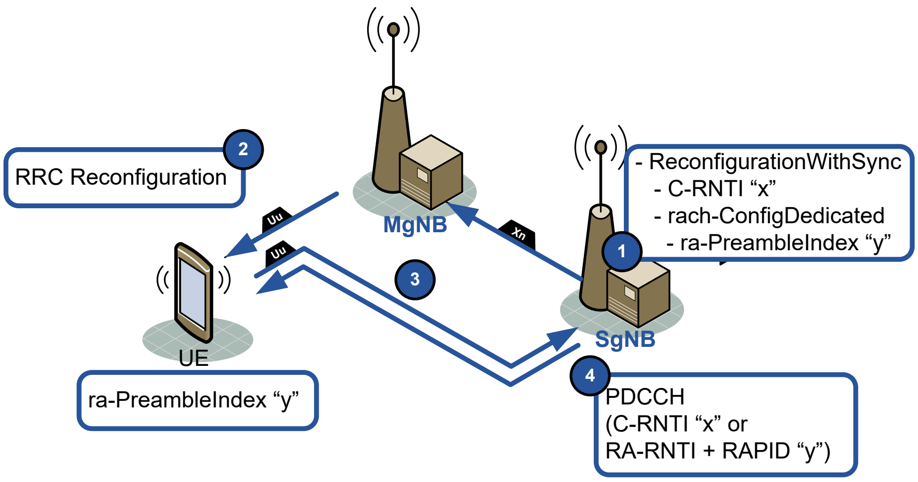


Figure 10-42 Contention Free Random Access

Figure 10-43 illustrates examples of the various parameters included. Note that the resources can be indicated on the UL (Uplink) or SUL (Supplementary Uplink).

In addition, two resources methods are defined:

- SSB Resources - this provides a SSB Index and an occasion Mask.
- CSI-RS Resources - this identifies a CSI-RS index which will have been configured in the Measurement Objects.

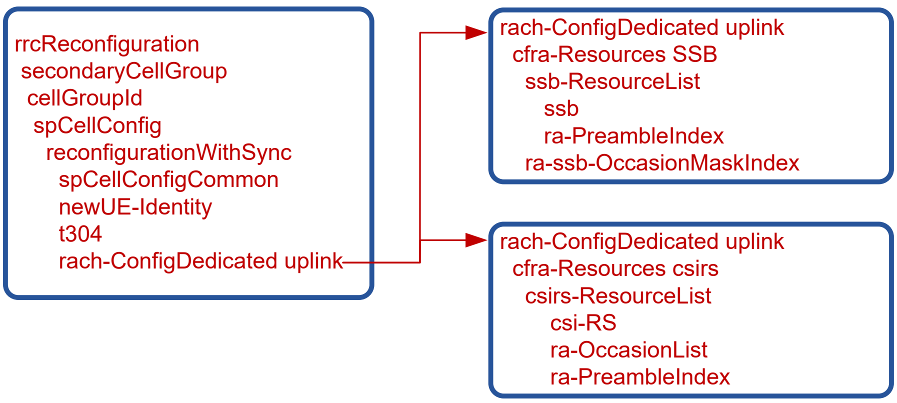


Figure 10-43 Reconfiguration With Sync (Dedicated RACH Uplink)

The ra-ssb-OccasionMaskIndex defines in which PRACH occasion associated with an SSB the MAC entity may transmit a Random Access Preamble.

10.5 5G Network Registration

10.5.1 RRC Setup

In order to perform a 5G Registration procedure the device must establish an RRC connection to the selected cell, which for NR is the "RRC Setup" procedure.

Figure 10-44 illustrates the combination of the Random Access and RRC Setup procedures. In so doing, illustrates the first RRC messages, namely the RRC Setup Request message. This is utilized if the device is accessing a new cell and is designed to move the device from the RRC Idle state to the RRC Connected state. The RRC Setup is a three-way handshake which will also result in the establishment of SRB1 (Signalling Radio Bearer 1).

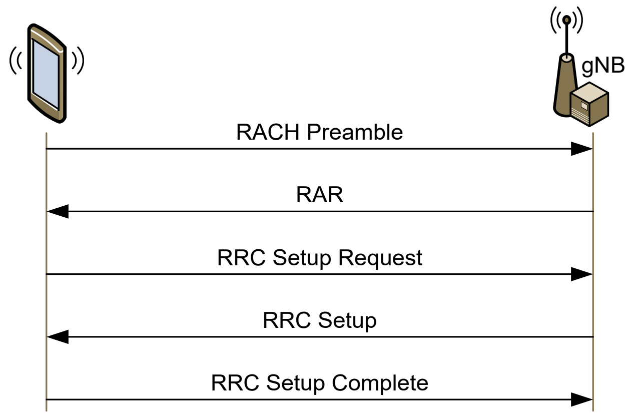


Figure 10-44 RRC Setup Procedure

Figure 10-45 illustrates the content of the RRC Setup Request message. The two key parameters are an identity and an establishment cause. Since most devices are used frequently, they will typically have a 5G-S-TMSI (5G Serving TMSI) and as such will include some of this in the initial RRC Setup Request message. Note that only 39bits out of the total 48bits of the 5G-S-TMSI can be included. In scenarios where the device has no 5G-S-TMSI a random value is used.

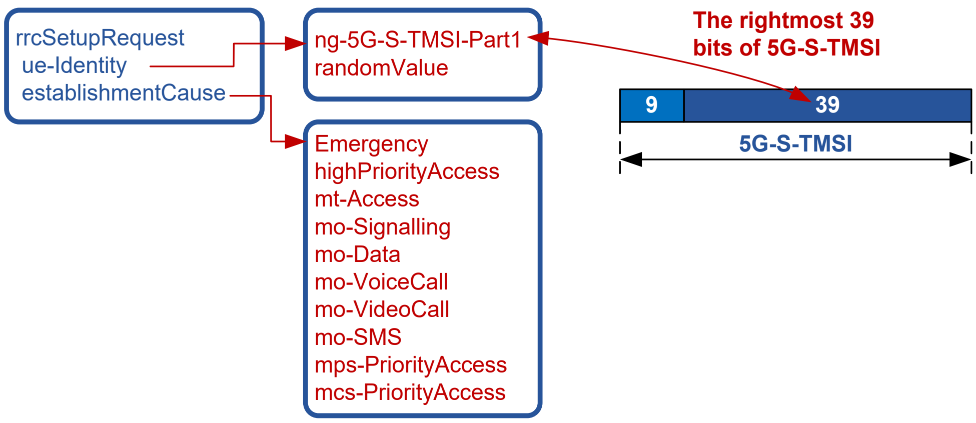


Figure 10-45 RRC Setup Request

The gNB responds with the RRC Setup message which is illustrated in Figure 10-46. The parameters included will depend on the scenario. The main parameters relate to the Radio Bearer Configuration and configuration of the MCG (Master Cell Group). Together these enable the configuration of SRB2.

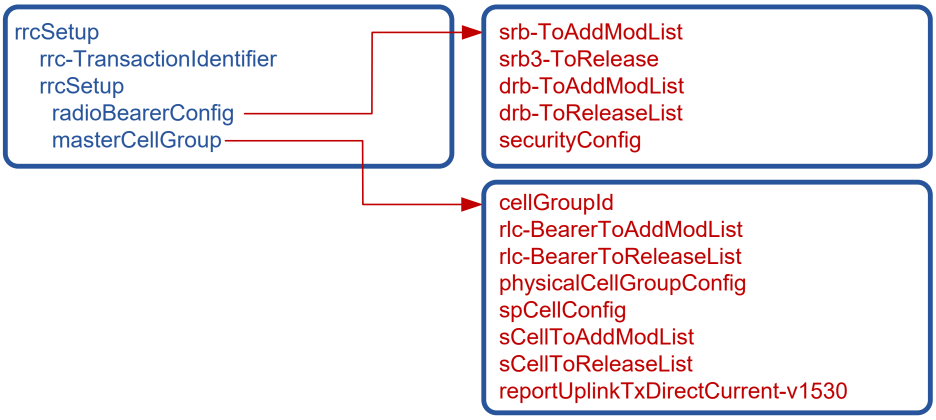


Figure 10-46 RRC Setup

The device, upon receiving the RRC Setup message from the gNB, should respond with the RRC Setup Complete, as illustrated in Figure 10-47. This includes:

- selectedPLMN-Identity - this is the index of the PLMN selected by the device from the plmn-IdentityList fields included in SIB1.
- guami-Type - this field is used to indicate whether the GUAMI (Globally Unique AMF Identifier) included is native (derived from native 5G-GUTI) or mapped. Being mapped relates to being derived from an EPS (Evolved Packet System) GUTI.
- ng-5G-S-TMSI-Value - this is either the ng-5G-S-TMSI-Part2 (left most 9bits of 5G-S-TMSI) or the full 5G-S-TMSI.
- registeredAMF - this field is used to transfer the AMF identity where the device is registered, as provided by upper layers.
- s-nssai-List - list of S-NSSAI (Single Network Slice Selection Assistance Information) which each identify a slice/service type and a slice differentiator.
- dedicatedNAS-Message - this is used to carry the NAS (Non Access Stratum) payload, eg. the 5GMM (5G Mobility Management) Registration message.

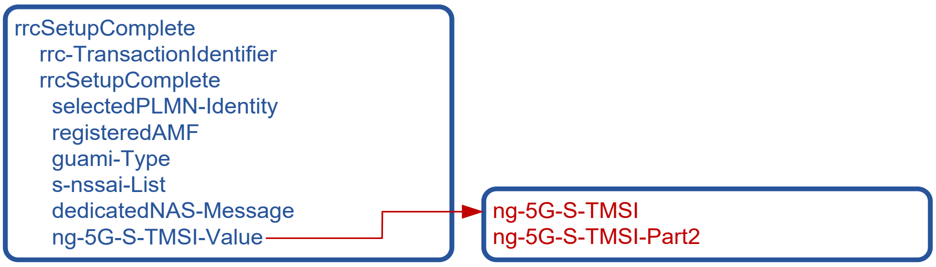


Figure 10-47 RRC Setup Complete

10.5.2 5G Registration Procedure

The 5G Registration process is performed whilst the device is in the RRC Connected state and has already established SRB, ie. the RRC Setup procedure has been performed. SRB1 enables both RRC procedures and NAS (Non Access Stratum) signalling to be transported. Figure 10-48 illustrates the initial stages of the 5G Registration Procedure.

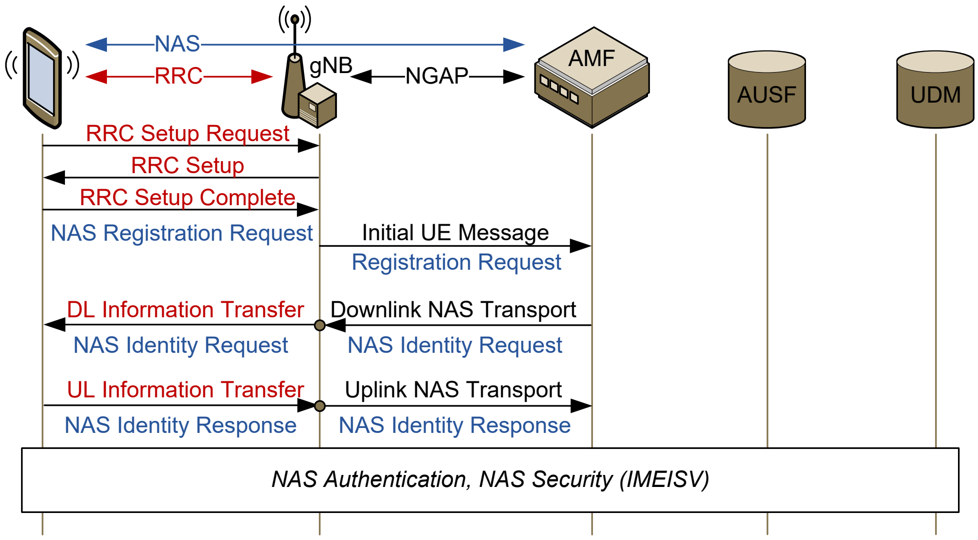


Figure 10-48 5G Registration – Part 1

The NAS Registration Request includes all of the essential information which the network will need in order to verify whether the device/subscriber should be allowed access to the 5G System. It is worth noting that some of the NAS Registration Request parameters are classified as "cleartext" and some "non-cleartext". As such, assuming the device does not have previous 5G security context, only the cleartext IE (Information Elements) can be included. In this scenario, the whole NAS Registration Request with both cleartext and non-cleartext IE's is sent in the NAS Security Mode Complete message. The 5G NAS specification[19] identifies the various registration parameters which are allowed to be "cleartext".

Assuming the AMF confirms the device identity and successfully registers the device on the UDM (Unified Data Management), it will be able to send the NAS Registration Accept to the device. This is initially sent to the device in a NGAP Initial Context Setup Request message, which also includes the KgNB security key which can trigger RRC security.

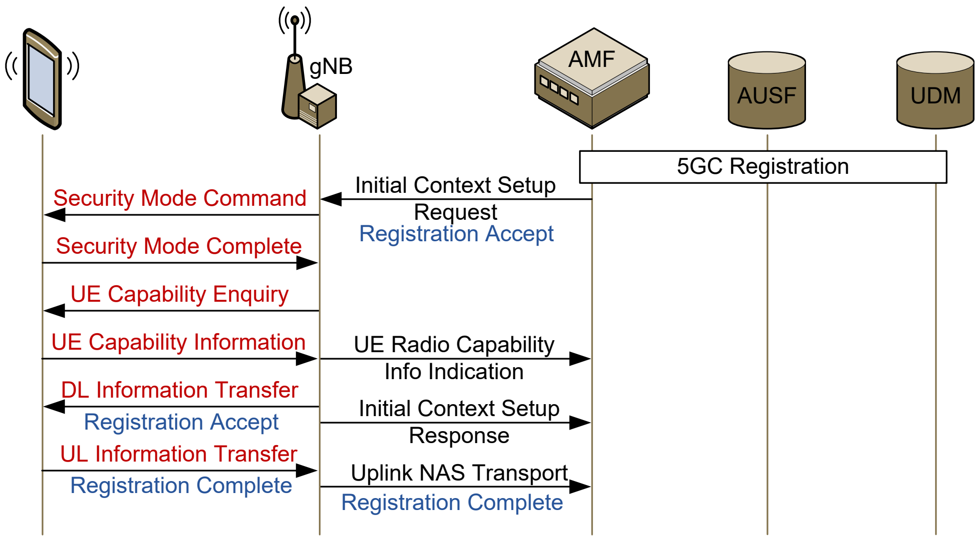


Figure 10-49 5G Registration – Part 2

Following RRC security, the device can be asked for it's UE Capabilities, before finally delivering the NAS Registration Accept embedded in the RRC

[19] 3GPP TS 24.501 - Non-Access-Stratum (NAS) protocol for 5G System (5GS)

DL Information Transfer message. Assuming the device has been allocated a new 5G GUTI, the device will respond with the NAS Registration Complete.

10.5.3 Device Capabilities

Figure 10-50 illustrates the gNB requesting the device's capabilities, which in this example includes "nr", "eutra-nr" and "eutra", i.e. NR, E-UTRA-NR and E-UTRA specific capabilities.

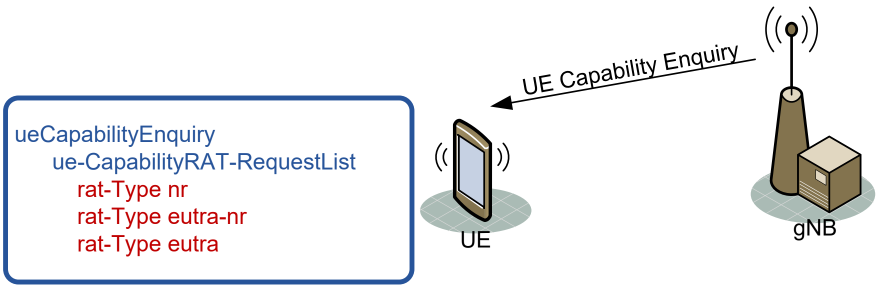


Figure 10-50 UE Capability Enquiry

In this case, the device will respond with a UE Capability Information message which will include the capabilities for NR, E-UTRA-NR and E-UTRA. Figure 10-51, Figure 10-52 and Figure 10-53 illustrate the key parameters included, as well as a few of the nested parameters. Highlighted in red are NR and E-UTRA-NR related parameters, with the blue parameters relating to normal E-UTRA.

The definition of each of these parameters are either in the E-UTRA RRC Specification (3GPP TS 36.331) or the NR RRC Specification (3GPP TS 38.331).

UE E-UTRA Capability indicates the support of Access Stratum Release 15, as well as the support of EN-DC operation. It also indicates various parameters related to PDCP (Packet Data Convergence Protocol) support.

Various parameters in the NR and E-UTRA-NR capabilities include the words: Common, XDD-Diff (FDD/TDD Difference) or FRX-Diff (FR1/FR2 Difference). As such, any parameters not Common to both FDD/TDD or FR1/FR2 will be placed in the corresponding parameter grouping.

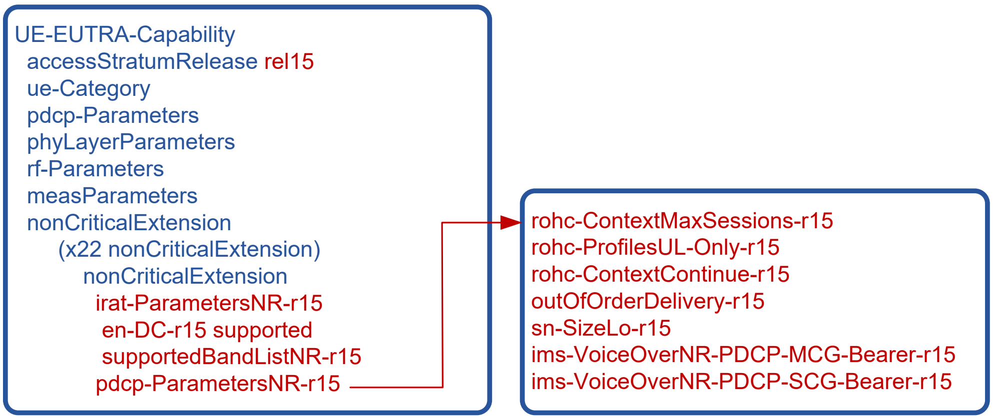


Figure 10-51 UE E-UTRA Capability Parameters

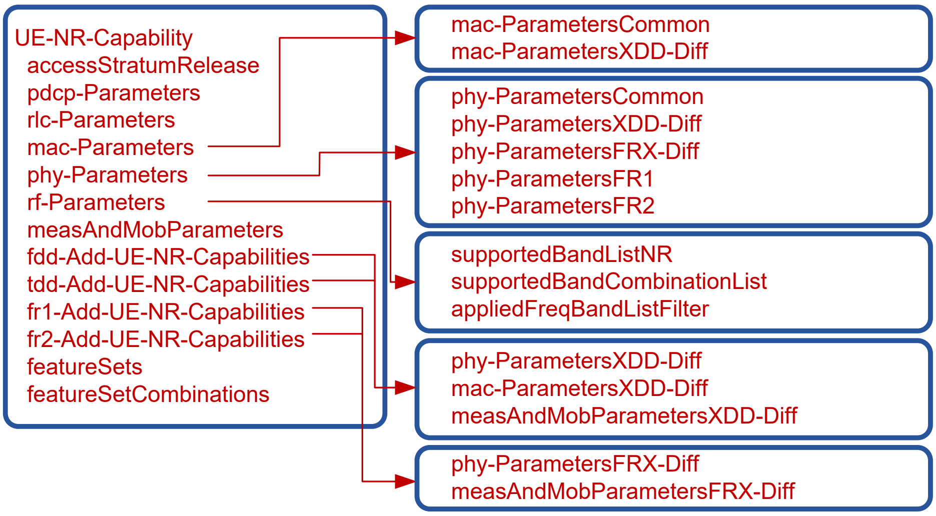


Figure 10-52 UE NR Capability Parameters

One key part of the MR-DC capabilities is the “general parameters”. This indicates the specifics about split SRB and split DRB, as well as the support for SRB3.

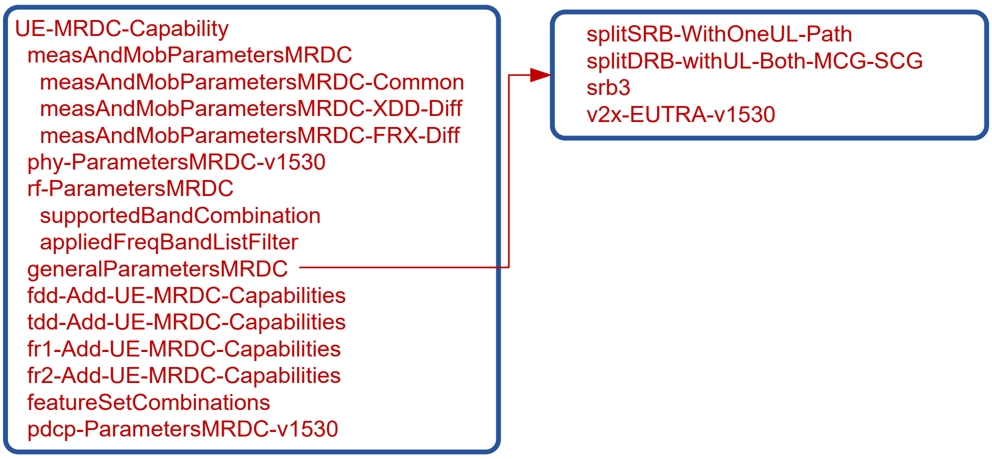


Figure 10-53 UE MR-DC Capabilities

Following UE Capability Information, the gNB can then proceed knowing how to best handle this device.

11 EN-DC Operational Procedures

11.1 Attaching and EN-DC Operation

11.1.1 Initial E-UTRA Attach

Activation of EN-DC (E-UTRA-NR Dual Connectivity) can only occur if the device, eNB (Evolved Node B) and MME (Mobility Management Entity) support it, as well as the necessary security additions for dialogue with the Secondary en-gNB. As such, various LTE procedures have been updated to include EN-DC indications, as well as exchange extra capabilities, e.g. security.

As shown in Figure 11-1, the initial RRC connection has no indication of EN-DC support from either the device or eNB. However, the eNB SIB2 (System Information Block 2) can utilize the upperLayerIndication-r15 parameter to indicate EN-DC support. The first indication of EN-DC support from the device is in the LTE NAS (Non Access Stratum) Attach Request message. This includes the UE Network Capability Information Element, which lists the various network capabilities that the device supports. It can also indicate the support of N1, i.e. the support of NR (New Radio) NAS. In addition, the UE Additional Security Capabilities parameter will indicate which of the NEA (NR Encryption Algorithms) and NIA (NR Integrity Algorithms) are supported.

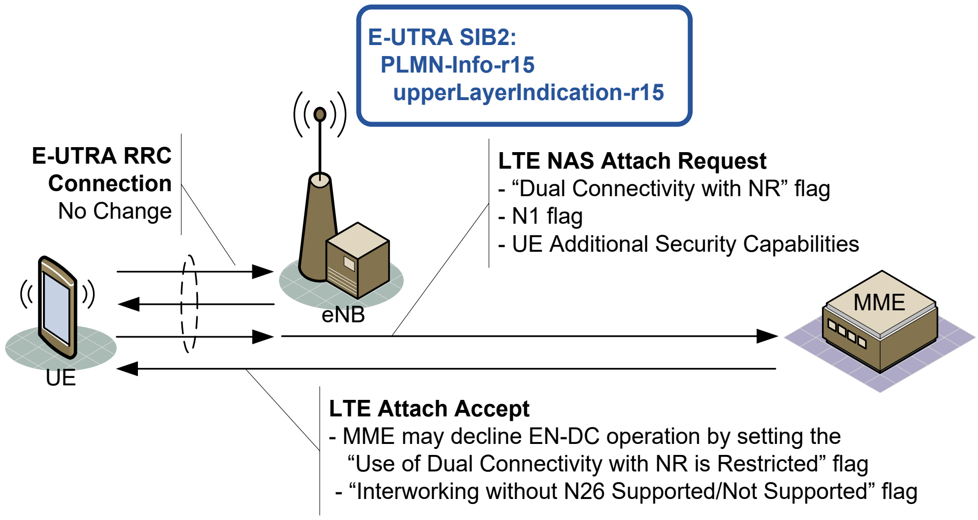


Figure 11-1 E-UTRA Attach - EN-DC Support

One of the capabilities indicated is "Dual Connectivity with NR", which will be set if the device supports EN-DC. Therefore, the MME will be aware that the device is EN-DC capable, although this does not mean EN-DC will actually be used. For example, the MME may set the "Use of Dual Connectivity with NR is Restricted" flag in the Attach Accept, which would prevent EN-DC from being used. The Attach Accept message also indicates if N26 interworking is supported.

11.1.2 UE Capabilities

The Initial Context Setup Request message is sent by the MME as part of the Attach procedure (as well as other procedures). As illustrated in Figure 11-2, if the device has not attached to a MME previously, the "detailed" UE radio capabilities would not be known. However, the MME would know the NR UE Security Capabilities (received in the Attach Request message) and the UE AMBR (Aggregate Maximum Bit Rate) which will have an "extended" value capable of indicating PBps (Petabytes per second) - not that this rate is available yet! The UE-AMBR would have been received from the HSS (Home Subscriber Sever).

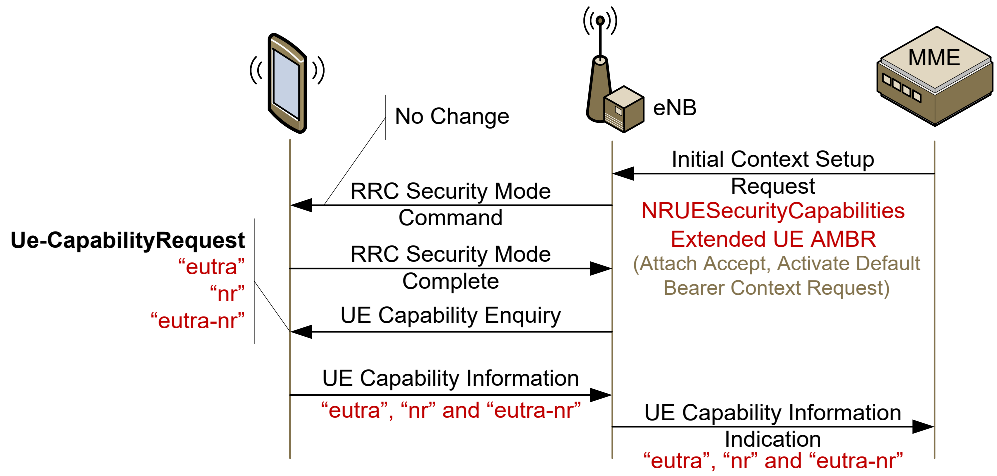


Figure 11-2 UE Capability Transfer

Figure 11-2 illustrates the eNB requesting the device’s capabilities, which for EN-DC operation include the request for “nr” and “eutra-nr”, i.e. NR and E-UTRA-NR specific capabilities. Figure 11-3 illustrates the E-UTRA RRC UE Capability Enquiry message. In addition, nested in one of the non-critical extensions is also the ability to request frequency bands for MR-DC (Multi-RAT Dual Connectivity).

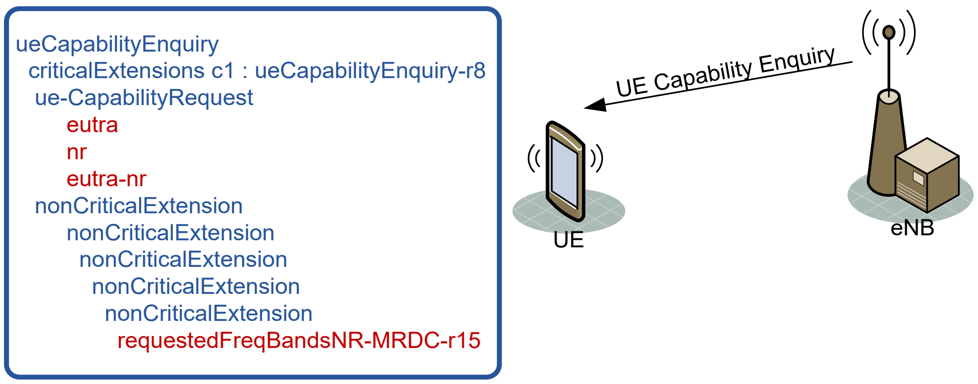


Figure 11-3 UE Capability Enquiry

Upon receiving the request, the device will formulate the UE Capability information message to be sent back to the eNB. The contents of this will include capabilities for E-UTRA, NR and E-UTRA-NR. Figure 10-51 and Figure 10-53 illustrate the key parameters included, as well as a few of the nested parameters. Highlighted in red are NR and E-UTRA-NR related parameters, with the blue parameters related to normal E-UTRA.

The definition of each of these parameters is either in the E-UTRA RRC Specification (3GPP TS 36.331) or the NR RRC Specification (3GPP TS 38.331).

UE E-UTRA Capability indicates the support of Access Stratum Release 15, as well as the support of EN-DC operation. It also indicates various parameters related to PDCP (Packet Data Convergence Protocol) support.

Various parameters in the NR and E-UTRA-NR capabilities include the words: Common, XDD-Diff (FDD/TDD Difference) or FRX-Diff (FR1/FR2 Difference). As such, any parameters not Common to both FDD/TDD or FR1/FR2 will be placed in the corresponding parameter grouping.

UE-EUTRA-Capability
accessStratumRelease rel15
ue-Category
pdcp-Parameters
phyLayerParameters
rf-Parameters
measParameters
nonCriticalExtension
(x22 nonCriticalExtension)
nonCriticalExtension
irat-ParametersNR-r15
en-DC-r15 supported
supportedBandListNR-r15
pdcp-ParametersNR-r15

rohc-ContextMaxSessions-r15
rohc-ProfilesUL-Only-r15
rohc-ContextContinue-r15
outOfOrderDelivery-r15
sn-SizeLo-r15
ims-VoiceOverNR-PDCP-MCG-Bearer-r15
ims-VoiceOverNR-PDCP-SCG-Bearer-r15

Figure 11-4 UE E-UTRA Capability Parameters

One key part of the MR-DC capabilities is the “general parameters”. This indicates the specifics about split SRB and split DRB, as well as the support for SRB3.

UE-MRDC-Capability
measAndMobParametersMRDC
measAndMobParametersMRDC-Common
measAndMobParametersMRDC-XDD-Diff
measAndMobParametersMRDC-FRX-Diff
phy-ParametersMRDC-v1530
rf-ParametersMRDC
supportedBandCombination
appliedFreqBandListFilter
generalParametersMRDC
fdd-Add-UE-MRDC-Capabilities
tdd-Add-UE-MRDC-Capabilities
fr1-Add-UE-MRDC-Capabilities
fr2-Add-UE-MRDC-Capabilities
featureSetCombinations
pdcp-ParametersMRDC-v1530

splitSRB-WithOneUL-Path
splitDRB-withUL-Both-MCG-SCG
srb3
v2x-EUTRA-v1530

Figure 11-5 UE MR-DC Capabilities

Following UE Capability Information, the eNB can then proceed with establishing SRB2 and the E-RAB associated DRB (Data Radio Bearer) on the air interface by sending the RRC Connection Reconfiguration message. This message typically includes the Measurement Configuration parameter, which may be set to monitor NR cells for EN-DC operation.

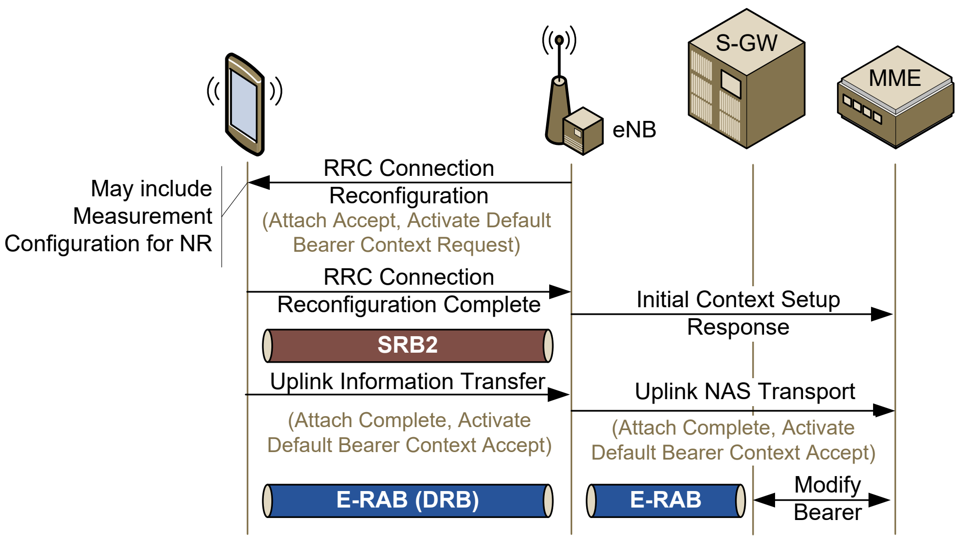


Figure 11-6 Initial E-UTRA RRC Connection Reconfiguration

11.2 E-UTRA Measurements for EN-DC

Prior to activating EN-DC the eNB must first clarify if the device is in range of NR cell(s). As such, in E-UTRA RRC Connected mode the device is configured to monitor and report, by sending an RRC Measurement Report, a suitable NR cell. Thus, triggering the addition of an en-gNB if one is available.

11.2.1 EUTRA Measurement Configuration Options

The RRC measurement configuration includes the following key parameters:

- Measurement objects - these are the objects on which the UE is configured to perform the measurements, i.e. the NR Carrier and SS (Synchronization Signal) Block information.
- Reporting configurations - this is a list of reporting attributes for NR. It includes the reporting type, namely Periodical or Event Based, as well as the associated attributes.
- Measurement identities - this is a list of measurement identities where each measurement identity links one measurement object with one reporting configuration. By configuring multiple measurement identities, it is possible to link more than one measurement object to the same reporting configuration, as well as to link more than one reporting configuration to the same measurement object. The measurement identity is used as a reference number in the measurement report.
- Quantity configurations - this is configured per RAT type and defines the associated filtering used for all event evaluation and related reporting of that measurement type.
- Measurement gaps - this defines the periods that the device may use to perform measurements, i.e. no downlink or uplink transmissions are scheduled. Since EN-DC has at least a dual radio it doesn't typically need gap configuration to add the PScell. However, gap configuration may occur when monitoring Scells, especially if on a different frequency band.
- S-Measure - this optional parameter is a serving cell quality threshold controlling whether or not the UE is required to perform measurements of intra frequency, inter frequency and inter RAT neighbouring cells.
- FR1-gap - this defines whether the configured gap is related to all LTE/NR cells or just LTE and FR1 NR Cells.

Figure 11-7 illustrates the main measurement configuration related parameters in the RRC Connection Reconfiguration Request message.

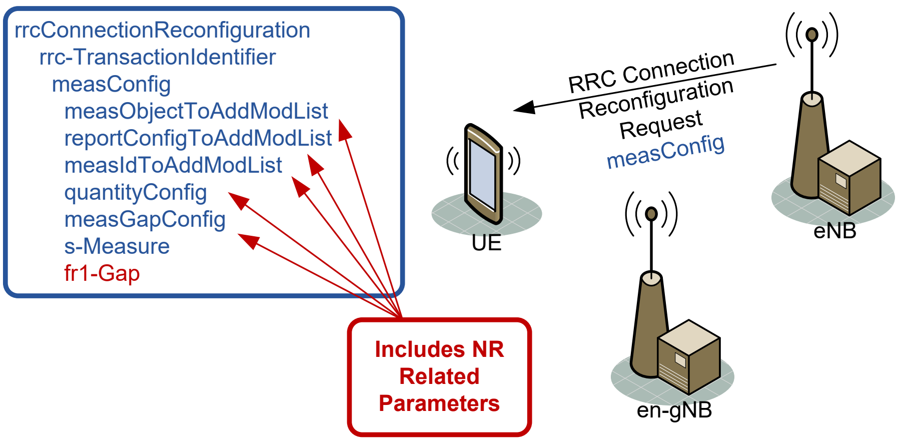


Figure 11-7 Measurement Configuration

11.2.2 Measurement Objects

Figure 11-8 illustrates some of the key parameters for an E-UTRA measurement object. They include:

- measObjectId - this is the identifier for the measurement object.
- measObject - this identifies the type of object, which for EN-DC is set to “measObjectNR-r15”.
- carrierFreq-r15 - this is the NR carrier frequency to measure.
- rs-ConfigSSB-r15 - this provides valuable information on the relative timing of the SSB when compared to the Pcell.
- offsetFreq - this defines the offset value applicable to the carrier frequency.
- quantityConfigSet-r15 - this includes reference to which one of the two NR Quantity Configurations in the NR Quantity Configuration List to be used.

Details of these parameters can be found in 3GPP TS 36.331.

```
rrcConnectionReconfiguration
  rrc-TransactionIdentifier
    measConfig
      measObjectToAddModList
        measObjectId
        measObject measObjectNR-r15
          carrierFreq-r15
          rs-ConfigSSB-r15
            measTimingConfig-r15
              periodicityAndOffset-r15
              ssb-Duration-r15
            subcarrierSpacingSSB-r15
          offsetFreq-r15
          quantityConfigSet-r15
```

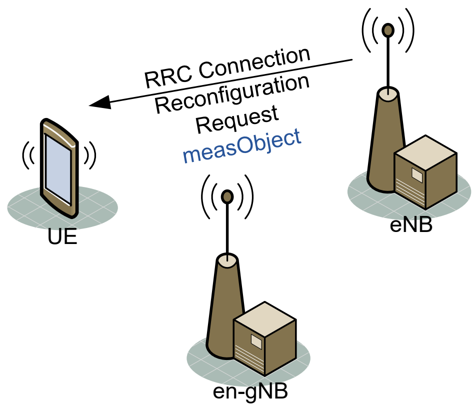


Figure 11-8 Measurement Object

11.2.3 Report Configuration

The Report Configuration parameter is an important part of the measurement process; a list of key parameters is illustrated in Figure 11-9, with the red text highlighting parameters specific to the NR or the NR measurement event being configured.

```
reportConfigId
reportConfig reportConfigInterRAT
  triggerType event
    eventId eventB1-NR-r15
    hysteresis
    timeToTrigger
  maxReportCells
  reportInterval
  reportAmount
  reportQuantityCellNR-r15
    ss-rsrp, ss-rsrq, ss-sinr
  maxReportRS-Index-r15
  reportQuantityRS-IndexNR-r15
    ss-rsrp, ss-rsrq, ss-sinr
  reportRS-IndexResultsNR
  reportSFTD-Meas-r15
```

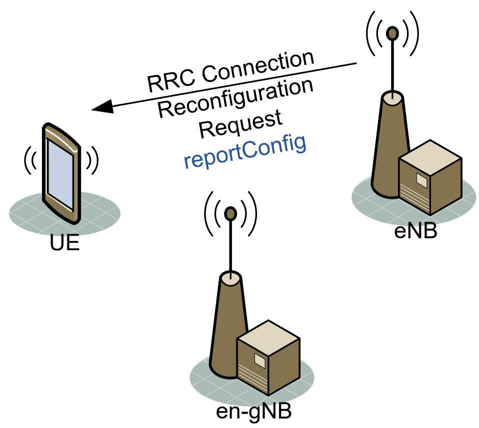


Figure 11-9 NR Report Configuration (Event B1 NR)

Key parameters include:

- triggerType - like LTE, there are two types of reporting methods: periodical and event based.
- maxReportCells - this indicates the maximum number of cells to report.
- reportInterval - this is used for periodic reporting, or if event based and the event trigger still exists the device will periodically send the measurement report.
- reportAmount - indicates the amount of Measurement Report messages to be sent.
- reportQuantityCellNR-r15 - this indicates the quantities to report, i.e. the SS-RSRP (Synchronization Signal based Reference Signal Received Power), SS-RSRQ (Synchronization Signal based Reference Signal Received Quality) and SS-SINR (Synchronization Signal based Signal to Interference and Noise Ratio).
- maxReportRS-Index-r15 - this indicates the maximum number of SS-Block Index’s (beams) to report.
- reportQuantityRS-IndexNR-r15 - this indicates the quantities to report, i.e. the SS-RSRP, SS-RSRQ and SS-SINR.
- reportRS-IndexResultsNR - this indicates whether Measurement Reports should be sent related to SS-Block index (beams).
- reportSFTD-Meas-r15 - this indicates that the device should report SFN (System Frame Number) and subframe time difference.

Figure 11-10 illustrates the periodical reporting concept with a configured Report Interval. In addition, the MeNB also configures the Report Amount which indicates how may reports to send (r1, r2, r4, r8, r16, r32, r64 or infinity).

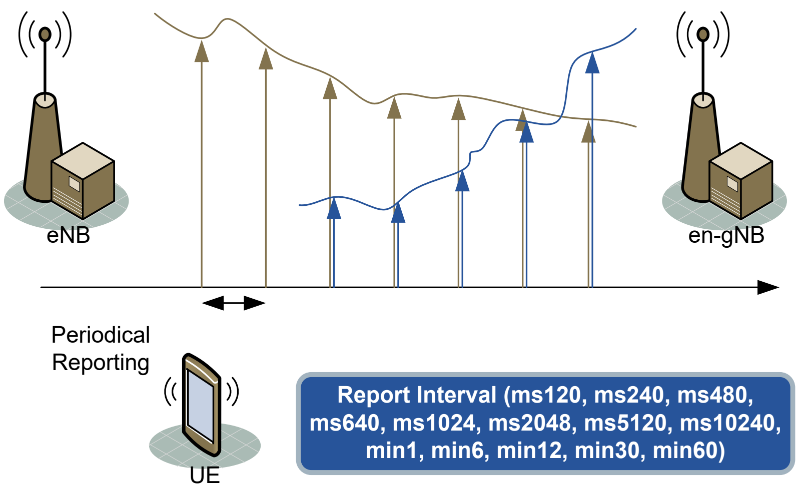


Figure 11-10 Periodical Reporting

11.2.4 LTE Events Summary

LTE includes a number of “intra E-UTRA” measurement based triggering events, these include:

- Event A1 - serving cell becomes better than the threshold.
- Event A2 - serving cell becomes worse than the threshold.
- Event A3 - neighbour cell becomes (including offset) better than the serving cell.

- Event A4 - neighbour cell becomes better than the threshold.
- Event A5 - serving cell becomes worse than Thresh1 (Threshold1) and the neighbour cell becomes better than Thresh2 (Threshold2).
- Event A6 - Neighbour becomes offset better than SCell (for CA (Carrier Aggregation)).
- Event C1 - CSI-RS resource becomes better than threshold.
- Event C2 - CSI-RS resource becomes offset better than reference CSI-RS resource.
- Event V1 - the channel busy ratio is above a threshold for a V2X device.
- Event V2 - the channel busy ratio is below a threshold for a V2X device.

In terms of “InterRAT” events the existing LTE variants are:

- Event B1 - Inter RAT neighbour cell becomes better than threshold.
- Event B2 - serving cell becomes worse than threshold1 and inter RAT neighbour cell becomes better than threshold2.

Note: Additional types of events exist for LTE/WLAN interworking.

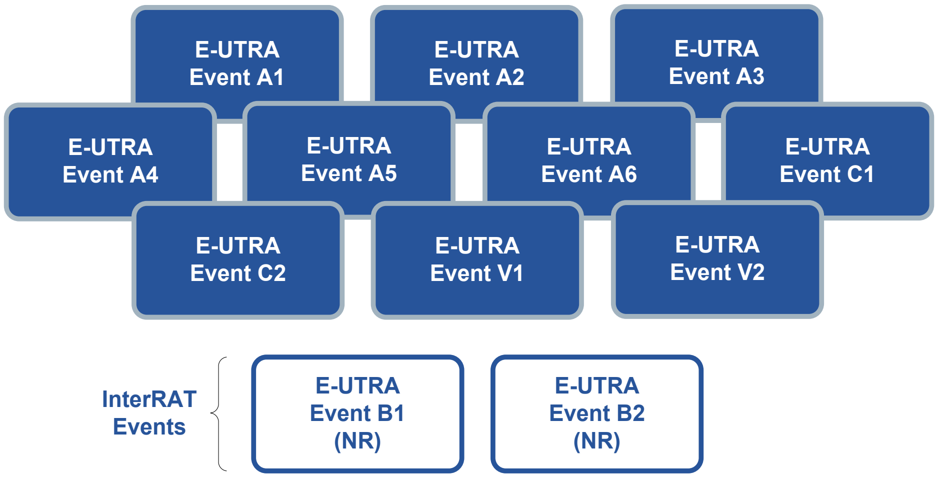


Figure 11-11 Existing and Updated E-UTRA Events

As illustrated in Figure 11-11, Event B1 and B2 can also enable NR reporting and thus will be utilized to trigger event based EN-DC reporting.

11.2.5 Measurement Identities

The concept of Measurement Identity is the same for E-UTRA and NR. As illustrated in Figure 11-12, each identity is a combination of a Measurement Object and Report Configuration. It is this Measurement Identity that is then utilized in the Measurement Report message, with the associated measured result.

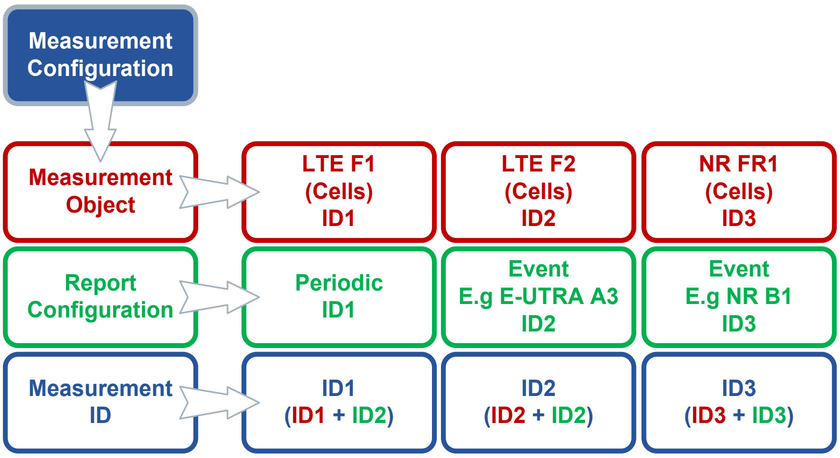


Figure 11-12 Measurement Identities

11.2.6 NR Measurement Timing Configuration

In order to take measurements for EN-DC operation, the device must first set up the SMTC (SS/PBCH Block Measurement Timing Configuration) in accordance with the received “periodicityAndOffset” parameter in the MTC (Measurement Timing Configuration) for the NR SSB, as illustrated in Figure 11-13.

On the identified frequency, the device does not consider SS/PBCH block transmission in subframes outside of the SMTC occasion for measurements.

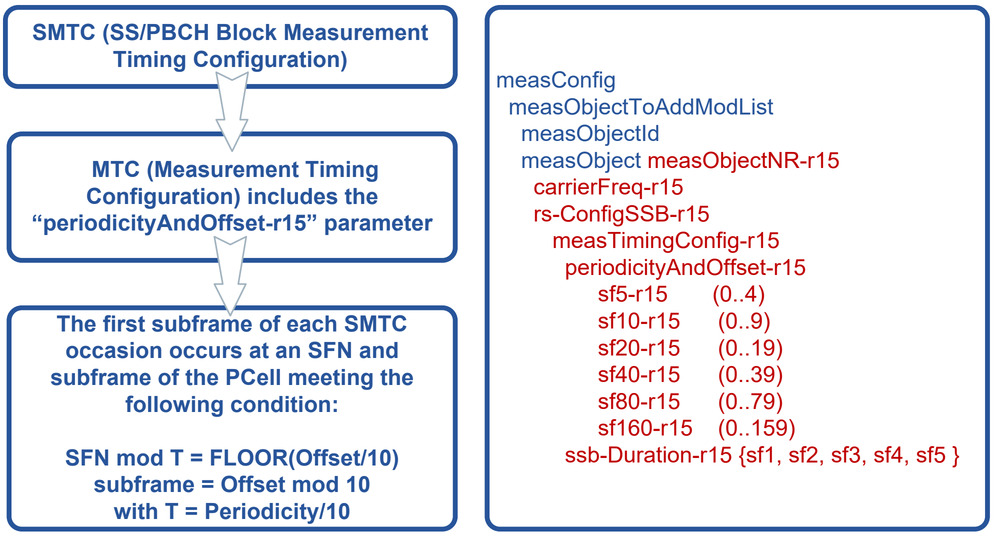


Figure 11-13 NR Measurement Timing Configuration

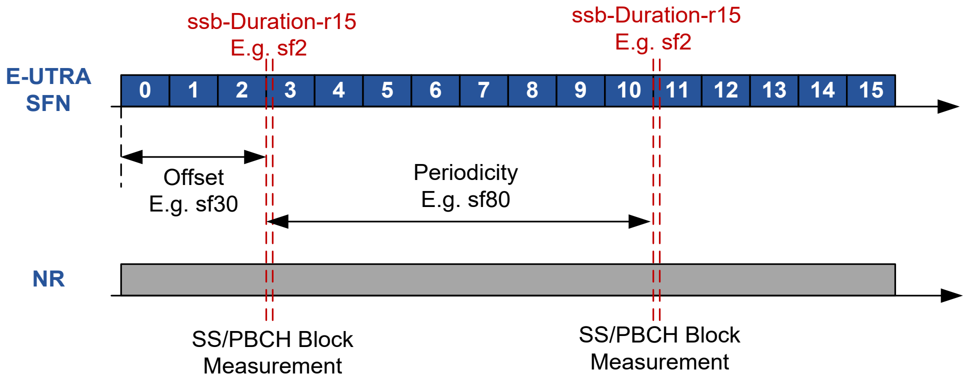


Figure 11-14 Example of SMTC

11.2.7 Identifying Suitable NR Cell

Assuming the device has already connected to the LTE PCell and EN-DC is supported, the eNB will have configured the device to send measurement reports. This will either be periodic or event based, with the EventB1-NR being configured for event based. This includes the threshold type, i.e. NR-RSRP, NR-RSRQ or NR-SINR, as well as the corresponding threshold value. The EventB1-NR also has an associated TTT (Time to Trigger) and Hys (Hysteresis) parameter. These, along with the Ofn (Frequency Specific Offset), defines a specific offset (+/-) for the frequency of the inter-RAT neighbour cell and are illustrated in Figure 11-15.

The EventB1-NR also includes an entering and leaving condition. As such, assuming the neighbouring meets the entering condition for the duration of TTT, then the Measurement Report message would be sent.

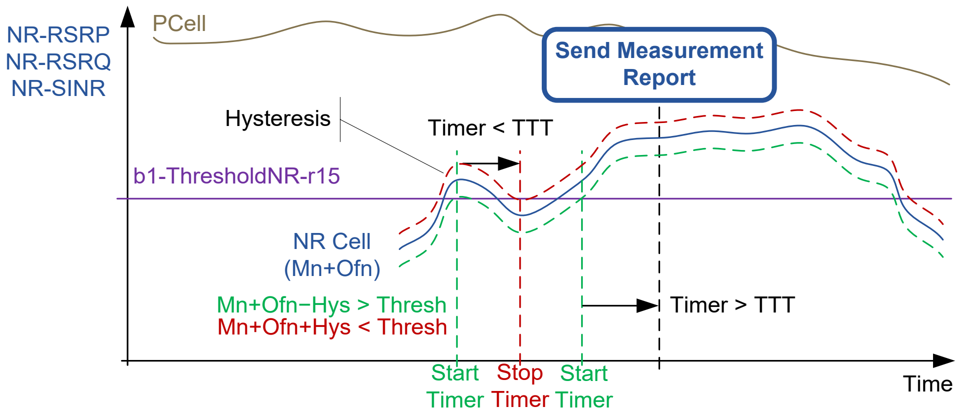


Figure 11-15 Example of EventB1-NR

11.2.8 Measurement Report

The E-UTRA Measurement Report message containing the NR PCI (Physical Cell Identity), as well as the requested measured quantities, will be sent to the eNB. It will also contain, if requested, the measured SS/PSCH block quantities, along with the SS Block Index. In addition, the SFN and Frame Timing Difference will be included. An example of a Measurement Report is illustrated in Figure 11-16.

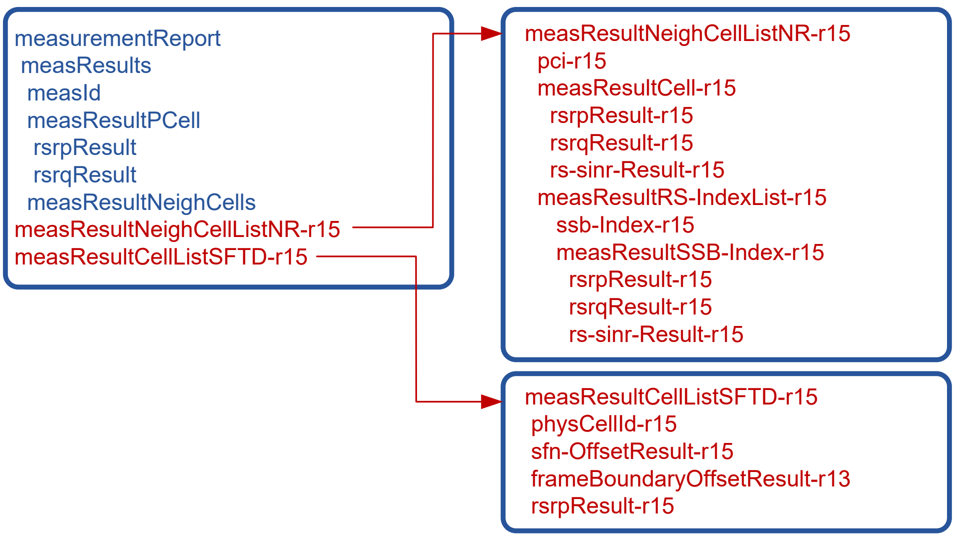


Figure 11-16 E-UTRA Measurement Report - NR Measurements

Upon receiving the Measurement Report from the device, the eNB would trigger the activation of EN-DC operation.

11.3 PSCell Addition

11.3.1 SgNB Addition Request and Request Acknowledge

SgNB Addition Request

After identifying the target NR cell from the device, the MeNB sends the X2AP SgNB Addition Request message to the en-gNB. One of the key parameters in the SgNB Addition Request messages is the CG-ConfigInfo parameter. In response, the SgNB Addition Request Acknowledge includes the CG-Config parameter that in turn includes the NR RRC Reconfiguration message.

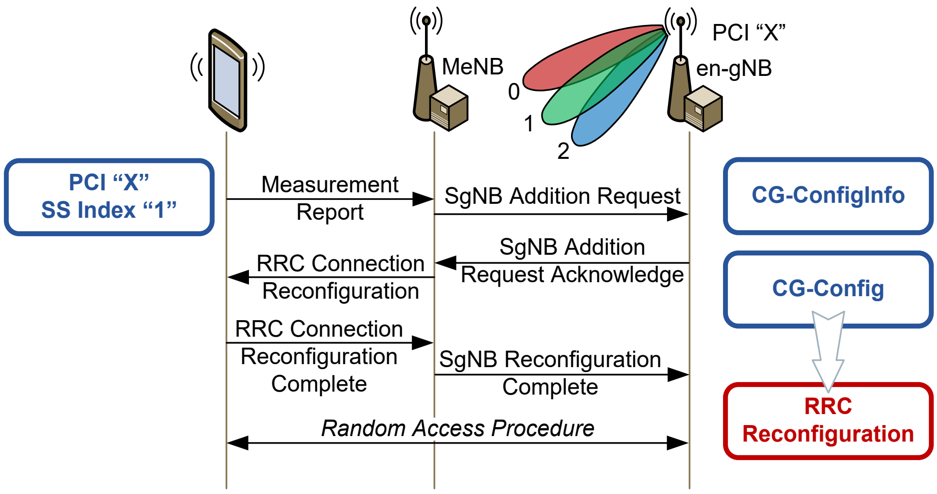


Figure 11-17 X2AP SgNB Addition

Key elements of the SgNB Addition Request message are outlined in Figure 11-18.

- MeNB UE X2AP ID - serves as a unique identifier to associate the X2AP connection with a specific subscriber device.
- NR Security Capabilities and SgNB Key - the MeNB will have been supplied both of these parameters during the initial attach procedure. These are now supplied to the en-gNB in support of user plane and potentially RRC security. Note that S-K_{gNB} is derived from K_{eNB} at the MeNB.
- SgNB UE AMBR (Aggregate Maximum Bit Rate) - overall, the UE AMBR will dictate the total permissible bandwidth that can be allocated to the subscriber, relative to the total bandwidth in use of all non-GBR (Guaranteed Bit Rate) bearers that the subscriber has active. In an EN-DC scenario, this UE AMBR limit is split by the MeNB into a MeNB UE AMBR and a SgNB UE AMBR allocation which will collectively not exceed the UE AMBR. As such, the SgNB will ensure that the SgNB UE AMBR is not exceeded. Within this parameter NR can make use of an "Extended Bit Rate" parameter.
- E-RAB(s) to be added - when adding the en-gNB, the MeNB will need to provide a variety of different information for each E-RAB that the en-gNB will need to support. This includes:
  - E-RAB ID - uniquely identifying the E-RAB.

- EN-DC Resource Configuration - for each E-RAB, this information element will dictate how the E-RAB is established in terms of EN-DC configuration, QoS and tunnel establishment.
- PDCP Present / Not Present in SN - this information element will dictate how the E-RAB will be configured with respect to PDCP (Packet Data Convergence Protocol). For instance, if this field determines that PDCP is present in the Secondary Node, this configures the E-RAB as an SCG (Secondary Cell Group) Bearer. See Figure 11-22 for further detail.
- Full E-RAB QoS Parameters - identifying QoS characteristics of the E-RAB such as QCI (Quality Class Identifier), ARP (Allocation and Retention Priority) and, if appropriate, GBR QoS information.
- Tunnel Endpoint Addressing - depending on the configuration of the E-RAB (MCG Bearer, MCG Split Bearer, etc), there will be a variety of different TEIDs (Tunnel Endpoint Identities) which will need to be established.

- MCG Split SRB Request - this will indicate if resources for Split SRB operation are required.
- MeNB to SgNB Container - this will contain the RRC (Radio Resource Control) SCG-ConfigInfo message, which supplies the en-gNB with the latest measurement results for the candidate SCG cells. This allows the en-gNB to choose and configure the SCG cell(s) that will be allocated to the subscriber.

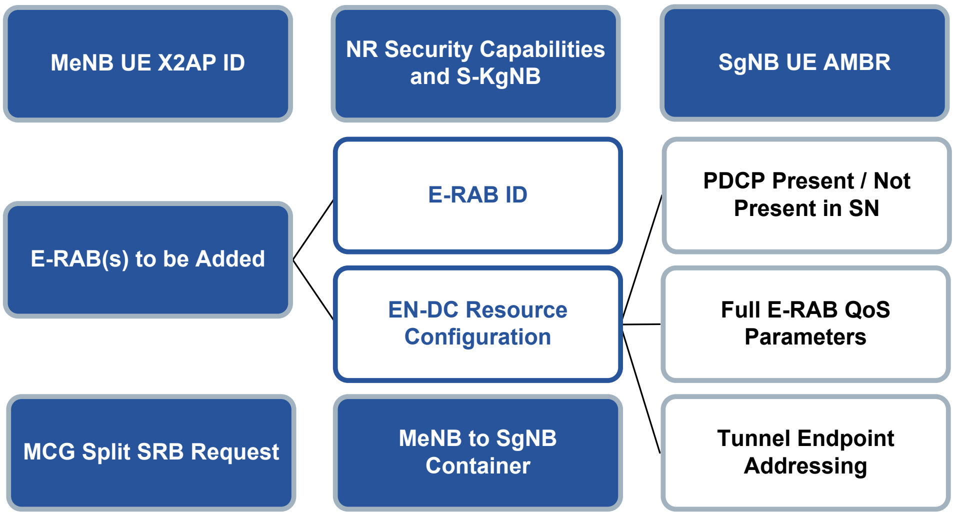


Figure 11-18 SgNB Addition Request

The contents of the CG-ConfigInfo parameter varies depending on the scenario (it is not only used for EN-DC operation). Figure 11-19 illustrates the main parameters which could be present when adding the en-gNB initially.

```
CG-ConfigInfo
  ue-CapabilityInfo
    rat-Type
    ue-CapabilityRAT-Container
  candidateCellInfoListSN
    cellIdentification
      physCellId
      dl-CarrierFreq
  measResultCellListSFTD
    physCellId
    sfn-OffsetResult
    frameBoundaryOffsetResult
  configRestrictInfo
  drx-InfoMCG
   drx-LongCycleStartOffset
  measConfigMN
  scg-RB-Config
```

Figure 11-19 CG-ConfigInfo (MeNB to en-gNB Example)

Key CG-ConfigInfo parameters include:

- ue-CapabilityInfo - this includes the NR and E-UTRA-NR capabilities received from the UE.
- candidateCellInfoListSN - this is the set of target candidates, including the measured quantities, as well as the SSB Index/quantities if configured.
- measResultCellListSFTD - this provides the results of the SFN Frame and subframe Time Difference.
- configRestrictInfo - this includes various aspects such as band combinations, baseband combinations, power coordination, serving cell indices range and the maximum number of allowed NR frequencies the SN should configure for measurements for the SCG.
- drx-InfoMCG - this provides configuration of DRX (Discontinuous Reception) cycles on the MCG.
- measConfigMN - this indicates the measured frequencies in MN (Master Node), as well as any configured gap periods.
- scg-RB-Config - this provides details of SRBs (including SRB3) and DRBs that need to be configured, as well as any security configuration.

SgNB Addition Request Acknowledgment

In response to the SgNB Addition Request, the en-gNB will send the SgNB Addition Request Acknowledge. Key information held within this message is shown in Figure 11-20.

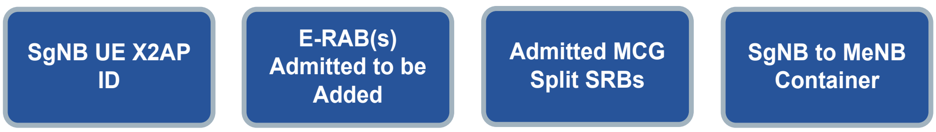


Figure 11-20 SgNB Addition Request Acknowledge

- SgNB UE X2AP ID - serves as a unique identifier to associate the X2AP connection with a specific subscriber device. Used in conjunction with the MeNB UE X2AP ID for all future signalling exchanges relative to this subscriber.
- E-RABs Admitted to be Added - for each E-RAB requested by the MeNB, the SgNB will provide a confirmation that the E-RAB was accepted. This would include information on assigned QoS, as well as

tunnel endpoint addressing information (dependent on the EN-DC configuration for the E-RAB).

- Admitted MCG Split SRBs - this will indicate that the request for Split SRB operation was successful.
- SgNB to MeNB Container - this will contain the SCG radio resource configuration that the device requires in order to start using the secondary cell(s). This will be provided as an RRC CG-Config message, which includes various parameters, as well as the NR RRC Reconfiguration message for the device.

The CG-Config message content (carried in the container) is listed in Figure 11-21. It includes:

- scg-CellGroupConfig - this includes the NR RRC Reconfiguration message that can be sent to the device.
- scg-RB-Config - depending on the use of this parameter, e.g. configuring PDCP, it includes a NR Radio Bearer Config parameter (which is also part of a NR RRC Reconfiguration message).
- drx-InfoSCG - this provided SCG DRX information to the eNB.
- candidateCellInfoListSN - this is used to enable a secondary node to suggest cells to a target secondary gNB to consider configuring, i.e. is part of mobility.
- measConfigSN - this identifies the measured frequencies configured by the SN.
- selectedBandCombinationNR - this indicates the band combination selected by SN for the EN-DC.

```
CG-Config
  scg-CellGroupConfig
              RRCReconfiguration
  scg-RB-Config
              RadioBearerConfig
  drx-InfoSCG
  candidateCellInfoListSN
  measConfigSN
  selectedBandCombinationNR
```

Figure 11-21 CG-Config

11.3.1.1 Determining the Bearer Configuration

There are a number of bearer configurations that are available for the operation of an E-RAB; these are MCG Bearer, MCG Split Bearer, SCG Bearer or SCG Split Bearer. The choice of configuration is made at the MeNB and the contents of the SgNB Addition Request will ensure the correct configuration is established. The key information required for each configuration is outlined below (MCG Bearer has been omitted due to the lack of involvement with the en-gNB). Firstly, Figure 11-22 outlines the information that will be included in the SgNB Addition message exchange for an E-RAB that is in MCG Split Bearer configuration.

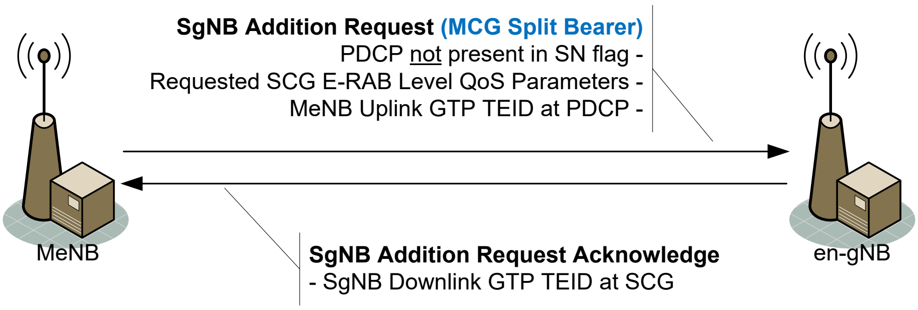


Figure 11-22 Determining the Bearer Configuration - MCG Split Bearer

Figure 11-23 outlines the key information that will be included in the SgNB Addition message exchange for an E-RAB that is in SCG Bearer configuration.

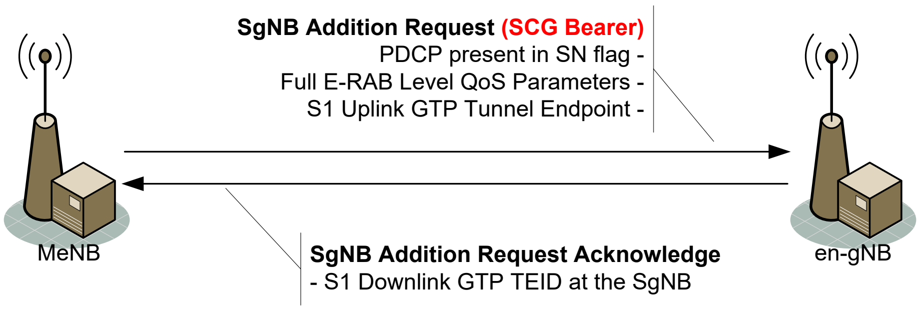


Figure 11-23 Determining the Bearer Configuration - SCG Bearer

Figure 11-24 outlines the key information that will be included in the SgNB Addition message exchange for an E-RAB that is in SCG Split Bearer configuration.

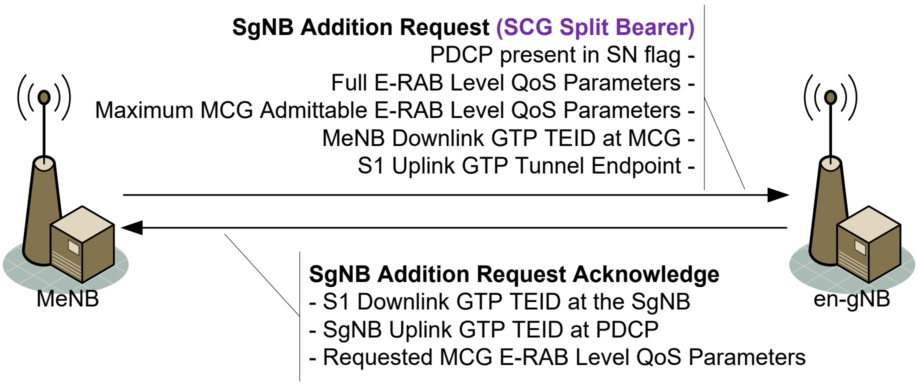


Figure 11-24 Determining the Bearer Configuration - SCG Split Bearer

11.3.2 RRC Connection Reconfiguration

The E-UTRA RRC Connection Reconfiguration message is used to configure various aspects of EN-DC operation. Figure 11-25 illustrates the key parameters, related to NR, that can be included.

```
rrcConnectionReconfiguration
 nonCriticalExtension
  nonCriticalExtension x5
   nonCriticalExtension
    nr-Config-r15 setup
      endc-ReleaseAndAdd-r15
      nr-SecondaryCellGroupConfig-r15
         RRCReconfiguration
      p-MaxEUTRA-r15
    sk-Counter-r15
    nr-RadioBearerConfig1-r15
```

```
RRCConnectionReconfigurationComplete
  nonCriticalExtension x6
    scg-ConfigResponseNR-r15
      RRCReconfigurationComplete
```

Figure 11-25 E-UTRA RRC Connection Reconfiguration Procedure

The NR parameters are nesting in several non-critical extensions. Note that the parameters included depend on the scenario. NR Parameters include:

- nr-Config-r15 - this contains:
  - endc-ReleaseAndAdd-r15 - this indicates whether the existing EN-DC configuration should be released before the new configuration is added.
  - nr-SecondaryCellGroupConfig-r15 - this is the main parameter since it includes a NR RRC Reconfiguration message.
  - p-MaxEUTRA-r15 - this indicates the maximum power for E-UTRA the device can use in LTE MCG.
- sk-Counter-r15 - this is a “one-shot” counter used upon initial configuration of security for EN-DC, as well as upon refresh of S-K_{gNB}. E-UTRAN provides this field upon configuring EN-DC to facilitate configuration of SRB3.
- nr-RadioBearerConfig1-r15 - this parameter is present in specific EN-DC scenarios, e.g. when there is a requirement to add, modify and release signalling and/or data radio bearers.

In response, the device sends the NR RRC Reconfiguration Complete message. This is included in either the SCG Configuration Response parameter of the E-UTRA RRC Connection Reconfiguration Complete or, if SRB 3 is configured, it can be sent directly to the en-gNB.

11.3.3 Reconfiguration with Sync

When the device is in the E-UTRA RRC Connected state the eNB is responsible for maintaining the timing relationship. During EN-DC operation, the TA (Timing Advance) used by the device for the uplink to the eNB can be different to the uplink TA to the en-gNB.

Initially, the en-gNB can get the device to access via dedicated RACH preamble information using the “rach-ConfigDedicated” parameter. This is included in the NR RRC Reconfiguration message, specifically part of the “reconfigurationWithSync” parameter.

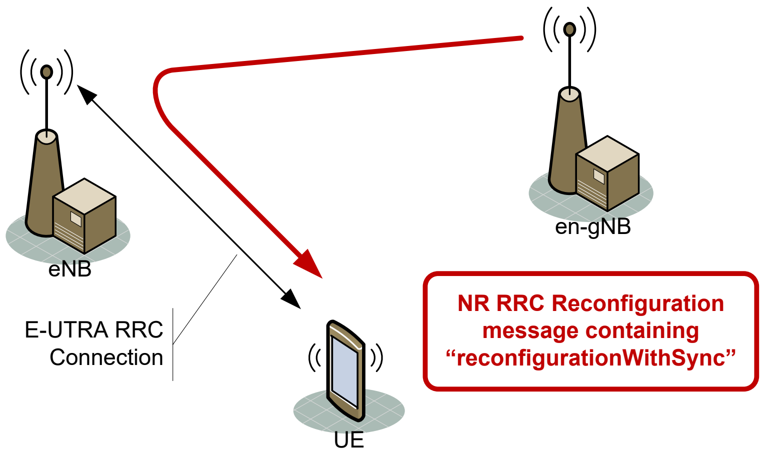


Figure 11-26 Reconfiguration with Sync

Figure 11-27 illustrates the parameters that are defined for the reconfigurationWithSync parameter.

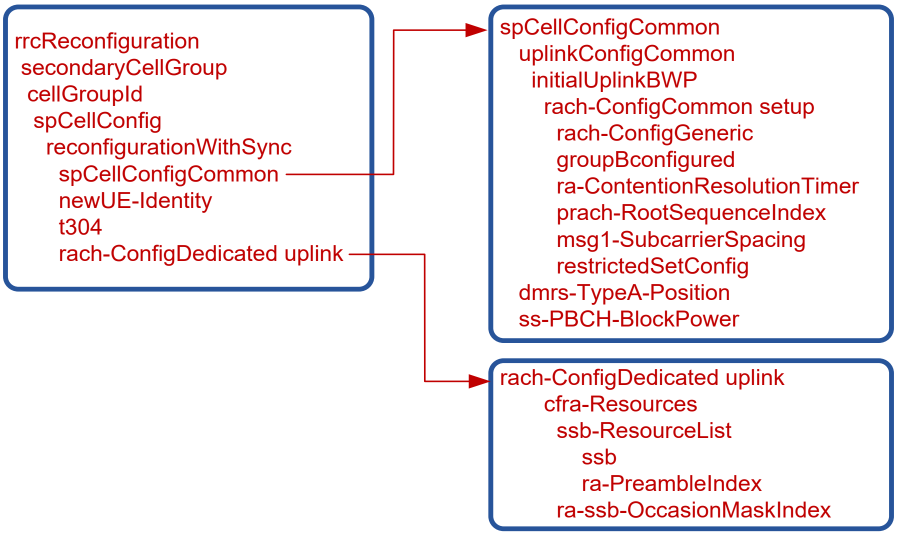


Figure 11-27 Reconfiguration with Sync Parameters

These include:

- spCellConfigCommon - this includes many parameters, but for RACH access, it specifically includes the RACH Configuration Common setup parameters. In so doing, it includes specifics to enable preamble sequence generation, as well as how the RACH is configured on the en-gNB.
- newUE-Identity - this includes the new C-RNTI, allocated by the en-gNB, for scheduling etc. This is in addition to the C-RNTI allocated by the MeNB.
- t304 - this timer relates to reconfiguration with sync procedure. If it expires the device would indicate an SCG failure.
- rach-ConfigDedicated uplink - this provides dedicated uplink RACH resources, either related to SSB or CSI-RS.

11.3.4 PSCell Split SRB

The PSCell Addition procedure can also configure Split SRB operation. If so, the nested NR RRC Reconfiguration message would indicate which SRB's are configured.

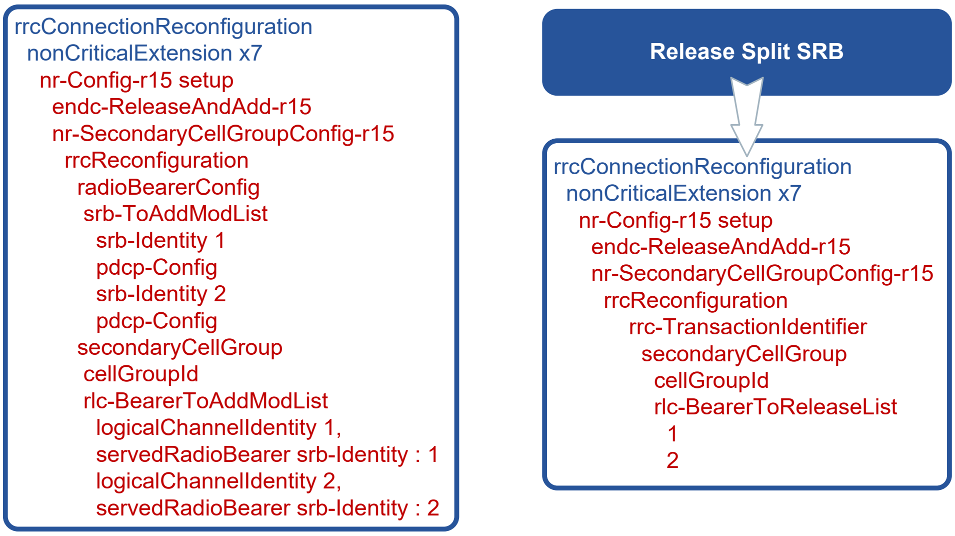


Figure 11-28 Configuring Split SRB

Figure 11-28 illustrates an example whereby SRB1 and SRB2 are included in the Secondary Cell Group Configuration, triggering Split SRB's. It also shows an example of the rlc-BearerToReleaseList parameter. This includes the Logical Channel Identities that the MeNB is now releasing, i.e. no longer split SRBs.

11.3.5 PSCell Split DRB

There are various configuration options for an EN-DC EPS Bearer, as illustrated in Figure 11-29. It is the responsibility of the MeNB to initially select which configuration option to configure.

Figure 11-29 DRB Bearer Options

The MeNB is also able to change the configuration, e.g. changing from a MCG Bearer to a SCG Split Bearer. Figure 11-30 illustrates this example with the MeNB sending an E-UTRA RRC Connection Reconfiguration message which contains two extensions for NR:

- nr-Config-r15 - this is a NR RRC Reconfiguration message.
- nr-RadioBearerConfig1-r15 - this is a NR Radio Bearer Configuration parameter. This is sent from the en-gNB to the MeNB in the scg-RB-Config parameter.

To enable SCG split bearer the DRB is added to the NR configuration. In addition, the PDCP Configuration parameter "moreThanOneRLC" indicates the primary path using the Cell Group Identifier. This is set to 0 to indicate the MCG and 1 to indicate the SCG.

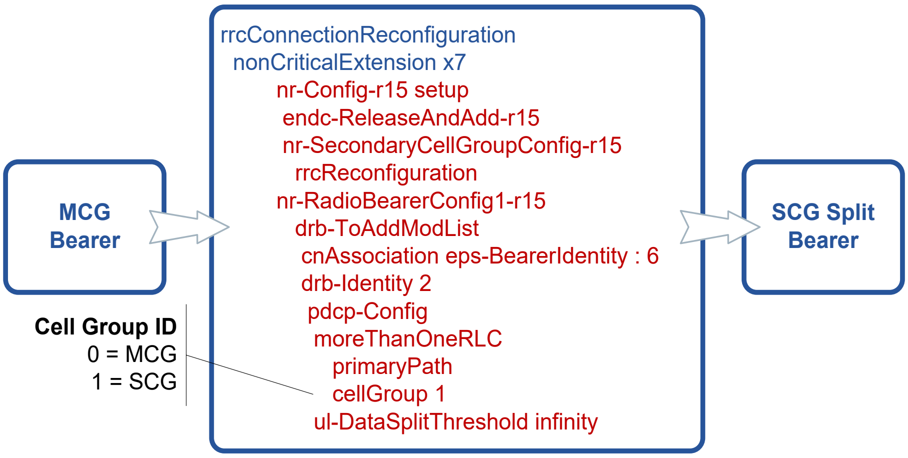


Figure 11-30 MCG DRB Bearer to SCG Split DRB Bearer

If the MeNB decided to configure a SCG bearer, the DRB on the MCG is released. In addition, the PDCP Configuration parameter does not include the “moreThanOneRLC” parameter. This is illustrated in Figure 11-31.

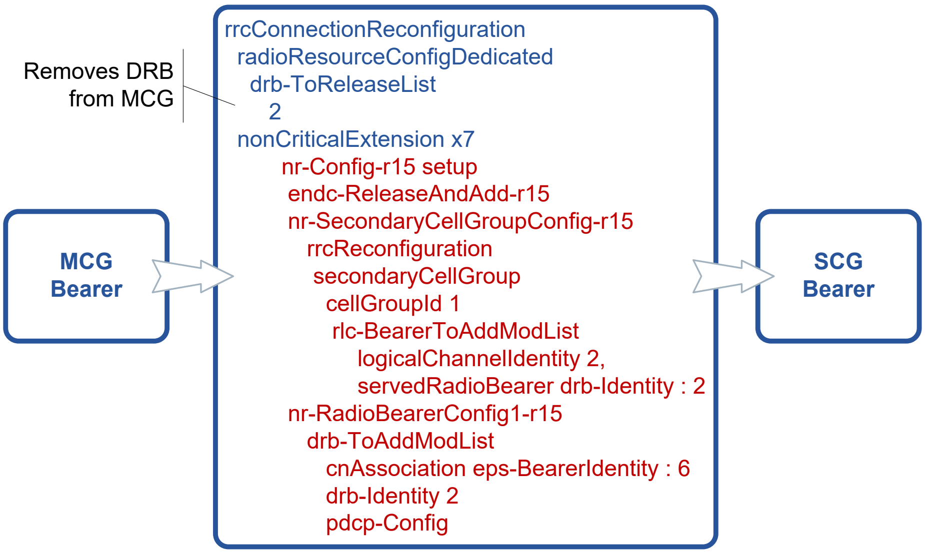


Figure 11-31 MCG DRB Bearer to SCG DRB Bearer

11.3.6 Secondary Node Release

The decision to release a secondary node is made by the MeNB. However, the trigger is typically related to measurements from the device. As such, the en-gNB will configure either periodic or event based measurements. As an example of event based, the NR Event A2 triggers the device to send a measurement report if the quantities (signal level, quality etc.) fall below a specific threshold.

Note that Secondary Node Release can also be triggered by the en-gNB, e.g uplink NR measurements.

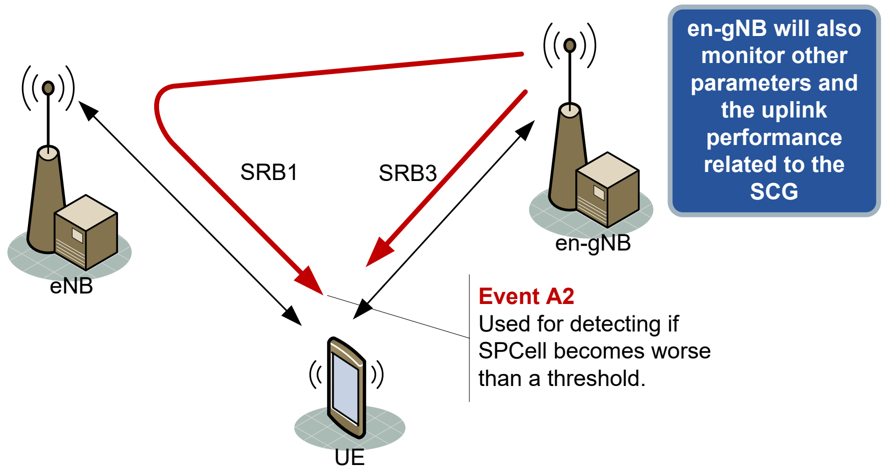


Figure 11-32 NR Event A2

Ultimately, if a secondary node is to be released, any user plane traffic handling responsibilities must be relinquished; all SCG and SCG Split Bearers must be redirected towards the MeNB and the device must be informed that the secondary node is no longer in use. Figure 11-33 outlines the procedure, whereby the en-gNB is the initiating node. In this example the trigger was a Measurement Report message received from the device, however other triggers at the en-gNB may also occur, e.g. the uplink connection performance to the en-gNB. Note that it is also possible for the MeNB to release the en-gNB using a X2AP SgNB Release Request.

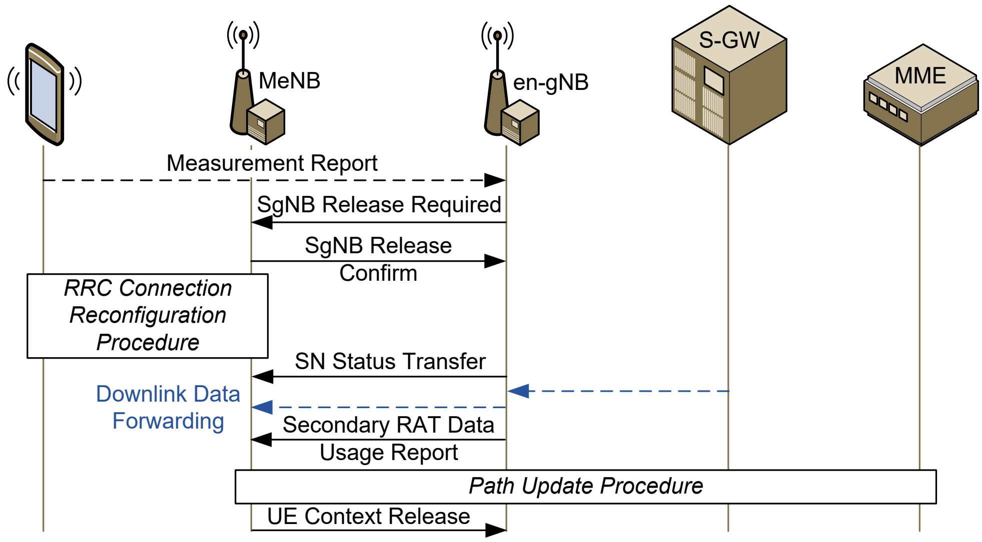


Figure 11-33 EN-DC Release of Secondary Node (SCG Bearer or SCG Split Bearer)

In Figure 11-33, receiving a Measurement Report triggered the exchange of the X2AP SgNB Release Required and subsequent Confirm messages. It is possible that some of the EPS bearers are configured for SCG Bearer / SCG Split Bearer operation and as such, the MeNB may request that data forwarding takes place until the release procedure concludes and the data path is updated. As such, the SgNB Release Confirm message may contain a TEID for data forwarding.

Next, the MeNB will conduct the RRC Reconfiguration procedure with the device, essentially to trigger the device into releasing the entire SCG configuration that it currently has. An example of the release is illustrated in Figure 11-34.

```
rrcConnectionReconfiguration
  nonCriticalExtension x8
      nr-Config-r15 release : NULL,
      nr-RadioBearerConfig1-r15
        drb-ToReleaseList
          2
```

Figure 11-34 Release SCG

If data forwarding is in operation, the en-gNB will provide the current PDCP sequence numbers in the SN Status Transfer message in order to catalogue what data has been sent and received. In addition, the en-gNB will also send the Secondary RAT Data Usage Report which includes the data volumes delivered to the UE over the NR leg of the radio interface.

The procedure concludes with the path update, ensuring that the S-GW is sending all user plane traffic to the MeNB. The MeNB will also delete the UE context from the en-gNB using the UE Context Release message.

11.3.7 Random Access Process

11.3.7.1 Contention Free Random Access Procedure

It is also possible for the en-gNB to allocate CFRA (Contention Free Random Access) opportunities, i.e. dedicated RACH configuration. Figure 10-42 illustrates an example of the process. This includes the en-gNB assigning a C-RNTI, as well as dedicated RACH resources, including a ra-PreambleIndex. This information will be passed via the eNB towards the device. Using the RACH configuration parameters, the device can access using the allocated preamble sequence. Assuming it is detected by the en-gNB, the successful confirmation can be either a PDCCH addressed to the allocated C-RNTI, or alternatively, a PDCCH based on the RA-RNTI which indicates a RAR carrying the correct RAPID value.

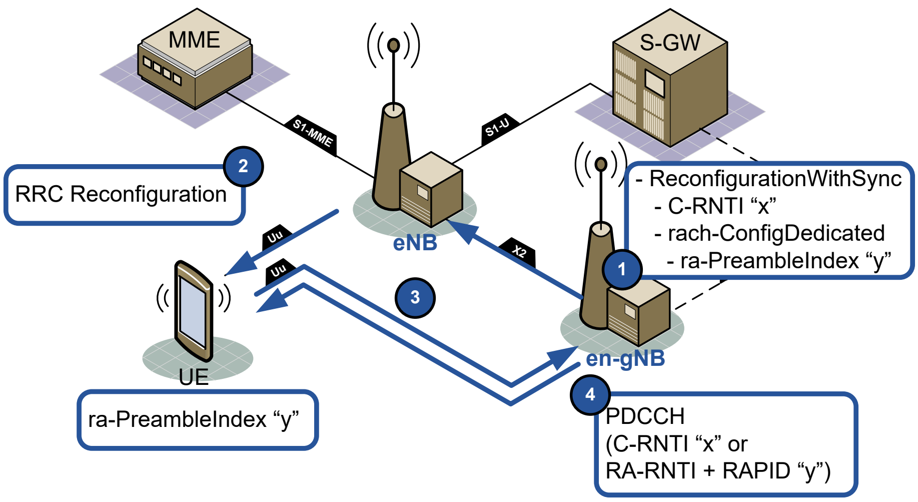


Figure 11-35 Contention Free Random Access

11.4 EN-DC Radio Link Failure

For the purpose of RLF (Radio Link Failure), the device physical layer monitors the downlink radio link quality of the primary cell for providing out-of-sync / in-sync status indications to the higher layers. RLF is declared separately for the MCG and for the SCG. As such, if radio link failure is detected for MCG, the device initiates the RRC Connection Re-establishment procedure. However, on detecting a SCG failure, the device suspends SCG transmissions for all radio bearers and reports the SCG Failure Information to the eNB, instead of triggering re-establishment. SCG Failures include: SCG RLF, SN change failure, SCG configuration failure (only for messages on SRB3) or SCG RRC integrity check failure (on SRB3).

11.4.1 RLF Configuration

The device is configured with various parameters related to RLF on the SCG SpCell (Special Cell). Figure 11-36 includes the key RLF configuration parameters, which identify the timers and counters.

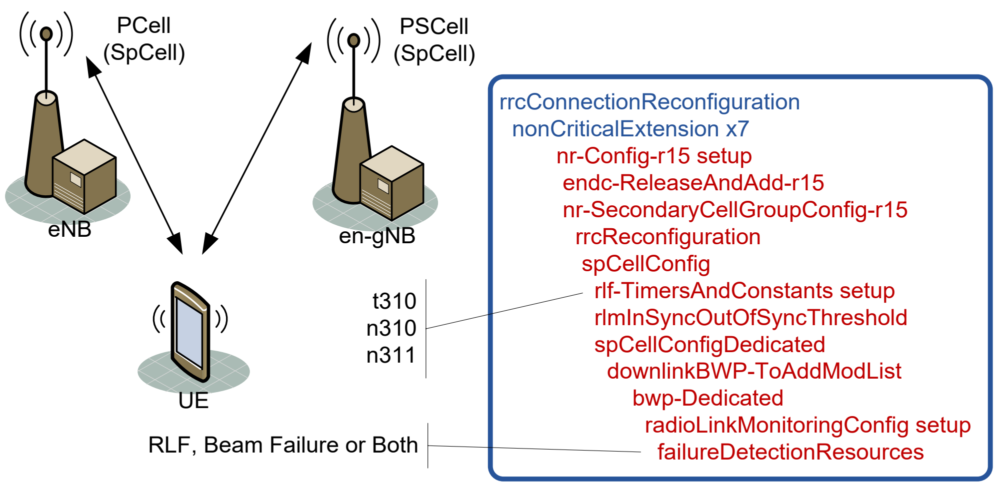


Figure 11-36 Radio Link Failure

The Radio Link Monitor Configuration indicates whether the device should be monitoring based on the SSB or CSI-RS. In addition, the failureDedectionResources parameter also includes a "purpose" parameter, which can indicate: RLF, Beam Failure or both. Note that multiple instances of the failureDedectionResources parameter can be included.

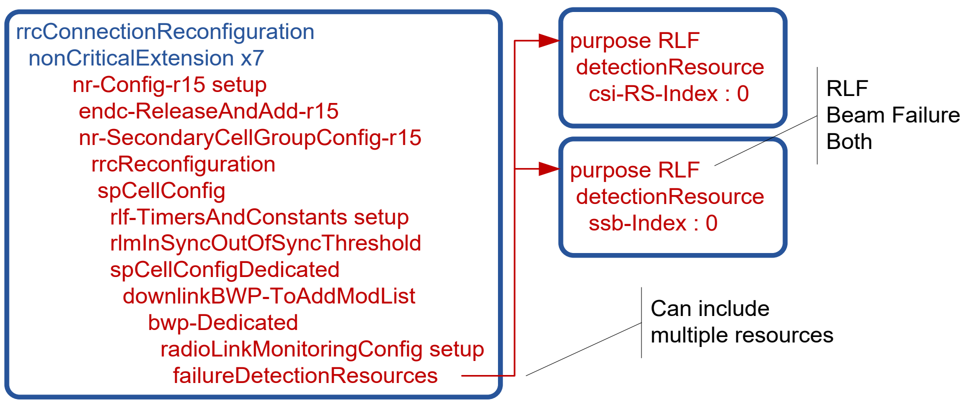


Figure 11-37 Radio Link Monitor Configuration

11.4.2 Out-of-Sync and In-Sync

Determination of Out-of-Sync and In-Sync is illustrated in Figure 11-38. The measurements of the RS (Reference Signal) BLER (Block Error Rate) can be configured for the SSB or CSI-RS. This example focuses on SSB based monitoring. The evaluation time will vary depending on whether DRX is configured, as well as the Frequency Range (FR1 or FR2).

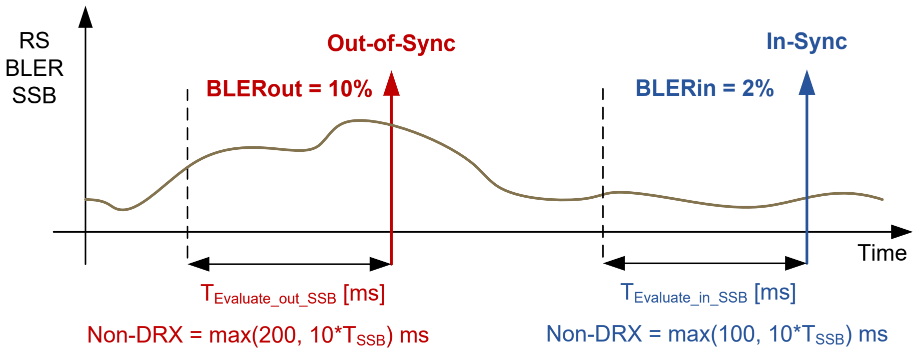


Figure 11-38 Out-of-Sync and In-Sync

Upon receiving n310 consecutive "out-of-sync" indications for the PSCell from lower layers the device starts timer t310. Assuming the device receives n311 In-Sync indication prior to the timer expiring, the t310 timer will stop. However, if not, the timer expires and the device triggers a RLF.

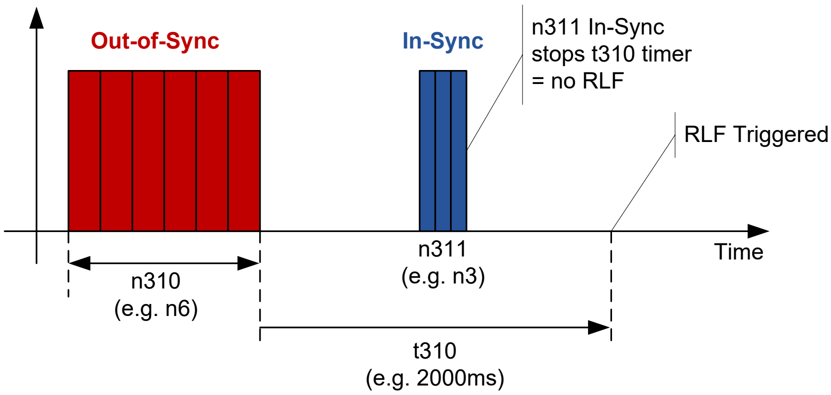


Figure 11-39 RLF Counter and Timers for SpCell

11.4.3 Failure Report

The device, on detecting Radio Link Failure on the SCG, sends a E-UTRA scgFailureInformationNR message to the eNB. This message is from the set of Class 2 messages added in LTE. Figure 11-40 illustrates the contents of the scgFailureInformationNR message.

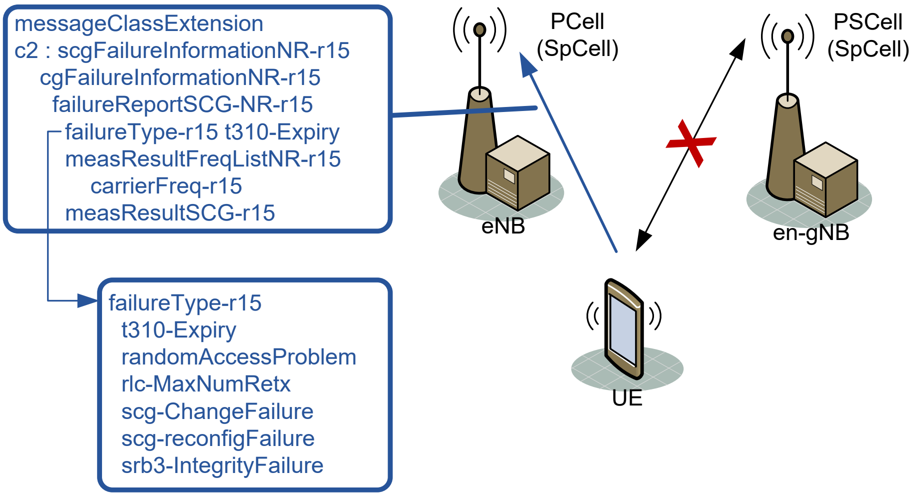


Figure 11-40 SCG Failure Information NR

There are multiple scenarios in which this message is utilized, and this is highlighted in the different failure types:

- t310-Expiry.
- randomAccessProblem.
- rlc-MaxNumRetx.
- scg-ChangeFailure.
- scg-reconfigFailure.
- srb3-IntegrityFailure.

The device will suspend SCG transmission for all SRBs and DRBs, reset SCG MAC, stop t304 (Reconfiguration with sync Failure), if running. It is the responsibility of the Master eNB to decide what to do next. Note that the scgFailureInformationNR message includes the measResultSCG-r15 parameter to assist the MeNB.

12 5G Connected Mode Procedures

12.1 NR Radio Link Failure

For the purpose of RLF (Radio Link Failure), the device physical layer monitors the downlink radio link quality of the primary cell for providing out-of-sync / in-sync status indications to the higher layers. RLF is declared separately for the MCG (Master Cell Group) and for the SCG (Secondary Cell Group). As such, if radio link failure is detected for MCG, the device initiates the RRC re-establishment procedure. However, on detecting a SCG failure, the device suspends SCG transmissions for all radio bearers and reports the SCG Failure Information to the MgNB, instead of triggering re-establishment.

12.1.1 RLF Configuration

The device is configured with various parameters related to RLF on the MCG SpCell (Special Cell). Figure 11-36 includes the key RLF configuration parameters, which identify the timers and counters.

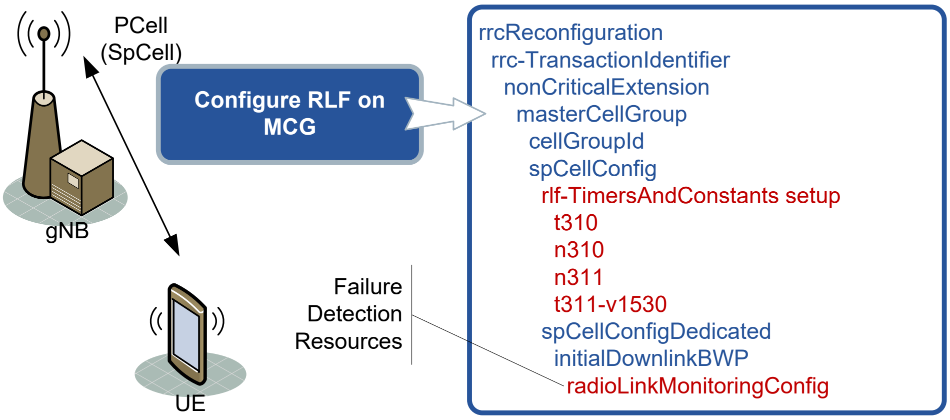


Figure 12-1 Radio Link Failure

The Radio Link Monitor Configuration indicates whether the device should be monitoring based on the SSB or CSI-RS. In addition, the failureDetectionResources parameter also includes a “purpose” parameter, which can indicate: RLF, Beam Failure or both. Note that multiple instances of the failureDetectionResources parameter can be included.

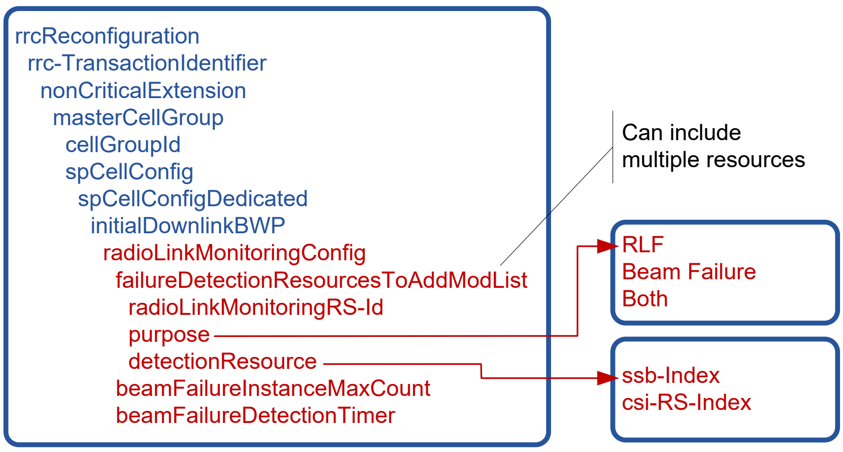


Figure 12-2 Radio Link Monitor Configuration

12.1.2 Out-of-Sync and In-Sync

Determination of Out-of-Sync and In-Sync is illustrated in Figure 11-38. The measurements of the RS (Reference Signal) BLER (Block Error Rate) can be configured for the SSB or CSI-RS. This example focuses on SSB based monitoring. The evaluation time will vary depending on whether DRX is configured, as well as the Frequency Range (FR1 or FR2).

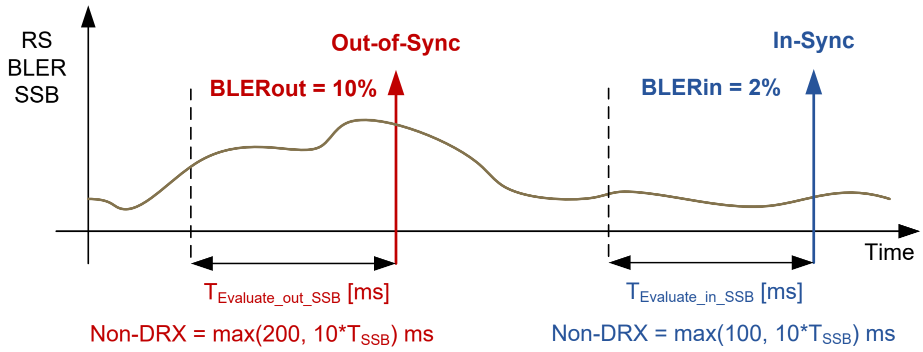


Figure 12-3 Out-of-Sync and In-Sync

Upon receiving n310 consecutive "out-of-sync" indications from lower layers the device starts timer t310. Assuming the device receives a n311 In-Sync indication prior to the timer expiring, the t310 timer will stop. However, if not, the timer expires and the device triggers a RLF.

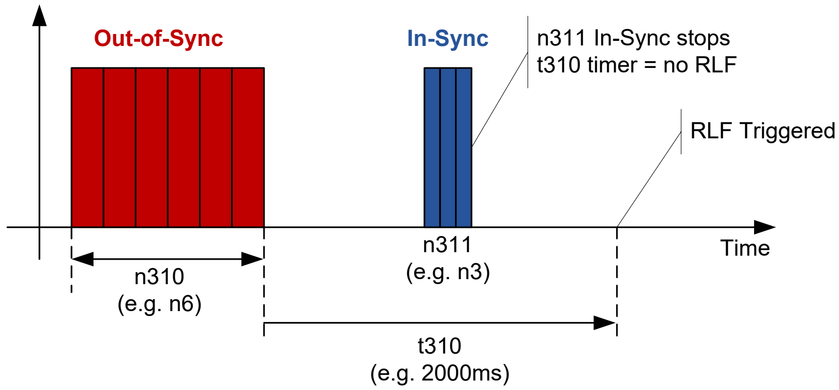


Figure 12-4 RLF Counter and Timers for SpCell

12.1.3 NR RRC Reestablishment Procedure

On detecting a failure on the MCG, the device triggers a NR RRC Reestablishment Procedure towards the gNB. As illustrated in Figure 12-5 the reestablishment cause is set to “otherfailure”.

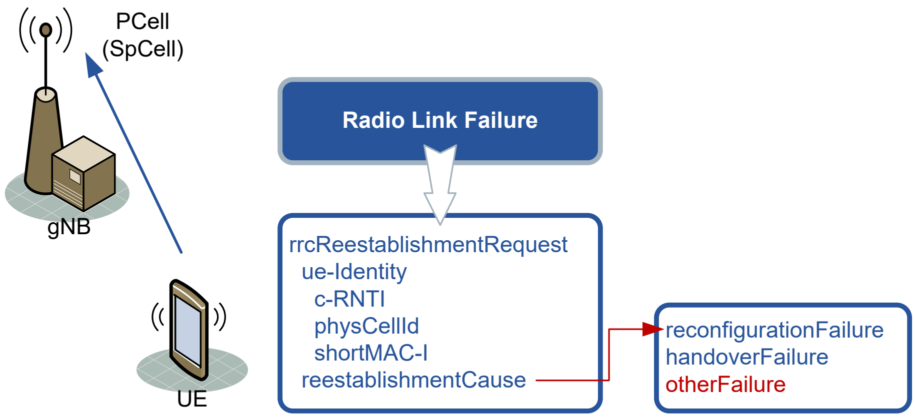


Figure 12-5 NR RRC Reestablishment Request (After RLF)

Figure 12-6 illustrates the NR RRC Reestablishment procedure. Note that the device is expecting a NR RRC Reconfiguration messages to resume the existing Radio Bearers.

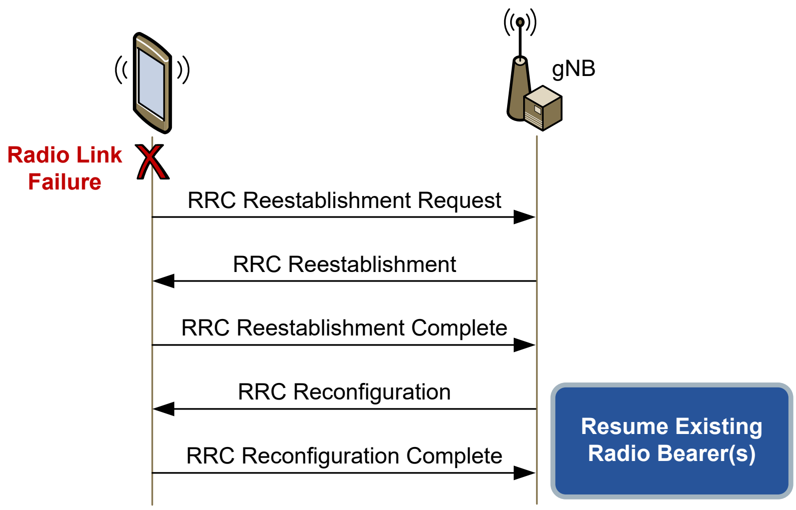


Figure 12-6 NR RRC Reestablishment Procedure

12.1.4 EN-DC SCG Failure

The device, on detecting Radio Link Failure on the SCG, sends a E-UTRA scgFailureInformationNR message to the eNB. This message is from the set of Class 2 messages added in LTE. Figure 11-40 illustrates the contents of the scgFailureInformationNR message.

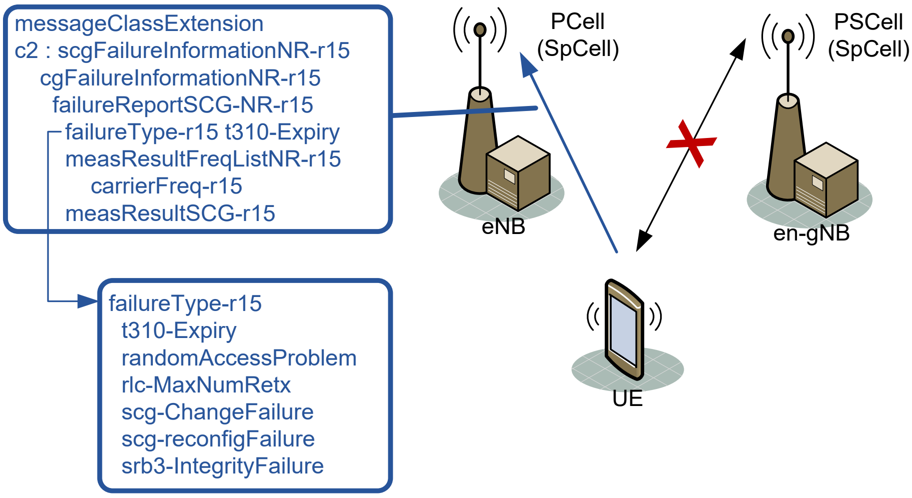


Figure 12-7 E-UTRA SCG Failure Information NR

There are multiple scenarios in which this message is utilized, and this is highlighted in the different failure types:

- t310-Expiry.
- randomAccessProblem.
- rlc-MaxNumRetx.
- scg-ChangeFailure.
- scg-reconfigFailure.
- srb3-IntegrityFailure.

The device will suspend SCG transmission for all SRBs and DRBs, reset SCG MAC, stop t304 (Reconfiguration with sync Failure), if running. It is the responsibility of the Master eNB to decide what to do next. Note that the scgFailureInformationNR message includes the measResultSCG-r15 parameter to assist the MeNB.

12.2 NR Beam Failure

The device may be configured with beam failure recovery. This is used for indicating a new SSB or CSI-RS when beam failure is detected on the serving SSB(s)/CSI-RS(s).

12.2.1 Beam Failure Parameters

Additional parameters are provided to the device to aid beam failure detection, as well as RACH parameters to aid beam failure recovery. The key parameters are illustrated in Figure 12-8.

beamFailureInstanceMaxCount	Used as part of beam failure detection.
beamFailureDetectionTimer	Used as part of beam failure detection.
beamFailureCandidateBeamThreshold	A RSRP threshold for the beam failure recovery.

Figure 12-8 Key Beam Failure Detection Parameters

12.2.2 Beam Failure Detection

Beam failure is detected by counting beam failure instance indications from the lower layers to the MAC entity. Figure 12-9 illustrates the beam failure detection process. Initially, the BFI (Beam Failure Instance) is set to 0. On detection of a failure, the counter is incremented by 1 and the beam failure detection timer started. Each beam failure increments the count. If the count reaches the beamFailureInstanceMaxCount + 1 the random access procedure is initialized. The beamFailureInstanceMaxCount range is n1, n2, n3, n4, n5, n6, n8 or n10.

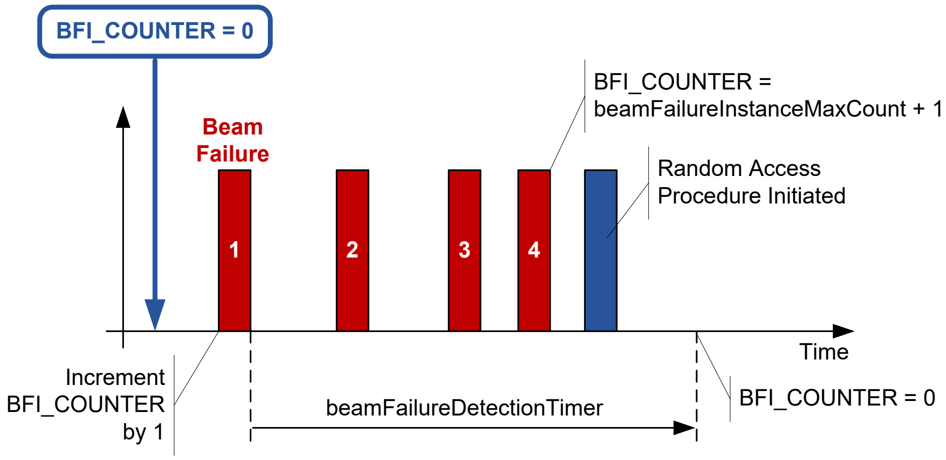


Figure 12-9 Beam Failure Detection

It the beamFailureDetectionTimer expires, the BFI_Counter is reset to 0. The beamFailureDetectionTimer duration is in PBFD (Periods of Beam Failure Detection).

Figure 12-10 illustrates the parameters used for configuring beam failure radio link monitoring.

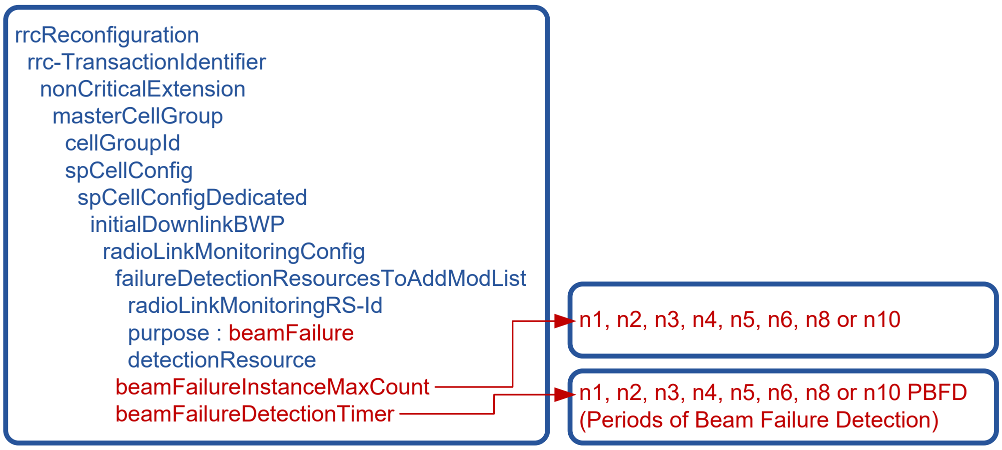


Figure 12-10 Beam Detection Failure Parameters

12.2.3 Beam Failure Recovery

The recovery after beam failure involves the device performing a random access procedure utilizing specific beam failure recovery parameters. These are very similar to the standard configuration parameters, however they point to a specific PRACH, sequences and control set.

Figure 12-11 illustrates the location of the beamFailureRecoveryConfig parameter, as well as the specific parameters it contains. One parameter, identified as rsrp-ThresholdSSB is used to provide a RSRP threshold of candidates to be considered.

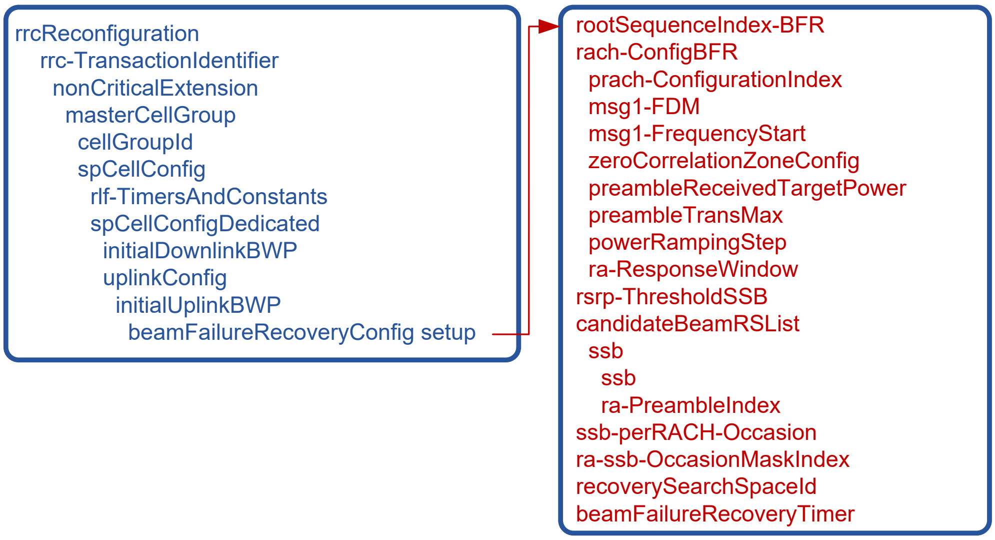


Figure 12-11 Beam Failure Recovery Parameters

A successful random access procedure implies the beam failure recovery procedure was successful.

12.3 NR Power Control

NR, like all other cellular radio systems, requires power control. This is typically to assist in:

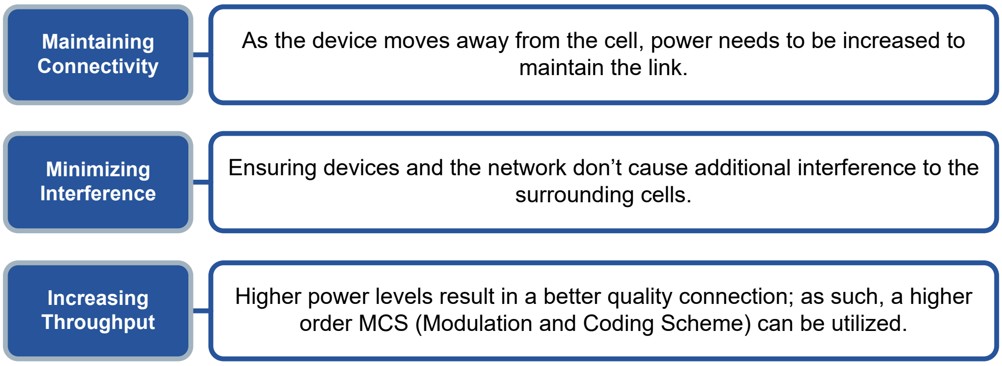


Figure 12-12 Power Control

12.3.1 Downlink Power Allocation

The gNB defines downlink power control and determines the EPRE (Energy Per Resource Element). The device assumes downlink EPRE is constant across the downlink bandwidth. However, different aspects of the NR air interface have different offsets and ratios.

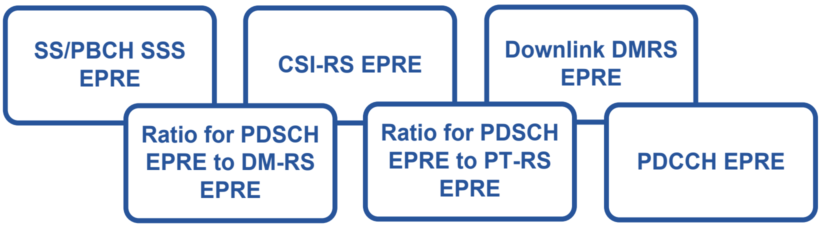


Figure 12-13 Downlink Power Allocation

SS/PBCH SSS EPRE

The downlink SS/PBCH SSS EPRE can be derived from the SS/PBCH downlink transmit power given by the parameter SS-PBCH-BlockPower provided by higher layers in the ServingCellConfigCommon parameter. The downlink SSS transmit power is defined as the linear average over the power contributions (in Watts) of all resource elements that carry the SSS within the operating system bandwidth.

CSI-RS EPRE

The downlink CSI-RS EPRE can be derived from the SS/PBCH block downlink transmit power given by the parameter SS-PBCH-BlockPower and CSI-RS power offset given by the parameter Pc_SS provided by higher layers (NZP-CSI-RS-Resource).

Downlink DMRS EPRE

For downlink DM-RS associated with PDSCH, the device assumes the ratio of PDSCH EPRE to DM-RS EPRE.

PTRS EPRE

The PTRS associated with the PDSCH, various configuration options define the ratio of PDSCH EPRE to PTRS EPRE per layer and relate to the port.

PDCCH EPRE

The downlink PDCCH EPRE is assumed as the ratio of the PDCCH EPRE to NZP CSI-RS EPRE and takes the value of 0 dB.

12.3.2 Uplink Power Control

There are multiple scenarios for uplink power control. These are summarized in Figure 12-14 and include power control for the PUSCH (Physical Uplink Shared Channel), PUCCH (Physical Uplink Control Channel), PRACH (Physical Random Access Channel) and SRS (Sounding Reference Signals).

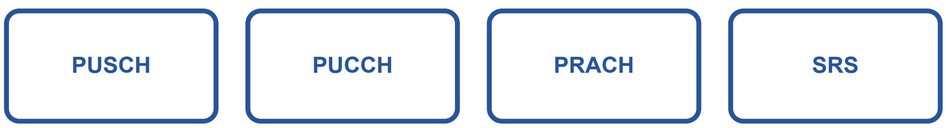


Figure 12-14 Uplink Power Control

Devices utilizing the PUSCH will also be configured to provide PH (Power Headroom) reports.

12.3.2.1 PUSCH Power

On the PUSCH, using a UL BWP “b” of carrier “f” of serving cell “c” using parameter set configuration with index “j” and PUSCH power control adjustment state with index “l”, the device determines the PUSCH transmission power $P_{PUSCH,f,c}(i, j, q_d, l)$ in PUSCH transmission period "i", as illustrated in Figure 12-15.

Configured Max Power

Path Loss

Provides a TPC Mechanism

$$P_{PUSCH,f,c}(i,j,q_d,l) = \min \begin{Bmatrix} P_{CMAX,f,c}(i), \\ P_{O\_PUSCH,f,c}(j) + 10\log_{10}(2^{\mu} \cdot M_{RB,f,c}^{PUSCH}(i)) + \alpha_{f,c}(j) \cdot PL_{f,c}(q_d) + \Delta_{TF,f,c}(i) + f_{f,c}(i,l) \end{Bmatrix}$$

Mixture of UE and Cell Specific Parameters

Bandwidth of PUSCH #RBs

Weighting

Transport Formatting

Figure 12-15 PUSCH Power Control

12.3.2.2 PUCCH Power

Figure 12-16 summarizes the UE power calculation whilst on the PUCCH (Physical Uplink Control Channel). Although similar to the PUSCH equation, the key differences include a PUCCH frame format offset, no weighting on the PL (Pathloss) and separate specifics parameters include TPC (Transmit Power Control).

Provides a TPC Mechanism

$$P_{PUCCH,f,c}(i,q_u,q_d,l) = \min \begin{Bmatrix} P_{CMAX,f,c}(i), \\ P_{O\_PUSCH,b,f,c}(q_u) + 10\log_{10}(2^{\mu} \cdot M_{RB,b,f,c}^{PUCCH}(i)) + PL_{b,f,c}(q_d) + \Delta_{F\_PUCCH}(F) + \Delta_{TF,b,f,c}(i) + g_{b,f,c}(i,l) \end{Bmatrix}$$

Frame format delta power offset (High Layer)

Figure 12-16 PUCCH Power Control

12.3.2.3 PRACH Power

Figure 10-41 summarizes the UE power calculation whilst on the PRACH (Physical Random Access Channel).

$$P_{PRACH,b,f,c}(i) = \min \left\{ P_{CMAX,f,c}(i),\ P_{PRACH,\,target,f,c} + PL_{b,f,c} \right\}$$

Preamble Format offset

preambleReceivedTargetPower
+
DELTA_PREAMBLE
+
(PREAMBLE_POWER_RAMPING_COUNTER – 1) × preamblePowerRampingStep

Figure 12-17 PRACH Power Control

12.3.2.4 Sounding Reference Signal Power

The SRS (Sounding RS) power equation is like the PUSCH's equation, in that it includes a weighting on the pathloss parameter. The major difference is it includes SRS specific parameters (configured by RRC).

12.3.2.5 Dual Connectivity

If a device is configured with a MCG using NR radio access in FR1 or in FR2 and with a SCG using NR radio access in FR2 or in FR1, respectively, the device performs transmission power control independently per cell group. However, when operating in EN-DC the device is configured a maximum power P_{LTE} for transmissions on the MCG by higher layer parameter P-LTE and a maximum power P_{NR} for transmissions on the SCG by higher layer parameter P-NR (part of the CellGroupConfig parameter).

Dynamic Power Sharing

Indicates whether the UE supports dynamic EN-DC power sharing or not. If the UE supports this capability it will dynamically share the power between NR and LTE if P_LTE + P_NR > Pcmax.

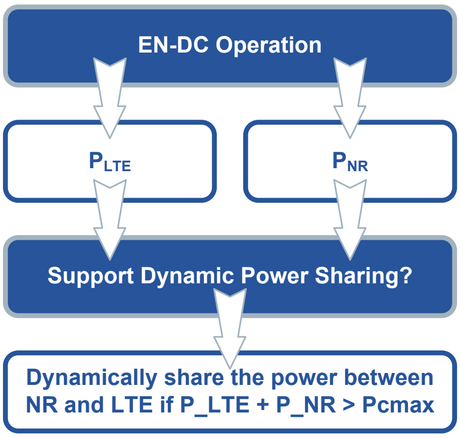


Figure 12-18 EN-DC Dynamic Power Sharing

Note various other configurations not supporting Dynamic Power Sharing are also available, mostly related to TDD configurations and TDM patterns.

13 5G Paging

13.1 5G Paging

13.1.1 NR RRC States

Paging for NR is performed whilst a device is in either RRC_IDLE or RRC_INACTIVE. In both cases, it enables the NG-RAN to trigger the device to return to the RRC_CONNECTED state.

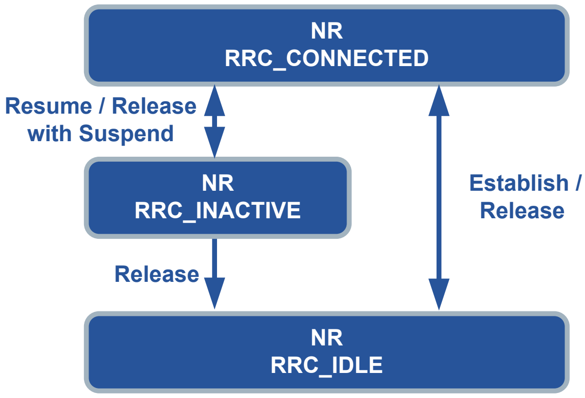


Figure 13-1 RRC States for NR

13.1.2 Network Paging Procedure

A device in the RRC_IDLE state will have no resources on the gNB and the 5G Core will have no awareness of the current cell or specific gNB that the device is camped on. As such, if downlink User Plane data arrives at the UPF, the Paging procedure must be triggered which will cause the device to conduct a Service Request procedure. Consequently, the 5G Core will discover the gNB that the device is using and establish the end to end PDU Session connectivity.

The Paging procedure is shown in Figure 13-2, whereby initially the User Plane data arrives at the UPF. This causes the UPF to generate the PFCP Session Report Request message, with the Report Type set to Downlink Data Report. The message will identify the PDU Session and its priority. In turn, the SMF will contact the AMF using the Namf_Communication_N1N2 Message Transfer Request, which contains the SUPI of the user, as well as information on the PDU Session such as the core network User Plane tunnel endpoint (UPF centric) and the QoS profile for the session.

The AMF will acknowledge this message and also generate the NGAP Paging message, which will contain the temporary ID of the subscriber. This Paging message is sent to each of the gNBs which are in the Tracking Area(s) currently on record at the AMF for this subscriber (bearing in mind that there could be several Tracking Areas in the Tracking Area Identity List stored at the AMF).

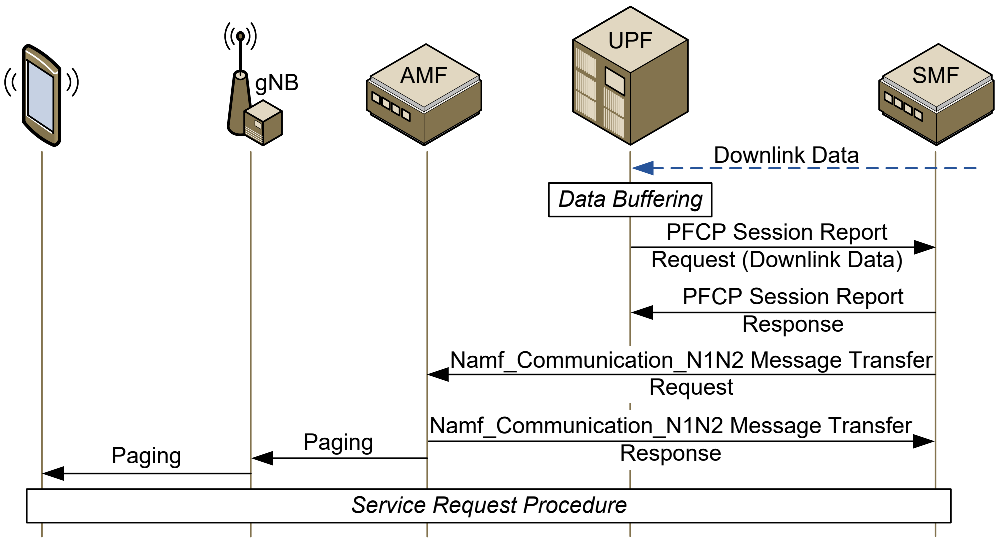


Figure 13-2 5G Paging Procedure

Assuming that the device is in coverage, on receiving the NR RRC Paging message broadcast from the gNB, the device will respond by triggering a RRC Setup for the Service Request procedure, which results in the User Plane being established across the RAN. Any downlink data buffered at the UPF can then be sent towards the appropriate gNB.

Paging Strategy

If a Tracking Area contains a large number of gNBs, or the subscriber has a large Tracking Area List, paging all gNBs within those Tracking Areas may be inefficient. As such, the service provider may utilize specific paging strategies to optimize the paging process.

Figure 13-3 outlines a number of considerations for the Paging Strategy.

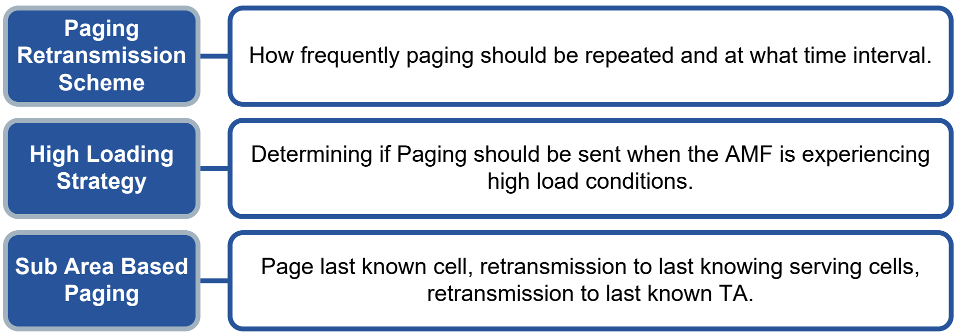


Figure 13-3 Paging Strategy

13.1.3 Paging Identity

The NR RRC Paging message is illustrated in Figure 13-4. It is able to contain a “Paging Record List”, i.e. a list of up to 32 identities.

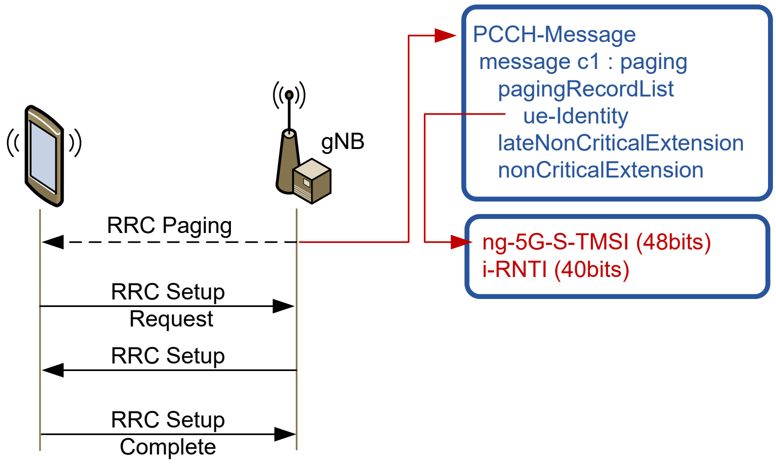


Figure 13-4 NR RRC Paging Message

As with LTE, a shortened version of the GUTI can be used to make common radio signalling procedures such as paging more efficient. This short version is termed the 5G-S-TMSI. The other option is the I-RNTI (Inactive RNTI), however this is part of operating in the RRC_INACTIVE state. Note that the "ng" in the "ng-5G-S-TMSI" relates to the ASN.1 coding.

5G-S-TMSI

The structure of the 5G-S-TMSI 48bits is shown in Figure 13-5.

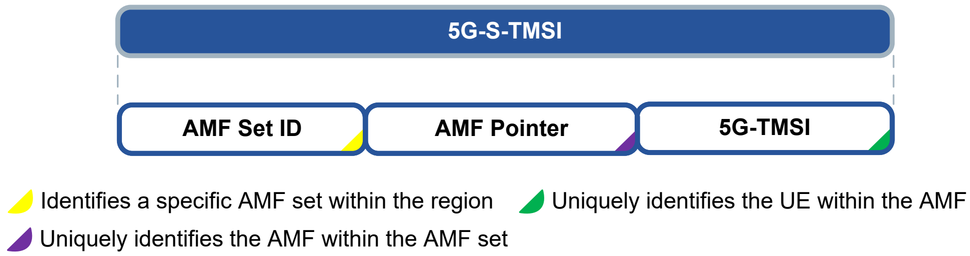


Figure 13-5 5G-S-TMSI Composition

13.1.4 RRC Setup Request (Responding to Page)

Figure 10-45 illustrates the content of the RRC Setup Request message when responding to a RRC Paging message. The two key parameters are an identity and an establishment cause. The device will use 5G-S-TMSI (5G Serving TMSI). Note that only 39bits out of the total 48bits of the 5G-S-TMSI can be included.

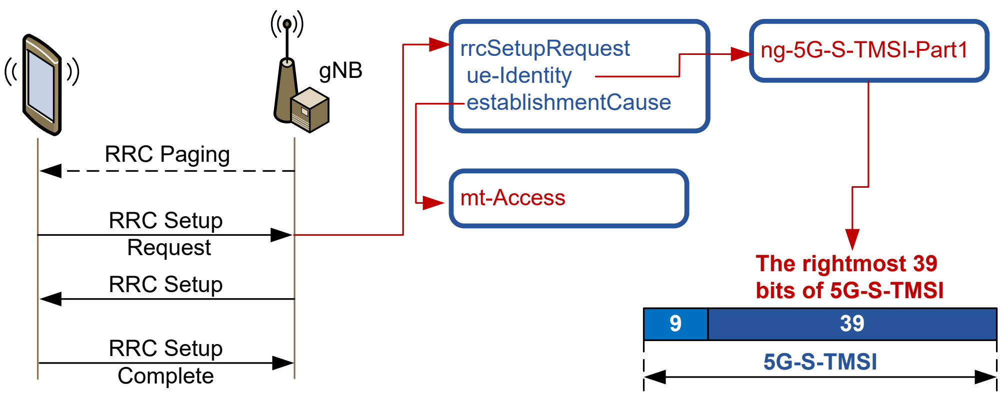


Figure 13-6 RRC Setup Request (Responding to Page)

The cause value is set to indicate MT (Mobile Terminated) Access.

13.2 Scheduling 5G Paging

13.2.1 Paging Frame and Occasion

Like LTE, NR utilizes the concept of a PF (Paging Frame) and PO (Paging Occasion).

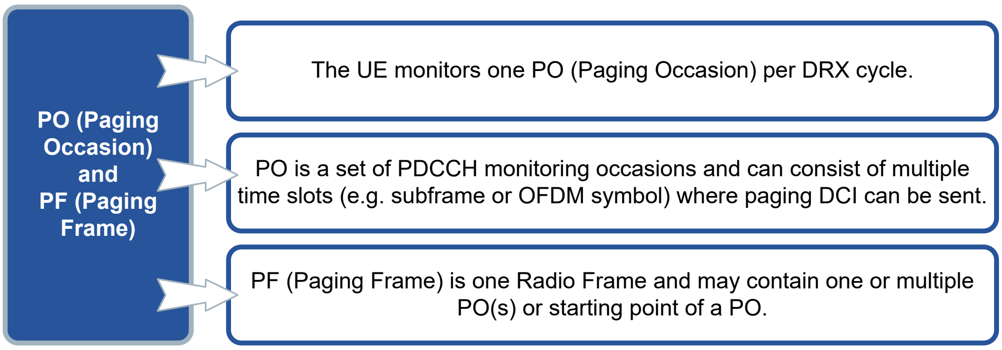


Figure 13-7 NR Paging

Figure 13-8 identifies specifics about NR multi-beam paging.

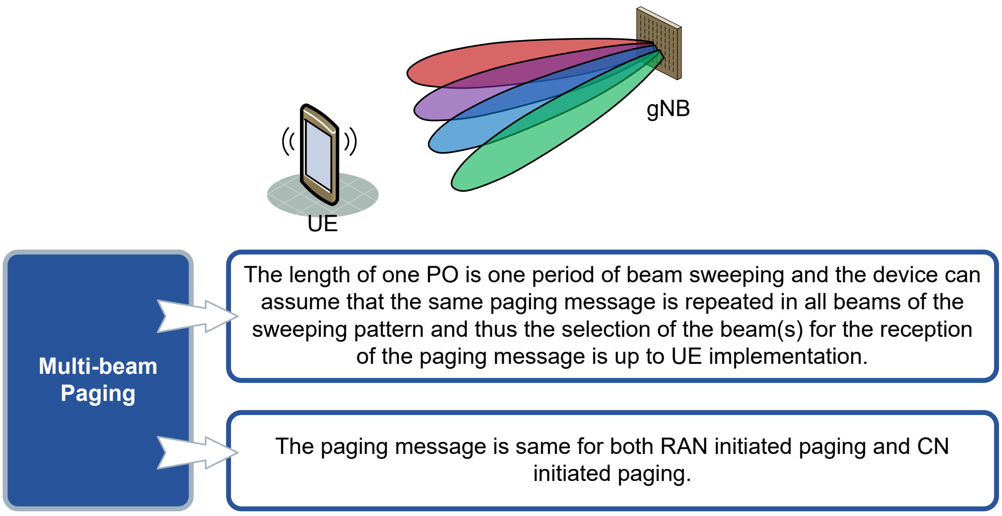


Figure 13-8 NR Paging - Multi-Beam Operation

Note that RAN paging is related to the RRC_INACTIVE state. Such that, the device will trigger a RRC Connection Resume procedure upon receiving RAN paging. However, if the device receives CN (Core Network) initiated paging in RRC_INACTIVE state, it moves to RRC_IDLE and informs NAS.

13.2.2 DCI Paging

In order to page a device, the NR RRC Paging message needs to be sent. This is scheduled by DCI format 1_0 with the CRC masked by the P-RNTI.

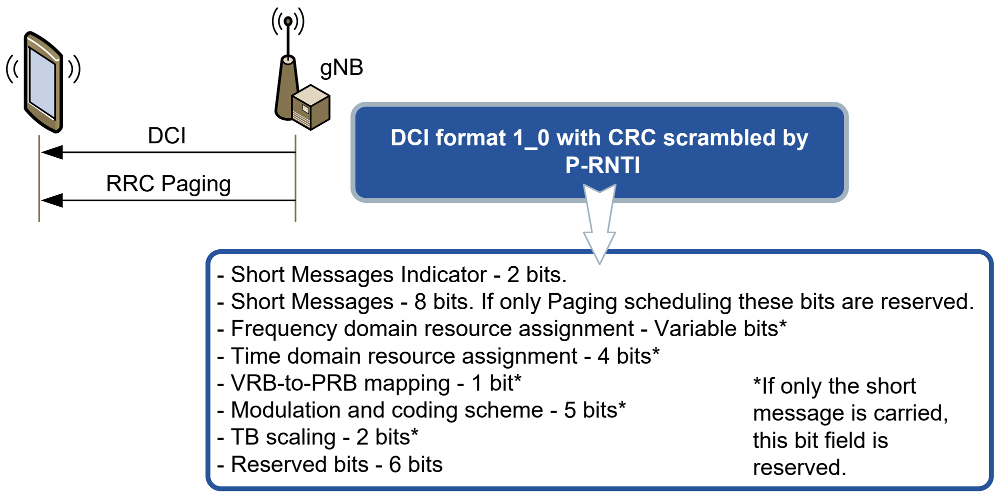


Figure 13-9 DCI format 1_0 with CRC scrambled by P-RNTI

The coding of the Short Message indicator parameter is illustrated in Figure 13-10.

Bit Field	Short Message Indicator
00	Reserved
01	Only scheduling information for Paging is present in the DCI
10	Only short message is present in the DCI
11	Both scheduling information for Paging and short message are present in the DCI

Figure 13-10 Short Message Indicator

Short messages can be transmitted on PDCCH using P-RNTI.

Bit 1 - systemInfoModification - If set to 1: indication of a BCCH modification other than SIB6, SIB7 and SIB8.

Bit 2 - etwsAndCmasIndication - If set to 1: indication of an ETWS primary notification and/or an ETWS secondary notification and/or a CMAS notification.

Bit 3-8 - Not used

Figure 13-11 Short messages can be transmitted on PDCCH

13.2.3 Discontinuous Reception for Paging

PF, PO are determined by the following formulae:

SFN for the PF is determined by:

(SFN + PF_offset) mod T = (T div N)*(UE_ID mod N)

Index (i_s), indicating the start of a set of PDCCH monitoring occasions for the paging DCI, is determined by:

i_s = floor (UE_ID/N) mod Ns

Where:

T: DRX cycle of the UE
N: number of total paging frames in T
Ns: number of paging occasions for a PF
PF_offset: offset used for PF determination
UE_ID: 5G-S-TMSI mod 1024

Figure 13-12 Determining PF and PO

Parameters N, Ns, first-PDCCH-MonitoringOccasionOfPO, PF_offset, and the length of default DRX Cycle are signalled in SIB1.

The specifics of PDCCH monitoring occasions can be found in:

3GPP TS 38.304
Section 7.1

Figure 13-13 PDCCH Monitoring Occasions

13.3 RRC Inactive State and Paging

When the device is RRC Inactive, it is still in a CM Connected state. Whilst RRC Inactive, the device can cell reselect to different cells, without informing the network. The only limitation is that the cells that the device considers for reselection must all be in the same RNA (RAN based Notification Area).

Figure 13-14 elaborates on the RRC Inactive concept, which shows that the last serving gNB (before the device transitioned to RRC Inactive) will hold the UE context, as well as the N2 and N3 connections. If downlink data arrives at this gNB (step 1), it will instigate the paging process in all of the cells within the RNA. This includes cells which may be managed by neighbouring gNBs (step 2). In this case, the gNB will send the XnAP (Xn Application Protocol) RAN Paging request to all relevant neighbouring gNBs.

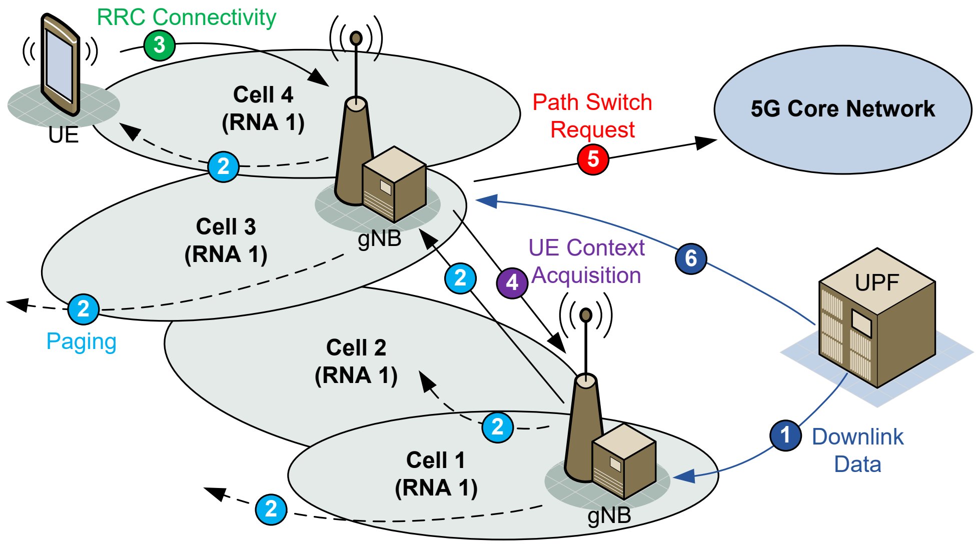


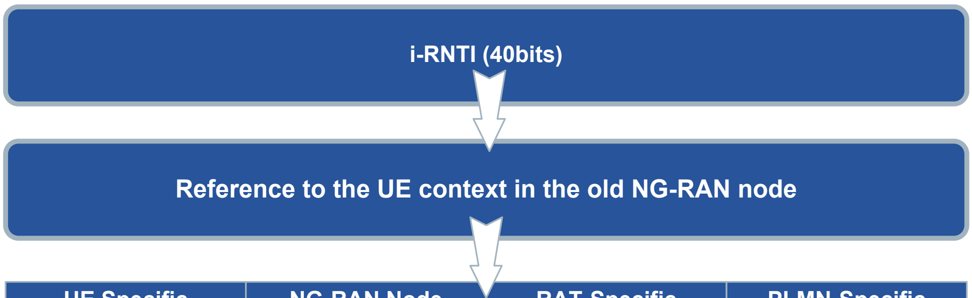
Figure 13-14 RRC Inactive Mobility Concept

If the device responds to the paging request via a cell which is not under the control of the last serving gNB (step 3), the gNB controlling the cell will request the UE Context from the last serving gNB. This is achieved with the XnAP Retrieve UE Context procedure (step 4), which may also establish a forwarding tunnel to stop downlink data being lost.

The new serving gNB will conduct the path switch procedure with the network (step 5), switching downlink data away from the old serving gNB (step 6). In addition, once the path switch is complete, the new serving gNB will instruct the old serving gNB to drop the UE Context.

13.3.1 I-RNTI

The I-RNTI (Inactive RNTI) provides the new NG-RAN node a reference to the UE context in the old NG-RAN node. How the new NG-RAN node is able to resolve the old NG-RAN ID from the I-RNTI is a matter of proper configuration in the old and new NG-RAN node. The implementation of the I-RNTI 40bits is also flexible, as illustrated in Figure 13-15. This shows three example profiles.



UE Specific Reference	NG-RAN Node Address Index	RAT-Specific Information	PLMN-Specific Information
20bits	20bits	N/A	N/A
20bits	16bits	N/A	4bits
24bits	16bits	N/A	N/A

Figure 13-15 I-RNTI

The system will also inform the device of a Short I-RNTI. This is 24bits and is indicated separately, as shown in Figure 13-16.

13.3.2 RAN Notification Area

The device will be informed about the RAN notification area, this will either be a “celllList” or a “ran-AreaConfigList”.

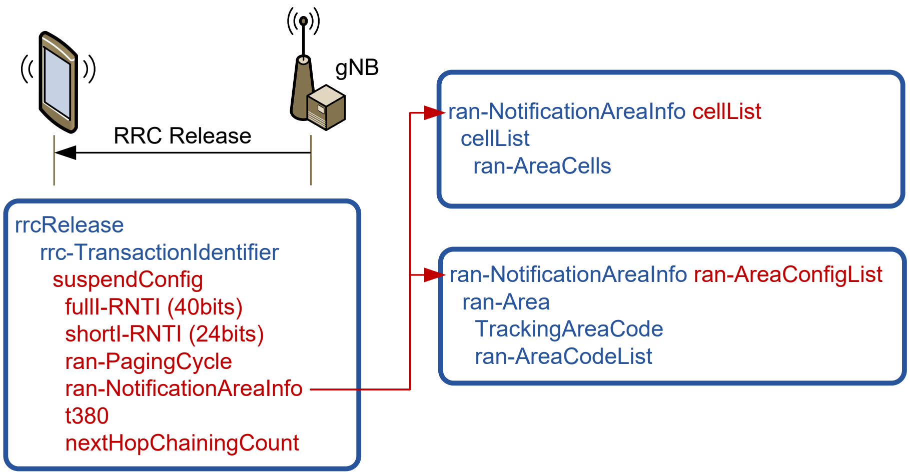


Figure 13-16 Suspend Configuration

Figure 13-14 illustrates the location of the RAN Area Code in SIB1 (System Information Block 1), as well as the indication to the device to use the Full I-RNTI or not. As such, the device will utilize an RRC Resume Request message for the Short I-RNTI and an RRC Resume Request1 messages for the Full I-RNTI.

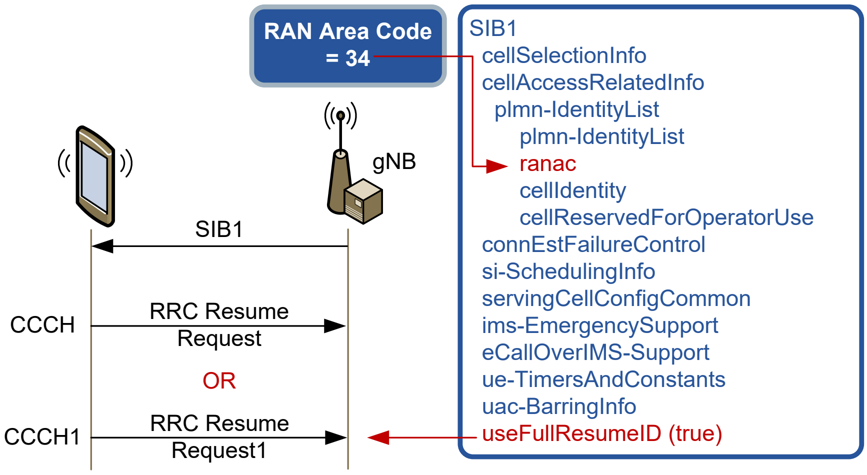


Figure 13-17 RRC Inactive Mobility Concept

13.3.3 RRC Resume Procedure

The RRC Resume procedure (using the Short I-RNTI) is illustrated in Figure 13-18. After receiving the RRC Resume Request from the device the gNB utilizes an RRC Resume message to provide the MCG (Master Cell Group) configuration. The procedure concludes with the device indicating RRC Resume Complete.

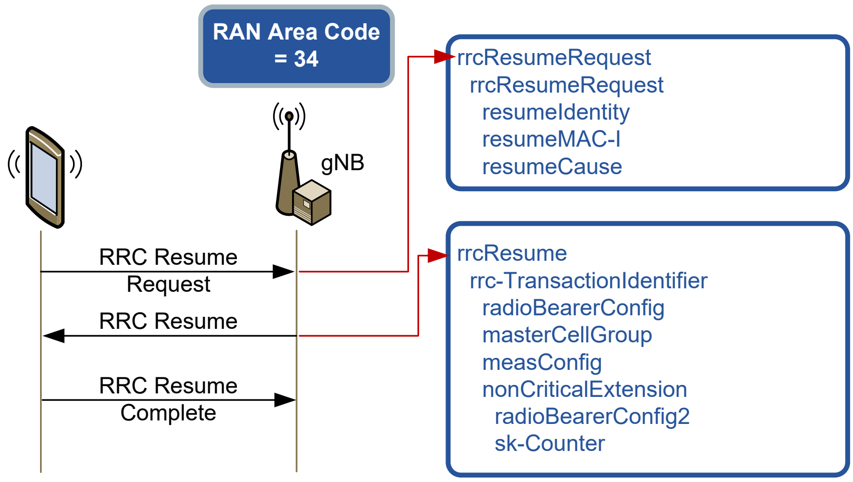


Figure 13-18 RRC Resume Procedure

13.3.4 Paging in the RRC Inactive

The source NG-RAN (NG-RAN1) is also able to send a paging message to the device utilizing the Full I-RNTI (40bits). Assuming the device is present and decodes the paging message it will respond with either RRC Resume Request or RRC Resume Request1 (if indicated to use Full I-RNTI in SIB1).

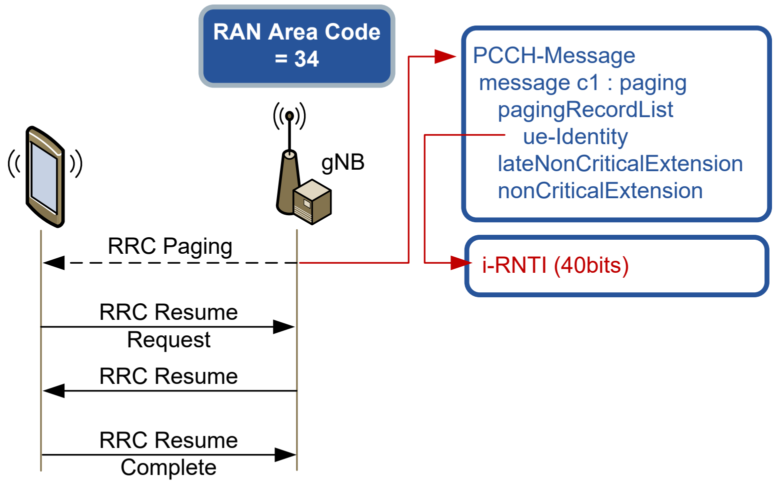


Figure 13-19 Paging in the RRC Inactive

Since the device is able to reselect other cells whilst in RRC Inactive, it may have reselected and camped on another cell within the RAN Notification Area. As such, NG-RAN1 needs to send an Xn RAN Paging message to other NG-RANs serving a RAN Notification Area, as illustrated in Figure 13-20.

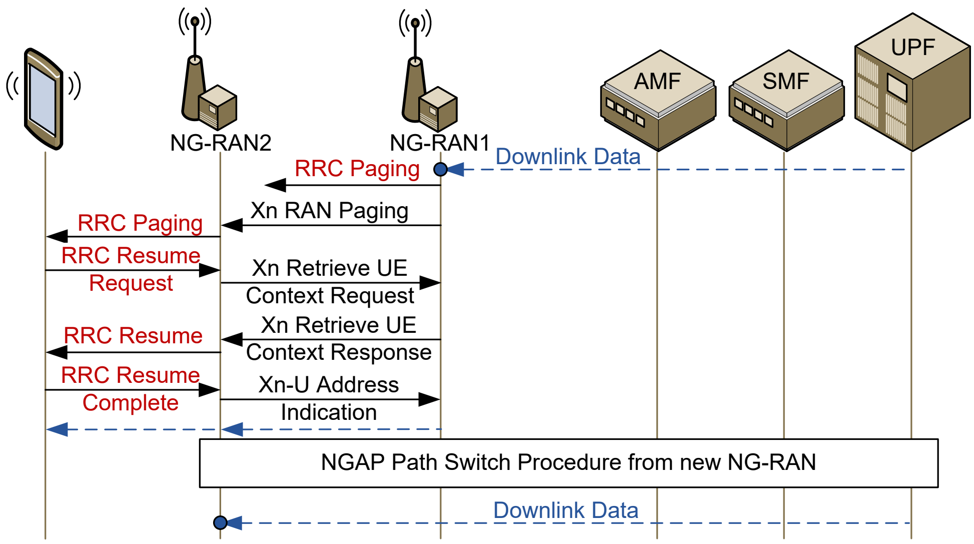


Figure 13-20 Paging in RRC Inactive

Assuming the device receives the RRC Paging message with it's I-RNTI from NG-RAN2, it will send a RRC Resume Request message. Note that the device is informed by SIB1 to utilize the Short I-RNTI (RRC Resume Request) or Full I-RNTI (RRC Resume Request1).

The NG-RAN2, upon receiving the RRC Resume Request message, will send the XNAP Xn Retrieve UE Context Request message to NG-RAN1. Effectively indicating that it has the device and that it requires UE Context information. The NG-RAN1 then responses with the necessary UE Context information which will assist in the NGAP Path Switch Procedure from NG-RAN2 to the AMF.

14 5G Measurements

14.1 NR Measurement Quantities

The main signal measurements in NR are illustrated in Figure 14-1. Note that other measurements related to timing and inter-RAT also exist.

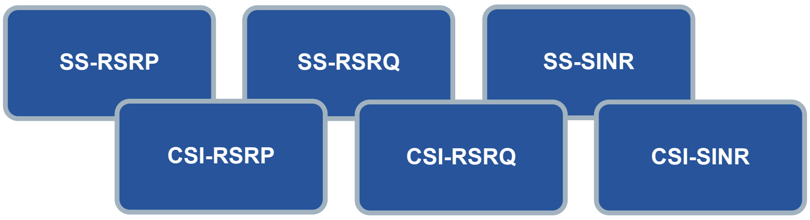


Figure 14-1 NR Measurements

14.1.1 SS-RSRP

SS-RSRP (SS Reference Signal Received Power) is based on the RE (Resource Elements) that carry SSS (Secondary Synchronization Signals). Key aspects are illustrated in Figure 14-2.

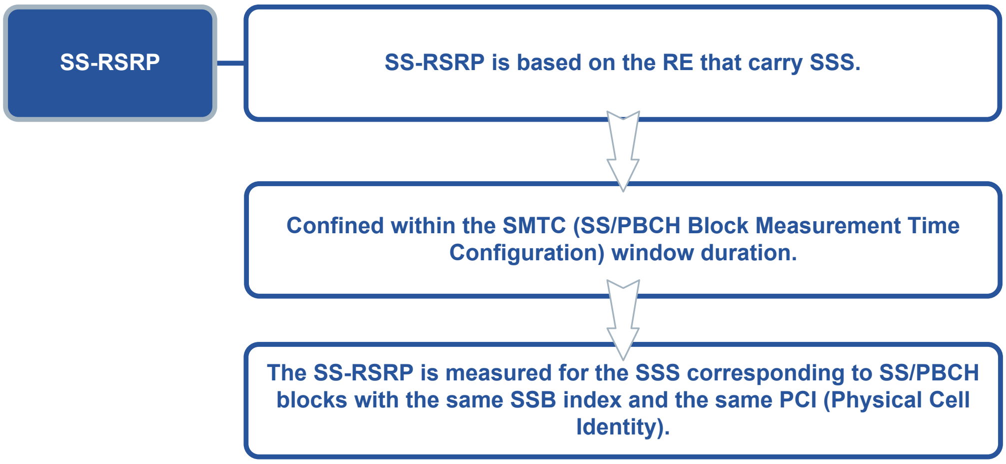


Figure 14-2 SS-RSRP

For SS-RSRP determination DMRS for PBCH and, if indicated by higher layers, CSI reference signals in addition to secondary synchronization signals may be used.

Figure 14-3 illustrates the states applicable to the SS-RSRP measurement.

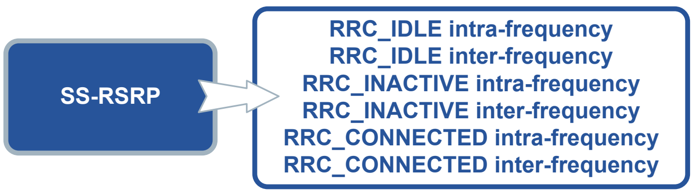


Figure 14-3 States for SS-RSRP Measurements

Note: If SS-RSRP is used for L1-RSRP, then only RRC_CONNECTED intra-frequency is applicable.

SS-RSRP in a Measurement Report

Figure 14-4 illustrates the range of SS-RSRP values that may be reported in a RRC Measurement Report message.

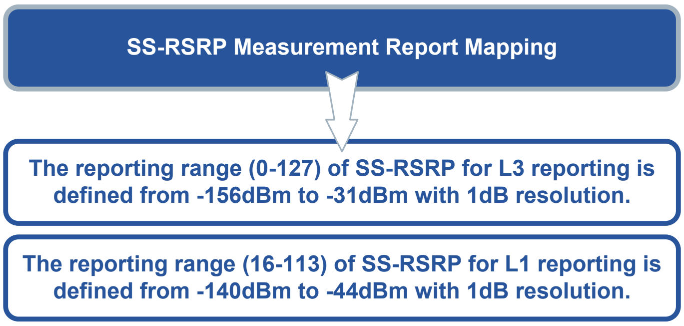


Figure 14-4 SS-RSRP Measurement Report Mapping

14.1.2 SS-RSRQ

SS-RSRQ (Secondary Synchronization Signal - Reference Signal Received Quality) is defined as the ratio of N×SS-RSRP / NR carrier RSSI (Received Signal Strength Indicator), where N is the number of resource blocks in the NR carrier RSSI measurement bandwidth.

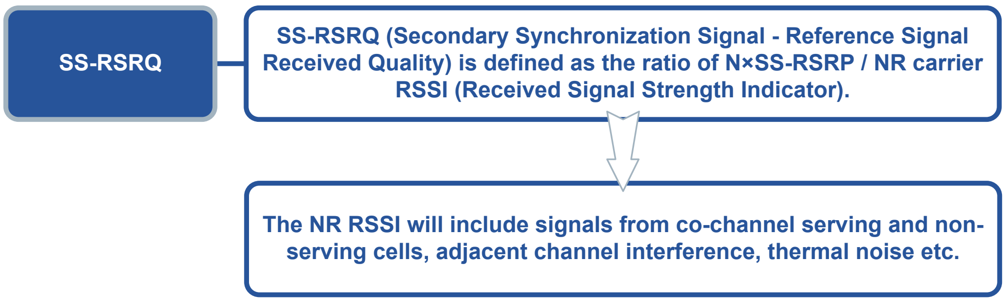


Figure 14-5 SS-RSRQ

Figure 14-6 illustrates the states applicable to the SS-RSRQ measurement.

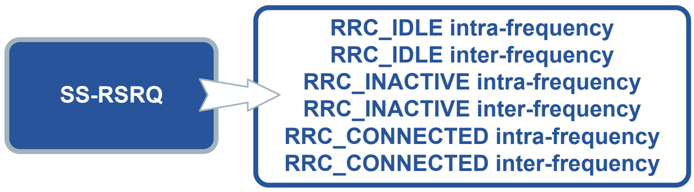


Figure 14-6 States for SS-RSRQ Measurements

SS-RSRQ in a Measurement Report

Figure 14-7 illustrates the range of SS-RSRQ values that may be reported in a RRC Measurement Report message.

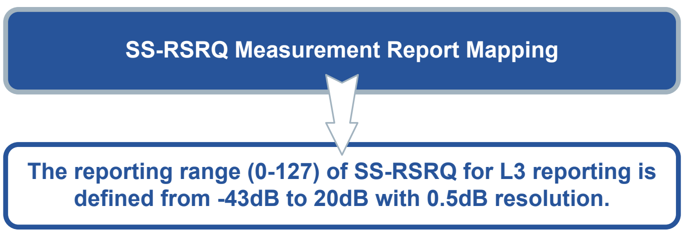


Figure 14-7 SS-RSRQ Measurement Report Mapping

14.1.3 SS-SINR

Key aspects of SS-SINR (SS Signal-to-Noise and Interference Ratio) are illustrated in Figure 14-8.

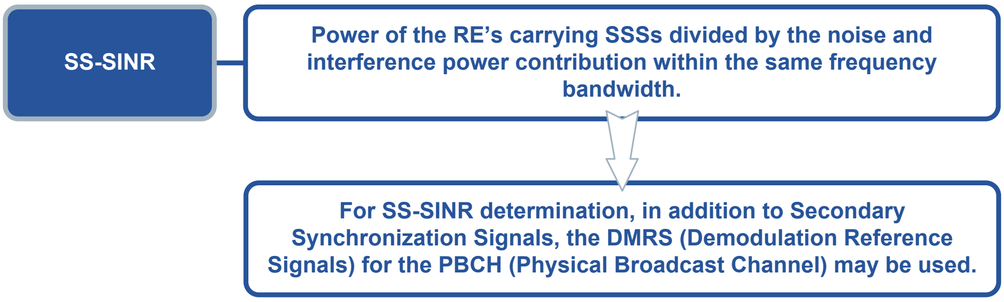


Figure 14-8 SS-SINR

The measurement time resource(s) for SS-SINR are confined within SMTC window duration.

The SS-SINR measurement is applicable in the states illustrated in Figure 14-9.

Figure 14-9 States for SS-SINR Measurements

SS-SINR in a Measurement Report

Figure 14-10 illustrates the range of SS-SINR values that that may be reported in a RRC Measurement Report message.

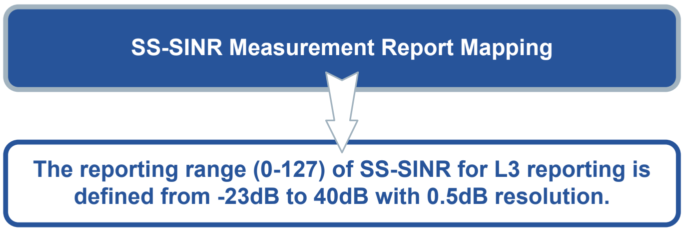


Figure 14-10 SS-SINR Measurement Report Mapping

14.1.4 CSI-RSRP

Key aspects of CSI-RSRP (CSI Reference Signal Received Power) are illustrated in Figure 14-11.

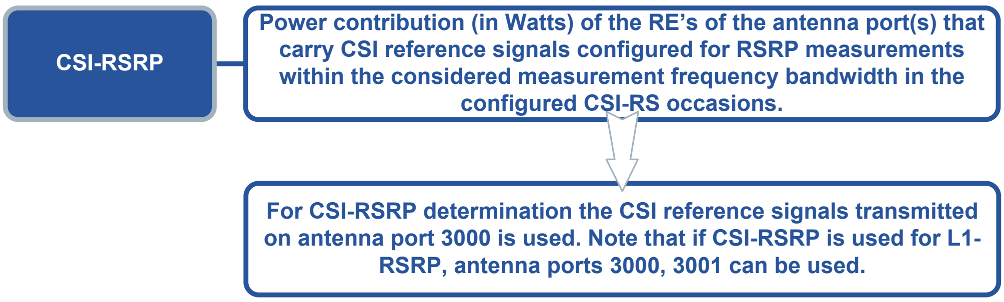


Figure 14-11 CSI-RSRP

The states applicable for CSI-RSRP measurements are illustrated in Figure 14-12.

Figure 14-12 States for CSI-RSRP Measurements

The measurement reporting values for CSI-RSRP are illustrated in Figure 14-13.

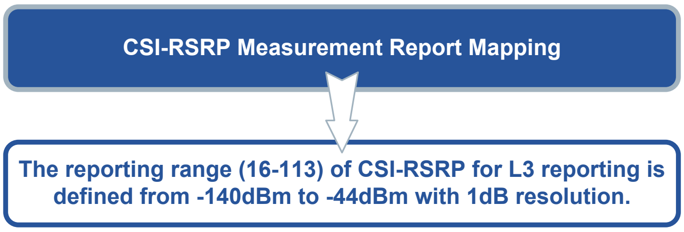


Figure 14-13 CSI-RSRP Measurement Report Mapping

14.1.5 CSI-RSRQ

Key aspects of CSI-RSRQ (CSI Reference Signal Received Quality) are illustrated in Figure 14-14.

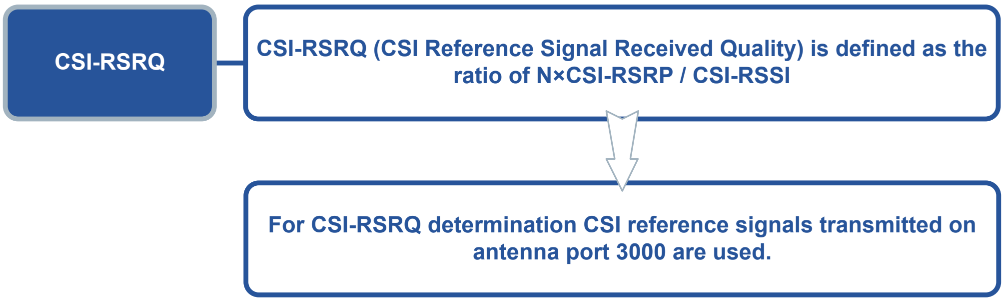


Figure 14-14 CSI-RSRQ

The states applicable for CSI-RSRP measurements are illustrated in Figure 14-15.

Figure 14-15 States for CSI-RSRQ Measurements

The CSI-RSRQ reporting mapping values for measurement reporting are the same as SS-RSRQ mapping values, as illustrated in Figure 14-7.

14.1.6 CSI-SINR

Key aspects of CSI-SINR (CSI Signal-to-Noise and Interference Ratio) are illustrated in Figure 14-16.

Figure 14-16 CSI-SINR

Figure 14-17 illustrates the RRC states applicable for CSI-SINR measurements.

Figure 14-17 States for CSI-SINR Measurements

The CSI-SINR reporting mapping values for measurement reporting are the same as SS-SINR mapping values, as illustrated in Figure 14-10.

14.2 NR Measurements Configuration Options

14.2.1 Measurement Configuration Options

The NR RRC measurement configuration includes various parameters, in summary these cover:

- Measurement objects - these are the objects on which the UE is configured to perform the measurements, i.e. the NR Carrier and SS (Synchronization Signal) Block information.
- Reporting configurations - this is a list of reporting attributes for NR. It includes the reporting type, namely Periodical or Event Based, as well as the associated attributes. It also enables CGI (Cell Global Identity) reporting.
- Measurement identities - this is a list of measurement identities where each measurement identity links one measurement object with one reporting configuration. By configuring multiple measurement identities, it is possible to link more than one measurement object to the same reporting configuration, as well as to link more than one reporting configuration to the same measurement object. The measurement identity is used as a reference number in the measurement report.
- S-Measure - this optional parameter is a serving cell quality threshold controlling whether or not the UE is required to perform measurements of intra frequency, inter frequency and inter RAT neighbouring cells.
- Quantity configurations - this is configured per RAT type and defines the associated filtering used for all event evaluation and related reporting of that measurement type.
- Measurement gaps - this defines the periods that the device may use to perform measurements, i.e. no downlink or uplink transmissions are scheduled.

Figure 11-7 illustrates the main measurement configuration related parameters in the NR RRC Reconfiguration Request message.

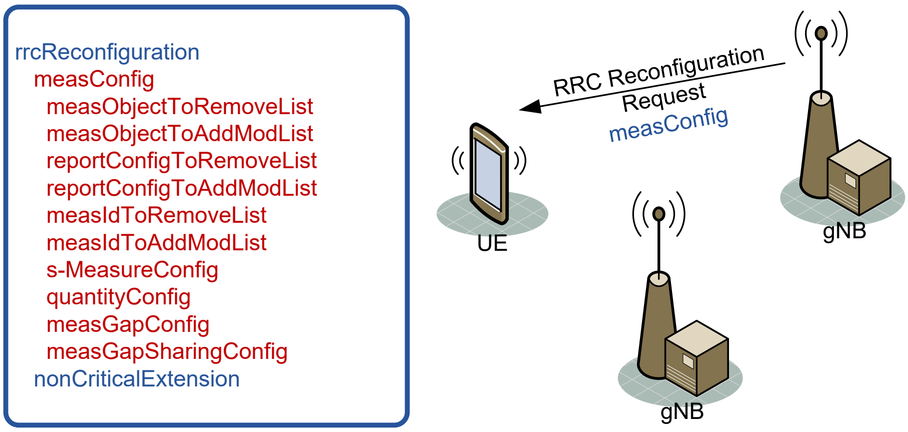


Figure 14-18 Measurement Configuration

14.2.2 Measurement Objects

Figure 11-8 illustrates some of the key parameters for an NR measurement object. Details of these parameters can be found in 3GPP TS 38.331.

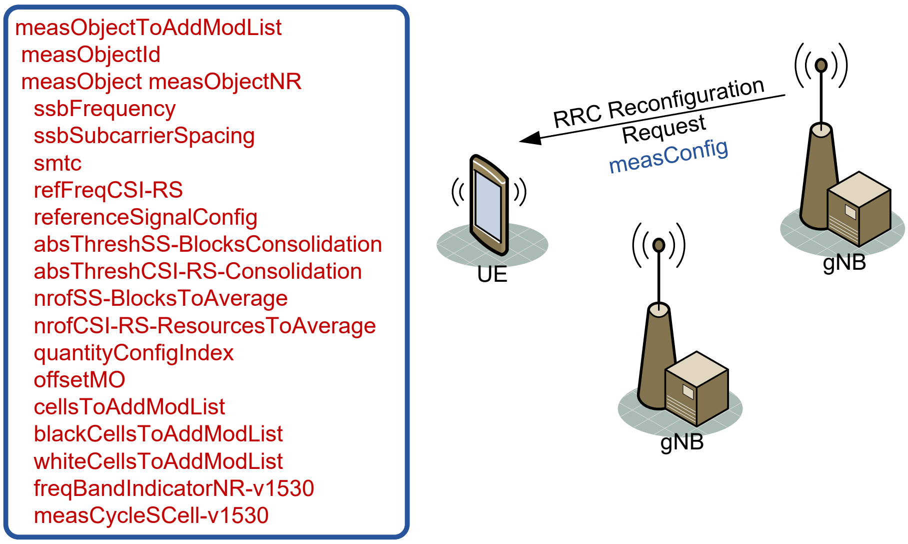


Figure 14-19 Measurement Object

14.2.3 Report Configuration

The Report Configuration parameter is an important part of the measurement process; an example of the parameters for an Event based report configuration is illustrated in Figure 11-9.

Key parameters include:

- Report Type - like LTE, there are two main types of reporting methods: periodical and event based. In addition, there is the option to report the CGI.
- Event ID - this parameter provides an indication of the event (assuming event based report type). In so doing, various parameters related to the NR event are available.
- rsType - this identifies SSB or CS-RSI.
- reportInterval - this is used for periodic reporting, or if event based and the event trigger still exists the device will periodically send the measurement report.

- reportAmount - indicates the amount of Measurement Report messages to be sent.
- reportQuantityCell - this indicates the quantities to report, i.e. RSRP, RSRQ and/or SINR.
- maxReportCells - this indicates the maximum number of cells to report.
- includeBeamMeasurements - this indicates that the device should also include measurement results for the SSB Index's.

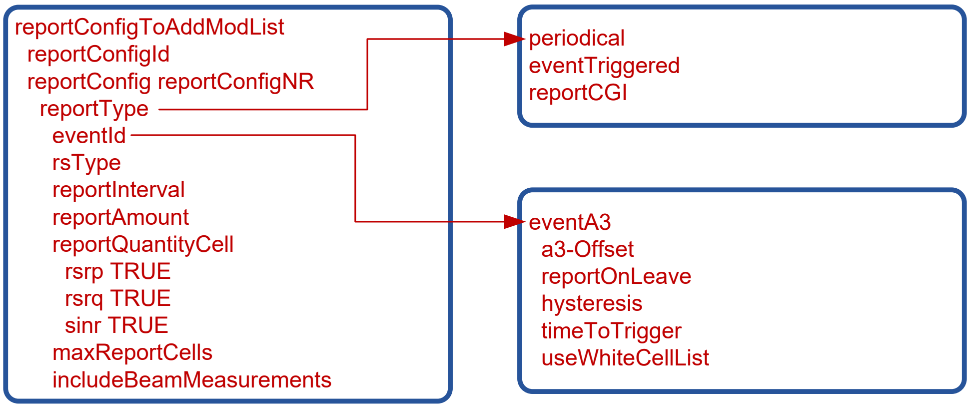


Figure 14-20 NR Report Configuration (Event A3 NR)

14.2.4 NR Measurement Events

The gNB can configure the device to perform measurements, either periodic or event based.

The specific NR events include:

- Event A1 - serving becomes better than threshold. For this measurement, consider the serving cell to be the NR SpCell or the NR SCell that is configured on the frequency indicated in the associated measObjectNR.
- Event A2 - serving becomes worse than threshold. For this measurement, consider the serving cell to be the NR SpCell or the NR SCell that is configured on the frequency indicated in the associated measObjectNR.
- Event A3 - neighbour becomes offset better than SpCell.
- Event A4 - neighbour becomes better than threshold.
- Event A5 - SpCell becomes worse than threshold1 and neighbour becomes better than threshold2.
- Event A6 - neighbour becomes offset better than SCell.

Depending on the NR measurement event type, various threshold(s) and hysteresis values may be provided.

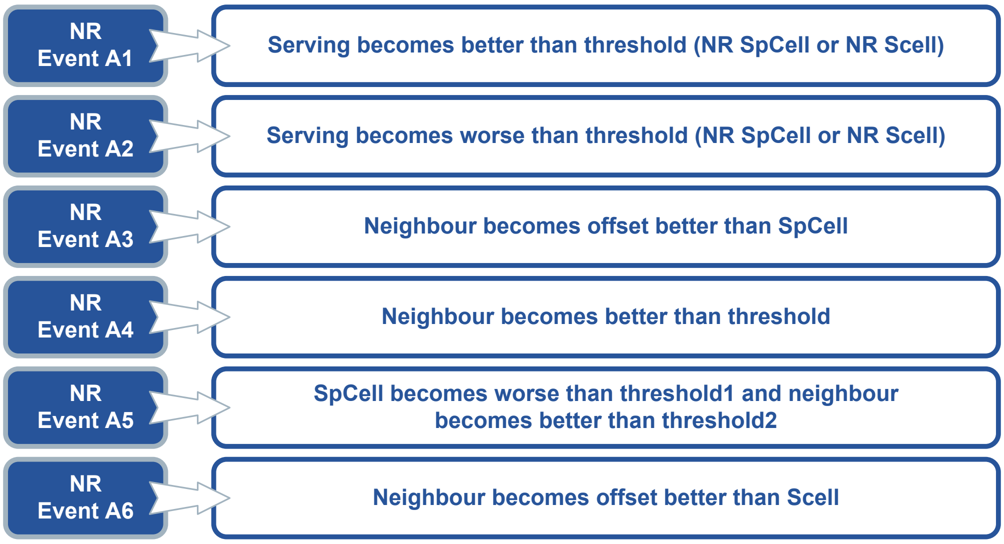


Figure 14-21 NR Events

In addition, inter RAT events also exist, as illustrated in Figure 14-22.

Figure 14-22 NR Inter-RAT Events

Example of Measurement Events

The configuration of a device and the event types to utilize are typically linked into a specific vendor's way of managing mobility. As such, a vendor may choose to implement a specific event to start the measurement configuration process. An example is illustrated in Figure 14-23, whereby the device (in dual connectivity) is first configured with NR Event A2 on the PSCell. Therefore, as the PSCell drops below a specified threshold a MR (Measurement Report), indicating a Measurement Identity relating to Event A2, is sent. At this point the gNB configures additional Events, for example Event A4 (on a neighbour) and Event A3. Once these conditions are met, the appropriate Measurement Report is sent.

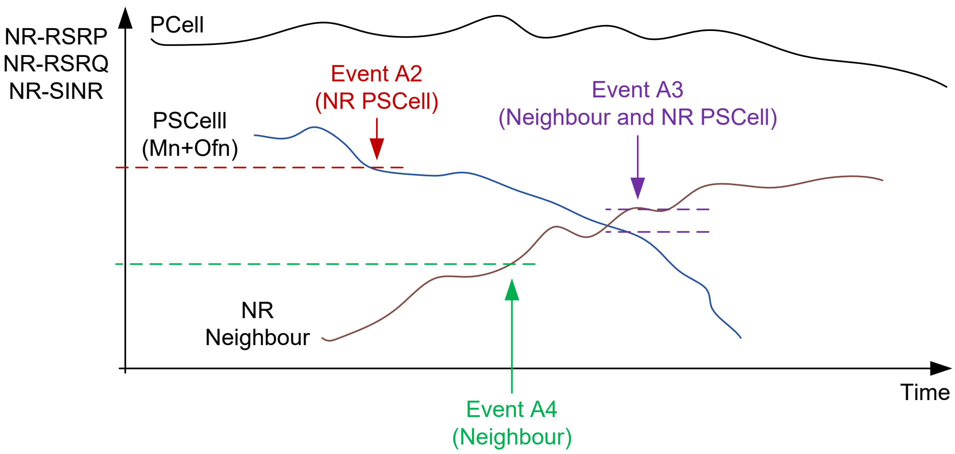


Figure 14-23 Example of NR Event Triggers

In reality, each vendor will have a multitude of measurement control permutations within the gNB.

14.2.5 Periodic Measurements

Figure 11-10 illustrates the periodical reporting concept with a configured Report interval. In addition, the gNB also configures the Report Amount which indicates how many reports to send (r1, r2, r4, r8, r16, r32, r64 or infinity).

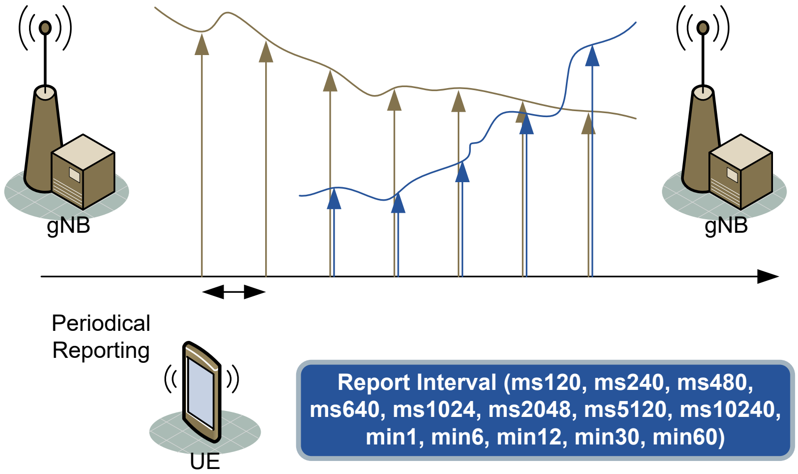


Figure 14-24 Periodical Reporting

14.2.6 Measurement Identities

The concept of Measurement Identity is the same for E-UTRA and NR. As illustrated in Figure 11-12, each identity is a combination of a Measurement Object and Report Configuration. It is this Measurement Identity that is then utilized in the Measurement Report message, with the associated measured result.

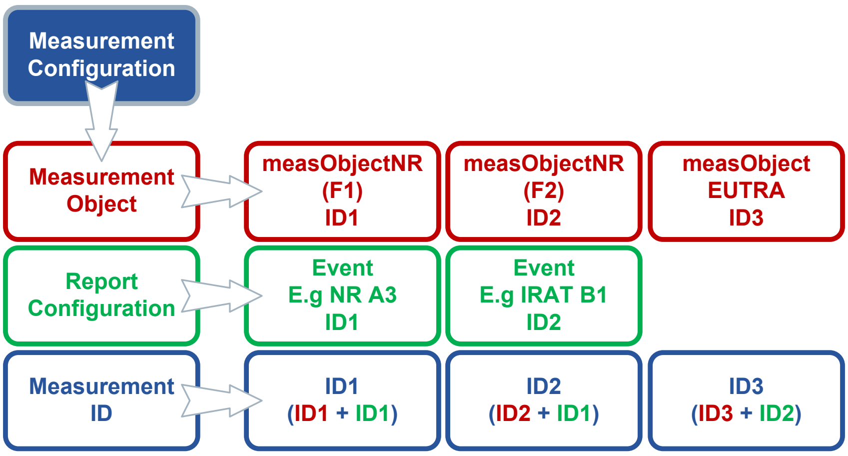


Figure 14-25 Measurement Identities

14.2.7 NR Measurement Timing Configuration

In order to take measurement, for example SS-RSRP, SS-RSRQ and SS-SINR, the device is configured with SMTC (SS/PBCH Block Measurement Timing Configuration) in accordance with the received “periodicityAndOffset” parameter in the MTC (Measurement Timing Configuration) for the NR SSB, as illustrated in Figure 11-13.

On the identified frequency, the device does not consider SS/PBCH block transmission in subframes outside of the SMTC occasion for measurements.

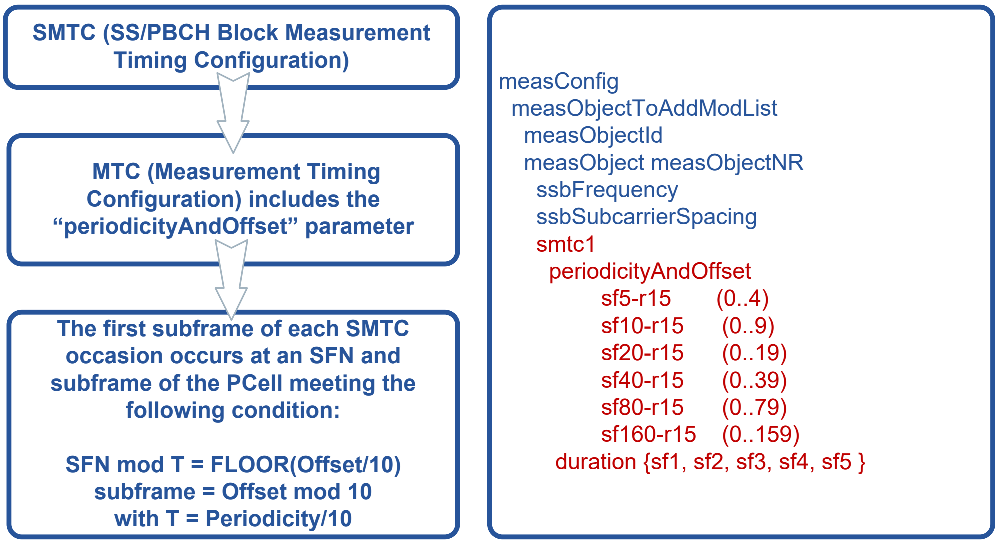


Figure 14-26 NR Measurement Timing Configuration

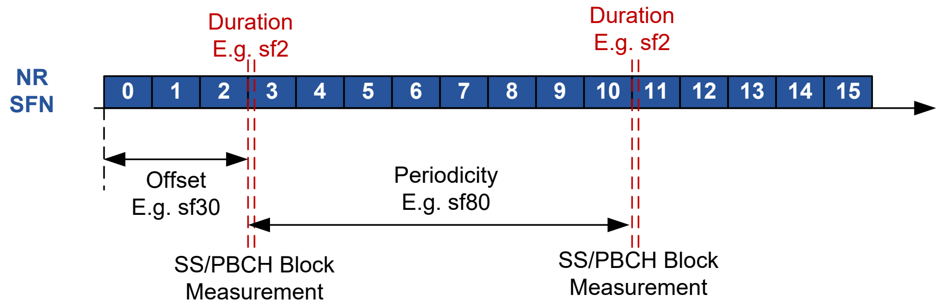


Figure 14-27 Example of SMTC

14.3 NR Measurement Gap Configuration

Whether a measurement is non-gap-assisted or gap-assisted depends on the capability of the device, the active BWP and the current operating frequency.

14.3.1 SSB Based Inter-Frequency Measurements

For SSB based inter-frequency, a measurement gap configuration is always provided in the following cases:

- If the device only supports per-UE measurement gaps.
- If the device supports per-FR measurement gaps and any of the configured BWP frequencies of any of the serving cells are in the same frequency range of the measurement object.

14.3.2 SSB Based Intra-Frequency Measurements

For SSB based intra-frequency measurements, a measurement gap configuration is always provided in the following case:

- Other than the initial BWP, if any of the device configured BWPs do not contain the frequency domain resources of the SSB associated to the initial DL BWP.

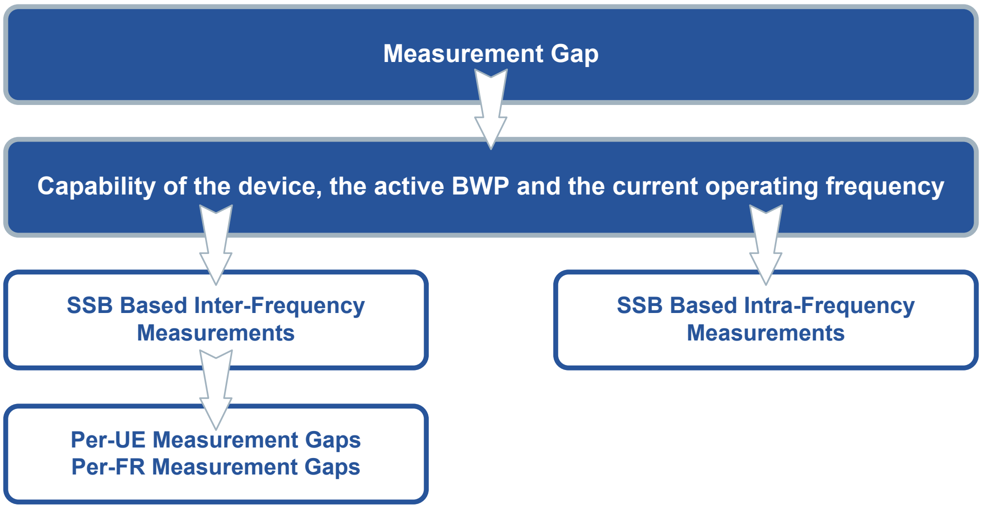


Figure 14-28 Measurement Gap Configuration

Non-Gap Assisted Scenarios

In non-gap-assisted scenarios, the device is able to carry out such measurements without measurement gaps.

14.3.3 Gap Pattern Parameters

The measurement gap configuration parameter indicates the gap pattern(s) in accordance with the received gapOffset parameter. Each gap starts at a SFN (System Frame Number) and subframe meeting the following condition:

SFN mod T = FLOOR(gapOffset/10)

Subframe = gapOffset mod 10

Where: T = MGRP/10

The MGRP (Measurement Gap Repetition Period) is defined in ms.

Figure 14-29 illustrates the E-UTRA and NR Gap pattern configurations. It includes various combinations of MGL (Measurement GAP Length) and MGRP.

Gap Pattern Id	Measurement Gap Length (MGL, ms)	Measurement Gap Repetition Period (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
8	4	80
9	4	160
10	3	20
11	3	160

Gap Pattern Id	Measurement Gap Length (MGL, ms)	Measurement Gap Repetition Period (MGRP, ms)
12	5.5	20
13	5.5	40
14	5.5	80
15	5.5	160
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

Figure 14-29 E-UTRAN and NR Gap Pattern Configurations

Note that 3GPP TS 38.133 includes various applicable pattern id's for different combinations of FR1 and FR2, as well as E-UTRA.

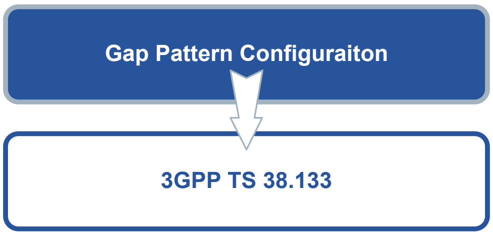


Figure 14-30 Specific Gap Pattern Configuration

14.3.4 EN-DC Measurement Gap

If the system is using a FR (Frequency Range) specific Gap, it will be required to configure them independently. Note that the FR1 Gap is configured by the E-UTRA RRC and provided to the en-gNB, whereas the FR2 Gap is part of NR RRC and will be passed to the device in a NR RRC Reconfiguration message.

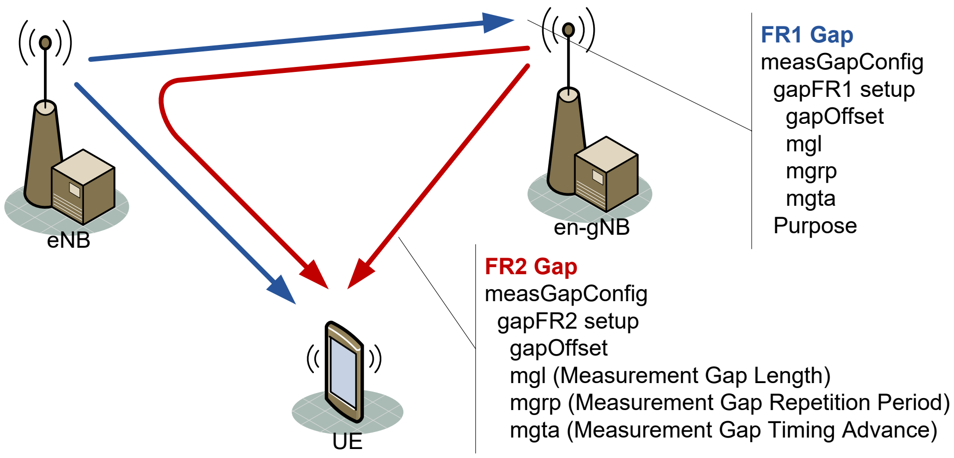


Figure 14-31 EN-DC Measurement Gap Configuration

15 5G Carrier Aggregation

15.1 NR Carrier Aggregation

15.1.1 Component Carriers

In NR CA (Carrier Aggregation), two or more CC (Component Carriers) are aggregated. A device may simultaneously receive or transmit on one or multiple CCs depending on its capabilities. CA is supported for both contiguous and non-contiguous CCs. When CA is deployed frame timing and SFN are aligned across cells that can be aggregated, with the maximum number of configured CCs for a device being theoretically 16 for DL (Downlink) and 16 for UL (Uplink). However, a device and/or gNB may restrict this due its capabilities.

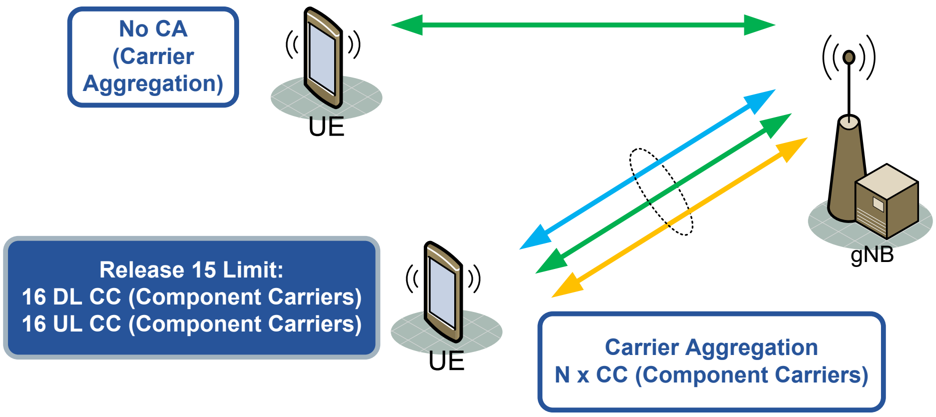


Figure 15-1 NR Carrier Aggregation

15.1.2 Contiguous and Non-Contiguous CA

Like LTE, NR supports contiguous and non-contiguous CA. This concept is illustrated in Figure 15-2, using 3 CC's as an example.

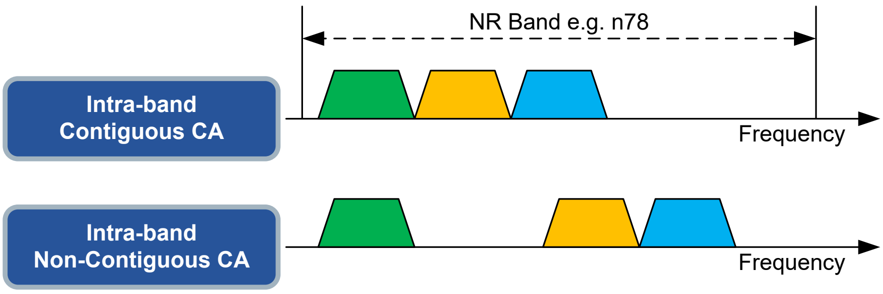


Figure 15-2 Contiguous and Non-Contiguous CA

15.1.3 Intra-Band and Inter-Band CA

There are various options of carrier aggregation utilizing either the same frequency band (intra-band), or as illustrated in Figure 15-3, component carriers from different bands, ie. inter-band. Note that not all band combinations are supported and initially Release 15 NR is quite limited.

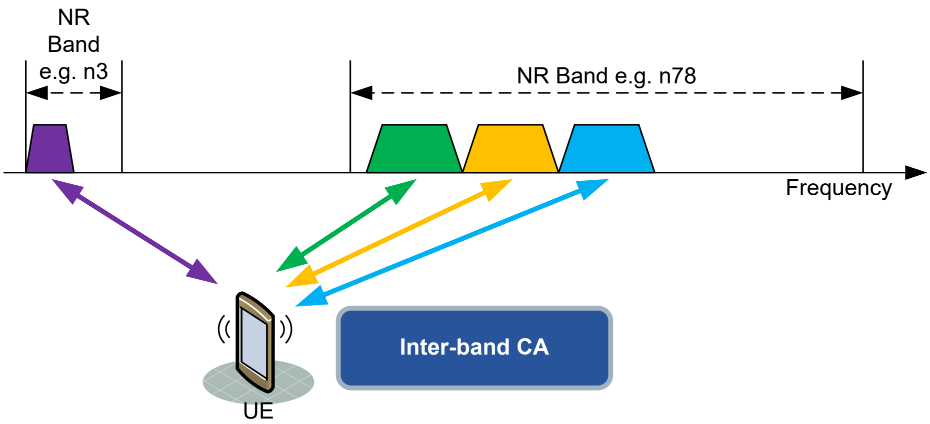


Figure 15-3 Inter-Band CA

15.1.4 PCell and SCell

The gNB must define one of the CC's as the PCell (Primary Cell), the rest are defined as SCell (Secondary Cells). However, as part of DC (Dual Connectivity), the term PSCell (Primary Secondary Cell) is also used to define the Primary SCell on a secondary RAN node.

Figure 15-4 illustrates an example whereby two devices are operating in carrier aggregation in a NR band, however they have different PCells, as well as the fact device "A" is currently operating with a non-contiguous assignment.

Like LTE, the gNB is able to change the CC's currently assigned via a combination of RRC (Radio Resource Control) signalling and MAC (Medium Access Control) scheduling. This may be as a result of buffer/loading, or related to other factors such as Quality, Mobility, inactivity or lack of uplink power i.e. PH (Power Headroom).

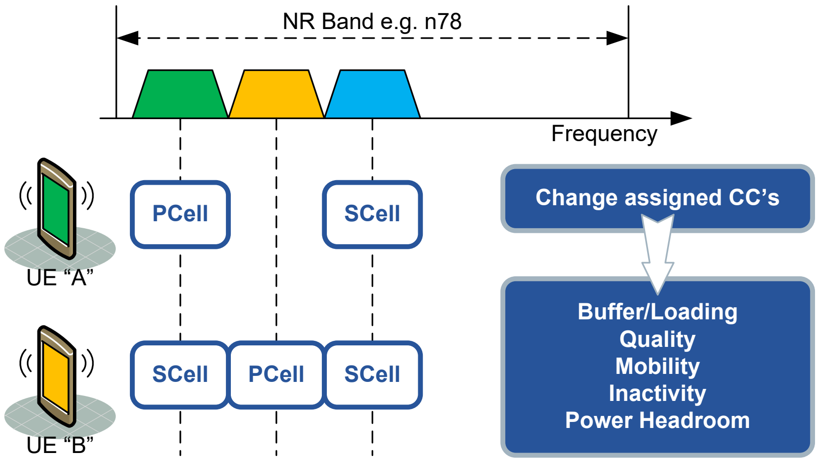


Figure 15-4 PCell and SCell(s)

The gNB vendor will also keep track of the current allocation of devices on each CC to ensure that the loading is managed.

15.1.5 Downlink and Uplink Carrier Aggregation

When defining Component Carriers for a device, the gNB is able to configure both the downlink CC and the uplink CC. As such, Figure 15-5 illustrates an example whereby one of the devices has an asymmetrical allocation of CC's.

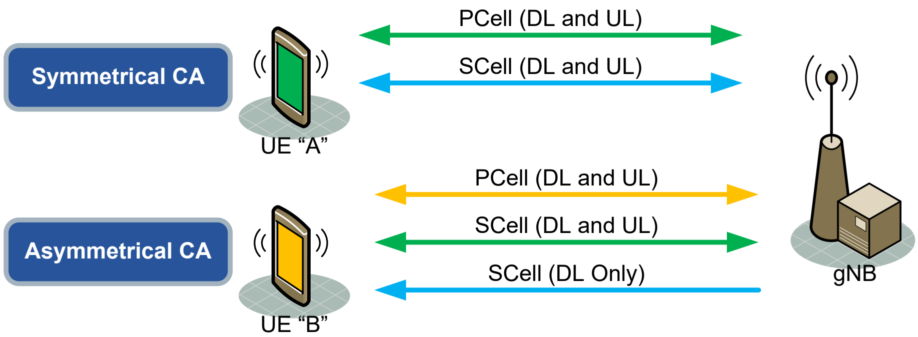


Figure 15-5 DL and UL Carrier Aggregation

15.1.6 Carrier Allocation Specifications

The 3GPP specifications define various capabilities for carrier aggregation, with the main specification identified in Figure 15-6.

Figure 15-6 NR CA Capabilities

15.2 Configuring NR Carrier Aggregation

A gNB vendor typically has different methods for activation and deactivation of the SCells. Figure 15-7 illustrates example methods.

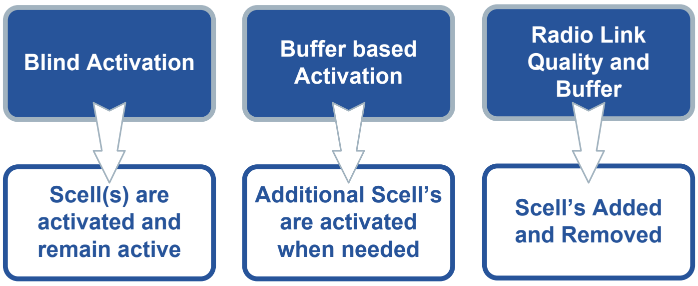


Figure 15-7 CA SCell Activation Options

15.2.1 Buffer Based SCell Activation

The gNB vendor is able to implement various buffer based SCell activation and deactivation methods. Figure 15-8 illustrates a basic concept whereby the buffer level triggers the activation of another SCell. Note that various timers, as well as other monitoring triggers, may be applied before the SCell is activated and deactivated.

In addition, if DC (Dual Connectivity) is active, additional methods and rules may be utilized.

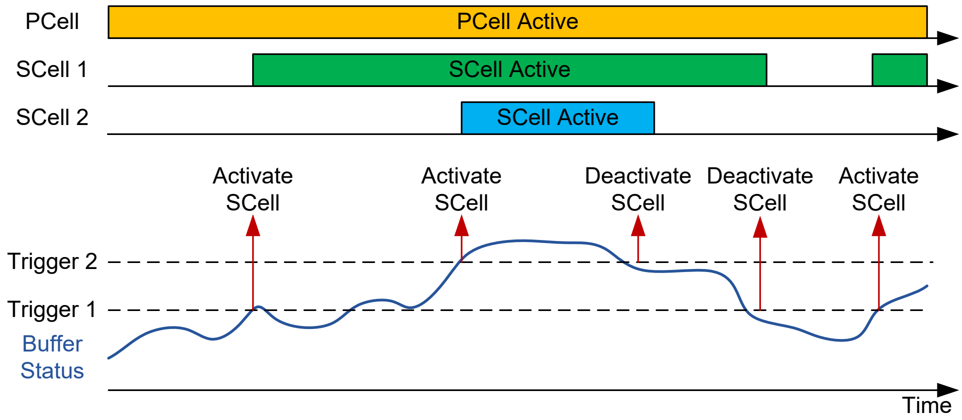


Figure 15-8 SCell Activation and Deactivation

15.2.2 Configuring CA SCells

Figure 15-9 illustrates two SCells being configured by the NR RRC Reconfiguration message. Note that each SCell is given an index (1 to 31). For each SCell the gNB can include both common and dedicated configuration information, e.g PCI, Downlink and Uplink BWP, etc.

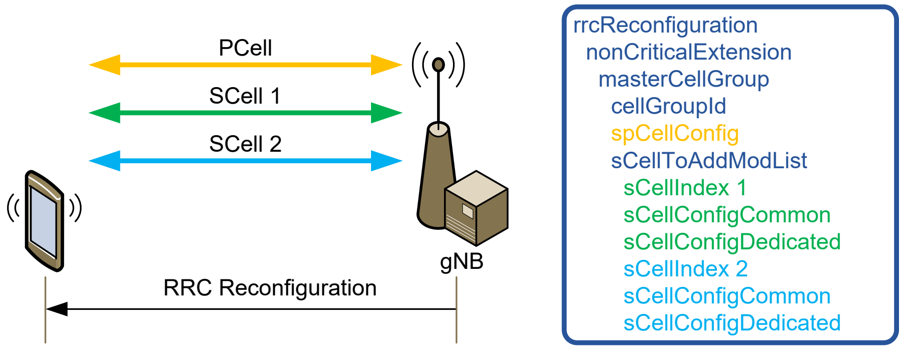
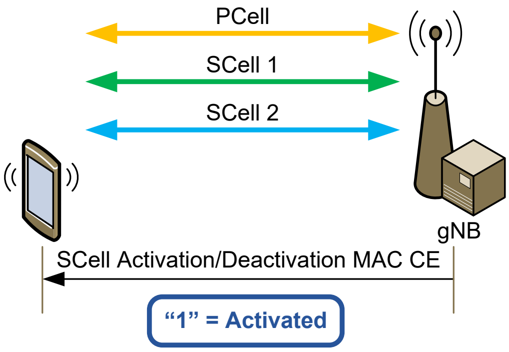


Figure 15-9 Configuring CA SCells

Note that on configuration of the SCell by RRC it is “deactivated”. As such, it needs to be activated by MAC (Medium Access Control).

15.2.3 MAC CA Activation

A key part of MAC operation relates to the passing of control information, with each being identified as a CE (Control Element). There are many CEs, however for CA there is one specifically related to SCell activation/deactivation.



1 Octet MAC CE

C_7	C_6	C_5	C_4	C_3	C_2	C_1	R	Oct 1

4 Octet MAC CE

C_7	C_6	C_5	C_4	C_3	C_2	C_1	R	Oct 1
C_{15}	C_{14}	C_{13}	C_{12}	C_{11}	C_{10}	C_9	C_8	Oct 2
C_{23}	C_{22}	C_{21}	C_{20}	C_{19}	C_{18}	C_{17}	C_{16}	Oct 3
C_{31}	C_{30}	C_{29}	C_{28}	C_{27}	C_{26}	C_{25}	C_{24}	Oct 4

Figure 15-10 NR MAC Control Elements

15.2.4 MAC Buffer Status and Power Headroom Reports

The gNB will also configure the device to send both the uplink BSR (Buffer Status Report) and PHR (Power Headroom Report). This enables the gNB scheduler to be aware of the requirements for SCell activation/deactivation.

Figure 15-11 illustrates the 4 BSR formats. These enable 1 or more buffer size values to be sent, each buffer size relates to a configured LCG (Logical Channel Group).

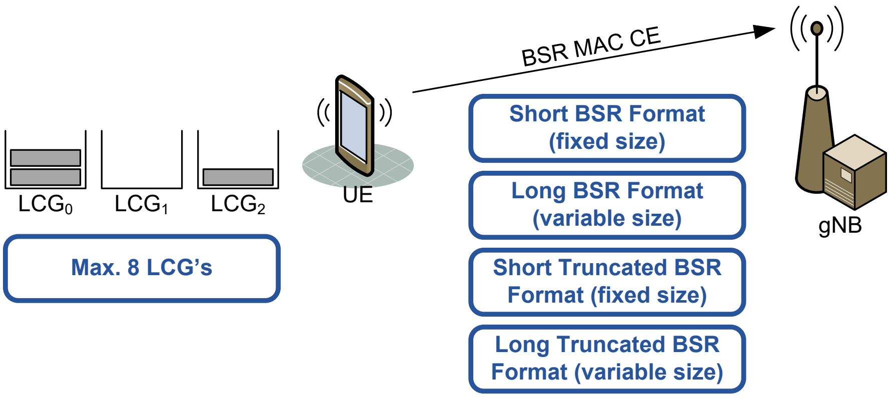


Figure 15-11 MAC BSR CE

In addition to BSRs, the device will also be configured to send PHRs, as illustrated in Figure 9-44, this enables the scheduler to determine ongoing scheduling requirements, which can influence the CA process.

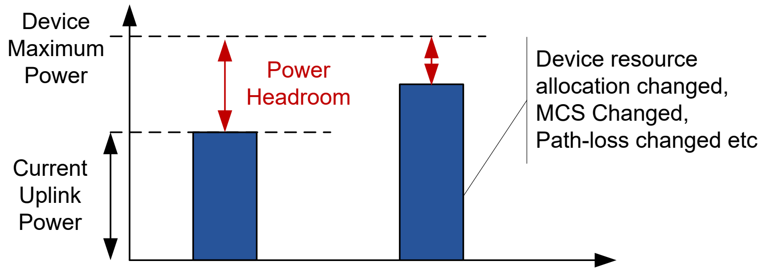


Figure 15-12 Power Headroom Reporting

A PHR (Power Headroom Report) is triggered based on various scenarios, one of which is the activation of a SCell (Secondary Cell) with configured uplink. As such, the device will send a MAC PHR CE which can include various PH (Power Headroom) values. Figure 15-13 illustrates an example of the Multiple Entry PHR MAC CE, it includes PH for the SpCell, PCell and 1 or more Serving Cells, each with the option to include the P_{CMAX}.

C_7	C_6	C_5	C_4	C_3	C_2	C_1	R
P	V	PH (Type 2, SpCell of the other MAC entity)					
R	R	$P_{CMAX,f,c}$ 1					
P	V	PH (Type 1, PCell)					
R	R	$P_{CMAX,f,c}$ 2					
P	V	PH (Type X, Serving Cell 1)					
R	R	$P_{CMAX,f,c}$ 3					
P	V	PH (Type X, Serving Cell n)					
R	R	$P_{CMAX,f,c}$ m					

Figure 15-13 Multiple Entry PHR MAC CE

The “P” bit indicates whether the MAC entity applies power backoff due to power management. In addition, the “V” bit indicates if PH based on real transmission or reference format. Note that Type 1, Type 2 and Type 3, defines what the PH is based on, for example PUSCH, PUCCH or SRS.

15.3 Releasing NR Carrier Aggregation

The scheduler can activate/deactivate a SCell at the MAC layer. However, there will be scenarios when the gNB will also want to completely remove the SCell from a device, i.e. change the RRC configuration.

15.3.1 SCell Release Procedure

Figure 15-14 illustrates an example with a PCell and two SCell’s active. Prior to removing the SCell at the RRC level the MAC layer can send a MAC CE to deactivate it. The actual removal from the RRC configuration is achieved by sending a NR RRC Reconfiguration message which includes the SCell Index as part of the “sCellToReleaseList” parameter. In response, the device confirms the configuration by sending the NR RRC Reconfiguration Complete message.

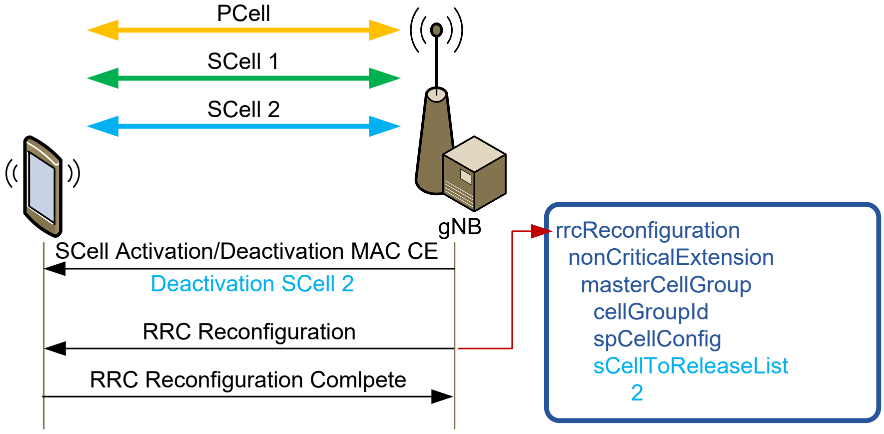


Figure 15-14 SCell Release Procedure

16 5G Dual Connectivity

16.1 NR Dual-Connectivity

16.1.1 Concept and Terminology

DC (Dual Connectivity) is used when a device consumes radio resources provided by at least two different network access points. In addition, each network access point involved in dual connectivity for a device may assume different roles.

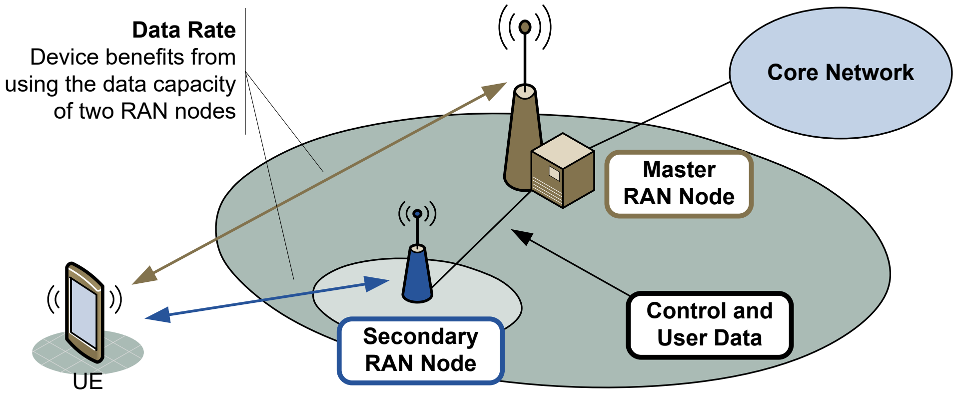


Figure 16-1 Dual Connectivity Concept

Terminology for Dual Connectivity includes:

- Dual Connectivity - is the operation where a device consumes radio resources provided by at least two different network points (Master and Secondary) connected with non-ideal backhaul while in the RRC (Radio Resource Control) Connected state.
- Master RAN Node - terminates the core network control/signalling connectivity and therefore acts as the mobility anchor towards the core network.
- Secondary RAN Node - in dual connectivity mode, this could be a gNB or ng-eNB. It provides additional radio resources to the device.
- MCG (Master Cell Group) - is the group of the serving cells associated with the Master RAN Node.
- SCG (Secondary Cell Group) - is the group of serving cells associated with the Secondary RAN Node.
- Split Bearer - in dual connectivity, this term refers to the ability to split a bearer over multiple RAN Nodes.

16.1.2 New Radio Dual Connectivity

Figure 1-6 illustrates an example of Dual Connectivity between two gNBs, namely NR-DC (New Radio Dual Connectivity).

In this case, one of the cells is a small cell, however it could equally be a second capacity layer or a higher macro coverage layer.

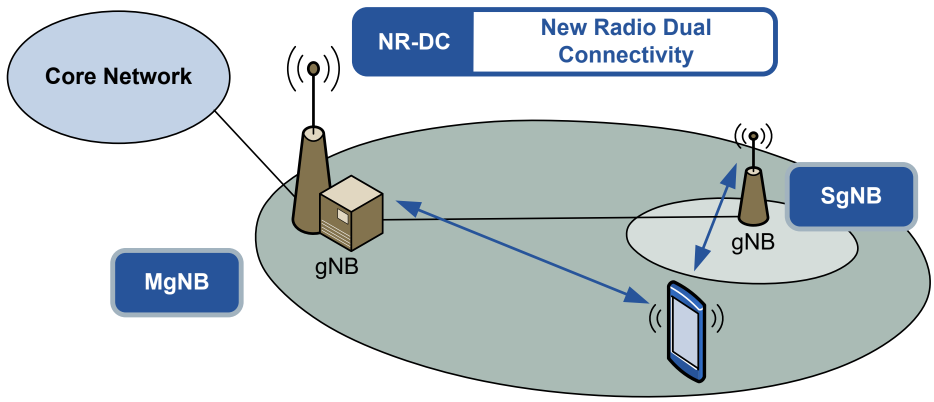


Figure 16-2 NR Dual Connectivity Options

16.2 NR-DC Operation

16.2.1 NR-DC Secondary Node Addition

Once the device is connected to NR via the MgNB, it may be configured to monitor neighbour cells for the purpose of dual connectivity. The signalling flow associated with this process is outlined in Figure 16-3, whereby the device will trigger a measurement report based on the MgNB measurement configuration. As the device indicates a suitable cell via a Measurement Report message, the MgNB is able to trigger the S-Node (Secondary Node) Addition procedure.

The XnAP (Xn Application Part) messages are able to "piggyback" parameters, as well as complete NR RRC messages between the MgNB and SgNB. These are located within containers which include "CGConfigInfo" and "CGConfig" parameters from the MgNB and SgNB respectively.

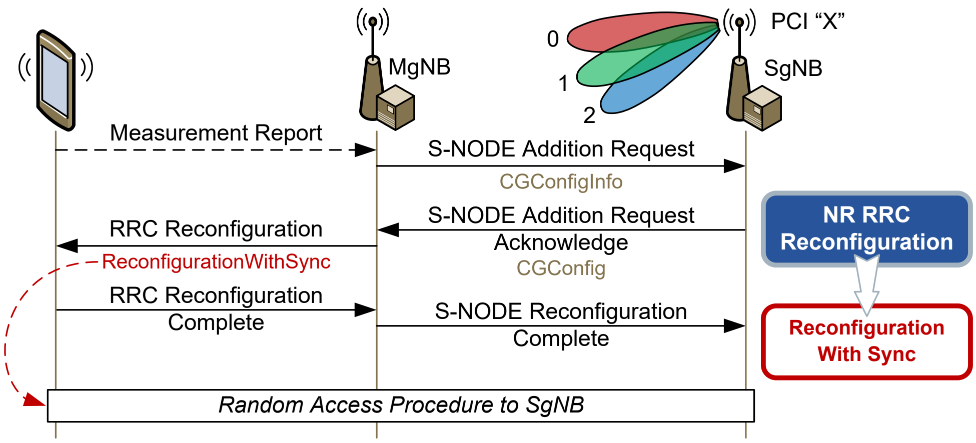


Figure 16-3 NR Secondary Node Addition

During the SgNB addition procedure, the SgNB will send via the MgNB a NR RRC Reconfiguration to the device is ReconfigurationWithSync. Figure 16-4 illustrates an example NR RRC Reconfiguration message which included the Secondary Cell Group parameter. In so doing, the device is allocated a C-RNTI (Cell-RNTI) for the SgNB, as well as all the necessary uplink and downlink configuration information.

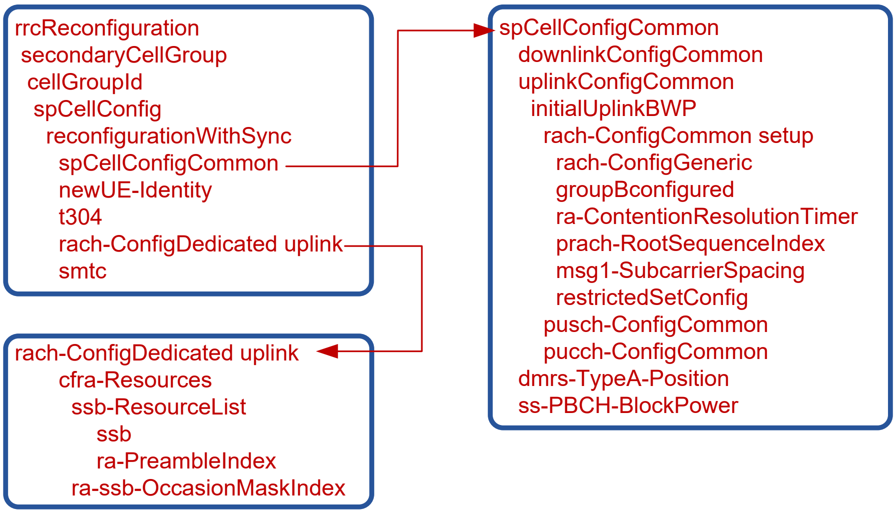


Figure 16-4 NR ReconfigurationWithSync Parameter

Utilizing the RACH parameters, including the CFRA (Contention Free Random Access) resources, the device is able to access the SgNB. Note that other parameters relating to the Initial BWP (Bandwidth Part) will enable the device to start listening to scheduling messages on the SgNB.

16.2.2 Determining the Bearer Configuration

There are a number of bearer configurations that are available for the operation of a PDU Session/QoS Flow; these are MCG Bearer, MCG Split Bearer, SCG Bearer or SCG Split Bearer. The choice of configuration is made at the MgNB and the contents of the S-Node Addition Request will ensure the correct configuration is applied at the SgNB.

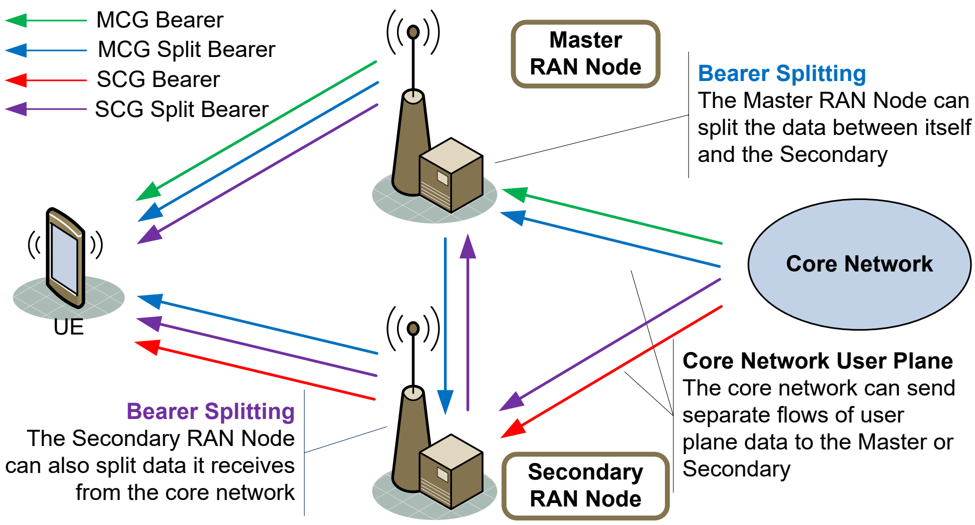


Figure 16-5 Bearer Configuration

Figure 16-6 illustrates the key parameters in the NR RRC Reconfiguration message which inform the device about the bearer configuration for each DRB (Dedicated Radio Bearer). The PDCP (Packet Data Convergence Protocol) configuration parameter is nested in the Radio Bearer Config parameter. This configures PDCP, as well as indicating if “moreThanOneRLC” is present. The device also needs to look specifically at the RLC (Radio Link Control) Bearer Configuration parameter, which is included in the Master Cell

Group and Secondary Cell Group parameters. This specifically enables QoS Flows and the mapped DRB to be scheduled.

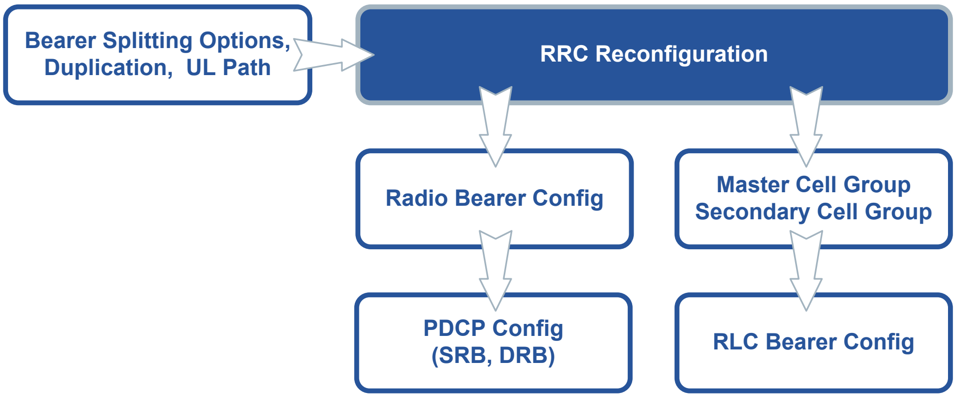


Figure 16-6 Configuring Bearer Options

16.3 NR Dual Connectivity Mobility

When Dual Connectivity is in operation, the Master RAN node will be conducting handovers to other Master RAN nodes based on Xn or N2 handover procedures. However, there will also be a requirement to conduct handovers between Secondary RAN nodes. For this, the correct terminology is a “change of Secondary Node”.

16.3.1 Change of Secondary Node

The procedure associated with a 5G based change of Secondary Node is outlined in Figure 16-7 and Figure 16-8. The procedure is triggered by the SgNB (Secondary gNB) in this case, although it is possible that the MgNB (Master gNB) could also trigger the procedure (the only difference between the procedure is that with the former, the SN Change Required message is sent from the SgNB as a trigger). It should be noted that Figure 16-7 and Figure 16-8 are related to a SCG (Secondary Cell Group) Bearer approach, whereby the UPF is sending data directly to the SgNB.

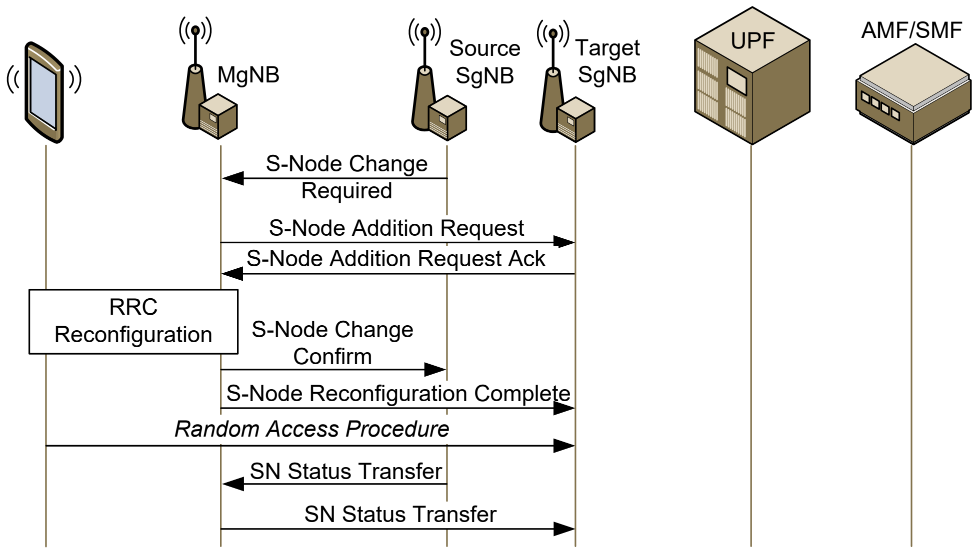


Figure 16-7 Change of Secondary Node (Part 1)

In Figure 16-7, the procedure begins with the Source SgNB sending the SN Change Required message to the MgNB. This message will identify the target cell or target SgNB ID and may also contain measurement results.

On the basis of receiving the SN Change Required message, the MgNB will contact the Target SgNB with the SN Addition Request message. This message will detail the PDU sessions and QoS flows which must be supported and may also request the establishment of a forwarding tunnel. Assuming the request is accepted, the Target SgNB will respond with an acknowledgement, identifying all of the PDU sessions and QoS flows which will be supported and also supplying a tunnel endpoint and IP address for data forwarding.

At this stage, the MgNB will direct the device to the Target SgNB through the RRC Reconfiguration procedure. In addition, the MgNB will notify the Source SgNB and the Target SgNB that the secondary node has been reconfigured. When the SN Change Confirm message is sent to the Source SgNB as part of this process, the MgNB data forwarding tunnel information can be provided. It is possible at this stage that the Source SgNB will supply its PDCP (Packet Data Convergence Protocol) sequence numbering for the uplink and downlink. This is achieved by sending the SN Status Transfer message to the Target SgNB via the MgNB.

In part 2 (Figure 16-8), the procedure continues with the device synchronized to the Target SgNB. At this stage, data forwarding may be in operation, as highlighted in Figure 16-8.

Due to the fact that split bearer is in operation, the MgNB will initiate a PDU Session Modification procedure, which will essentially redirect the user plane traffic away from the old SgNB and towards the new SgNB. Note that this will require interaction between the AMF and the SMF, which is not shown in Figure 16-8. Once the new path is established, resources which may still be in place at the old SgNB can be torn down using the UE Context Release message.

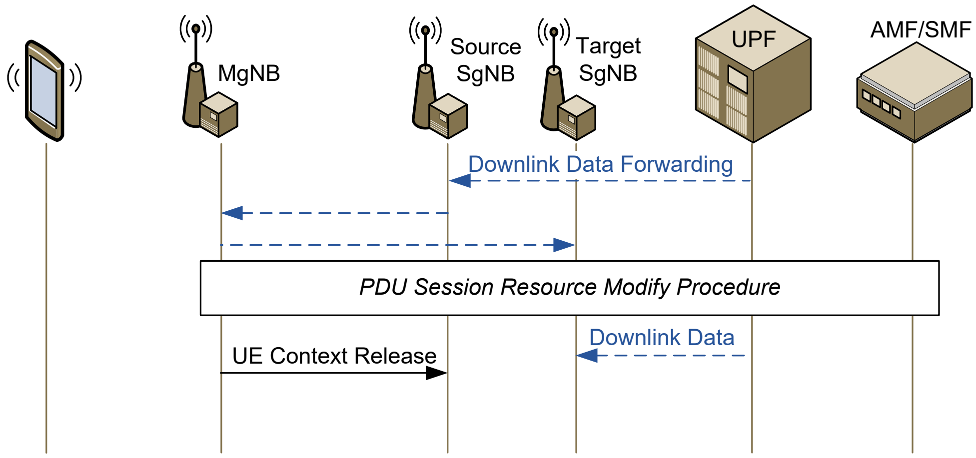


Figure 16-8 Change of Secondary Node (Part 2)

16.4 NR-DC Secondary Node Release

The decision to release a secondary node is made by the MgNB. However, the trigger is typically related to measurements from the device. As such, the MgNB and SgNB will configure either periodic or event based measurements.

As an example of event based, the NR Event A2 triggers the device to send a measurement report if the quantities (signal level, quality etc.) fall below a specific threshold.

Note that Secondary Node Release can also be triggered by the SgNB, e.g. uplink NR measurements. However, it would still need to notify the MgNB.

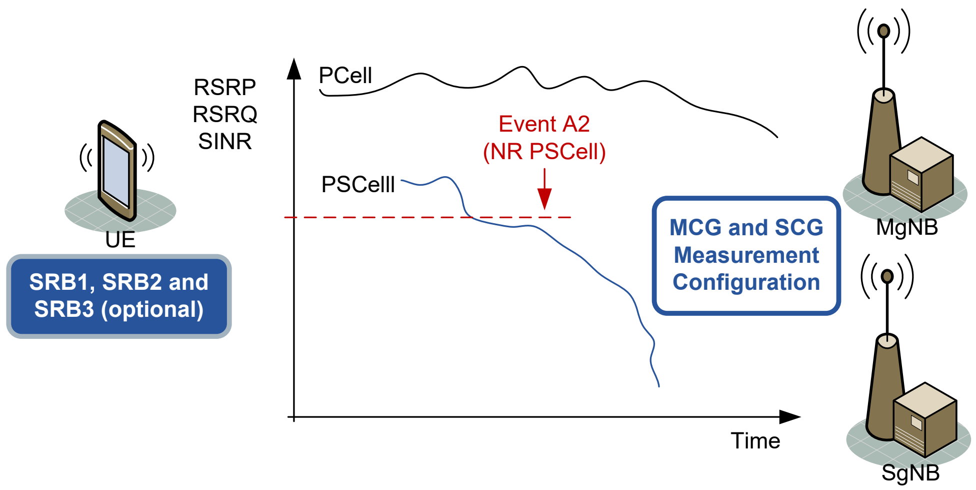


Figure 16-9 NR Event A2

Ultimately, if a secondary node is to be released, any user plane traffic handling responsibilities must be relinquished; all SCG and SCG Split Bearers must be redirected towards the MgNB and the device must be informed that the secondary node is no longer in use. Figure 11-33 outlines the procedure, whereby the SgNB is the initiating node. In this example the trigger was a Measurement Report message received from the device, however other triggers at the MgNB/SgNB may also occur, e.g. the uplink connection performance to the SgNB. Note that it is also possible for the MgNB to release the SgNB.

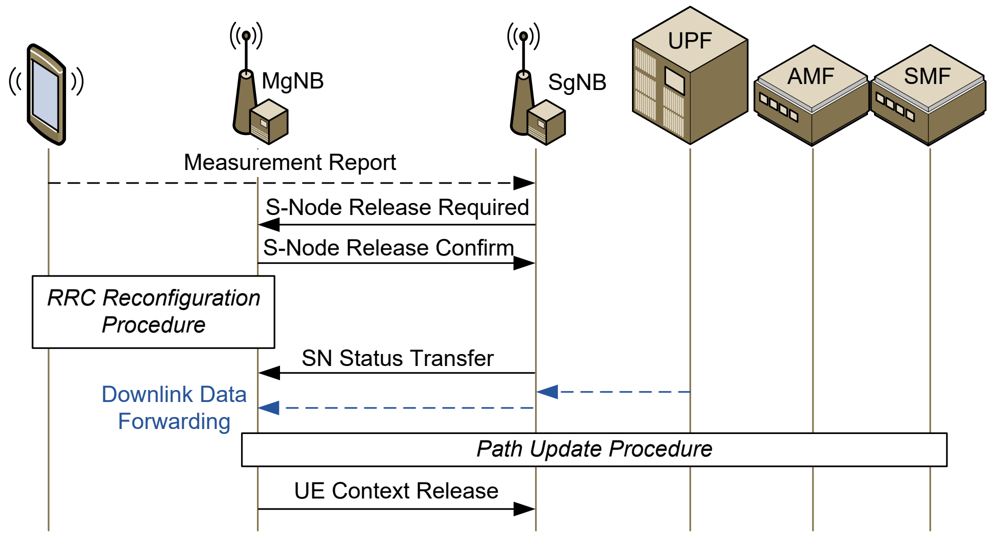


Figure 16-10 SgNB Release of Secondary Node

In Figure 11-33, receiving a Measurement Report triggered the exchange of the XnAP S-Node Release Required and S-Node Release Confirm messages. It is possible that some of the QoS Flows are configured for SCG Bearer / SCG Split Bearer operation and as such, the MgNB may request that data forwarding takes place until the release procedure concludes and the data path is updated. As such, the S-Node Release Confirm message may contain tunnel forwarding information.

Next, the MgNB will conduct the RRC Reconfiguration procedure with the device, essentially to trigger the device into releasing the entire SCG configuration that it currently has.

17 5G Mobility

17.1 NR Idle Mode Mobility

Mobility in NR will be dependent on a device's capability, network configuration and current RRC state. Like LTE, the main mobility scenarios relate to cell selection, cell reselection and handover. In addition, there is also the ability to perform redirection, i.e. indicate to the device to perform an inter-RAT (Radio Access Technology) cell reselection to E-UTRA.

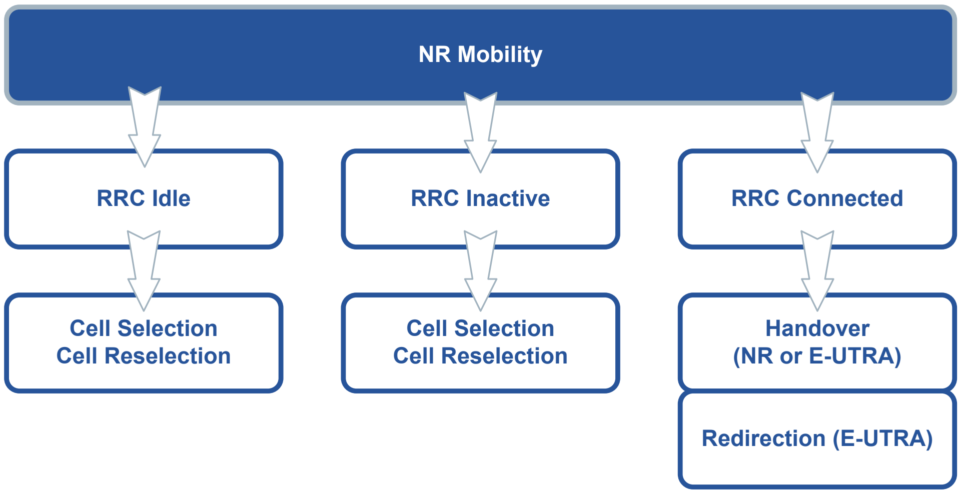


Figure 17-1 NR Mobility Options

17.1.1 Multi-Beam Measurement Quantity

Whilst in the RRC Idle and RRC Inactive states a NR device performs cell selection and reselection measurements. In so doing, it is able to evaluate which is the best cell.

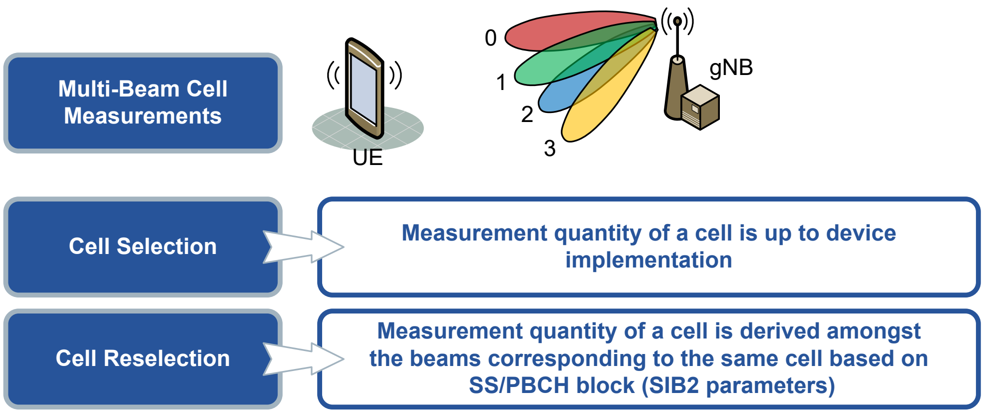


Figure 17-2 Multi-Beam Cell Measurements

Since NR is designed in the majority of cases to utilize multi-beam the device needs to evaluate the measurement quantity. For cell selection in multi-beam operations, measurement quantity of a cell is up to device implementation. However, for cell reselection (in multi-beam operations), the measurement quantity of this cell is derived amongst the beams corresponding to the same cell based on SS/PBCH block. Typically, this involves the highest beam measurement quantity value. However, various parameters in SIB2 (System Information Block 2), such as "nrofSS-BlocksToAverage", "absThreshSS-BlocksConsolidation" and "absThreshSS-BlocksConsolidation" may influence this.

17.1.2 NR Cell Reselection

Whilst in the RRC Idle mode the device will regularly search for a better cell. This change of cell may also imply a change of RAT.

It is worth noting that the reselection parameters in NR are typical based on RSRP (Reference Signal Received Power). Whereas cell selection includes a criterion for RSRP and RSRQ (Reference Signal Received Quality).

Ranking of Cells and Equal Priority Reselections

The cell reselection evaluation process and associated criterion includes the cell ranking "R". This is used for reselection towards intra-frequency cells. Note that the absolute priority for inter-frequency and inter-RAT cells is applied first.

$$R_s = Q_{meas,s} + Q_{hyst} - Qoffset_{temp}$$

$$R_n = Q_{meas,n} - Q_{offset} - Qoffset_{temp}$$

Figure 17-3 Cell Ranking

Where:

- Qmeas - this is the RSRP (Reference Signal Received Power).
- $Qhyst_s$ - this specifies the hysteresis value for ranking criteria.
- Qoffset - this is different for intra and inter frequency options:
    - intra-frequency: Equal to $Qoffset_{s,n}$, if $Qoffset_{s,n}$ is valid, otherwise this equals to zero.
    - inter-frequency: Equal to $Qoffset_{s,n}$ plus $Qoffset_{frequency}$, if $Qoffset_{s,n}$ is valid, otherwise this equals to $Qoffset_{frequency}$.

In all cases, the device reselects the new cell, only if the following conditions are met:

- The new cell is better ranked than the serving cell during a time interval $Treselection_{RAT}$.
- More than 1 second has elapsed since the device camped on the current serving cell.

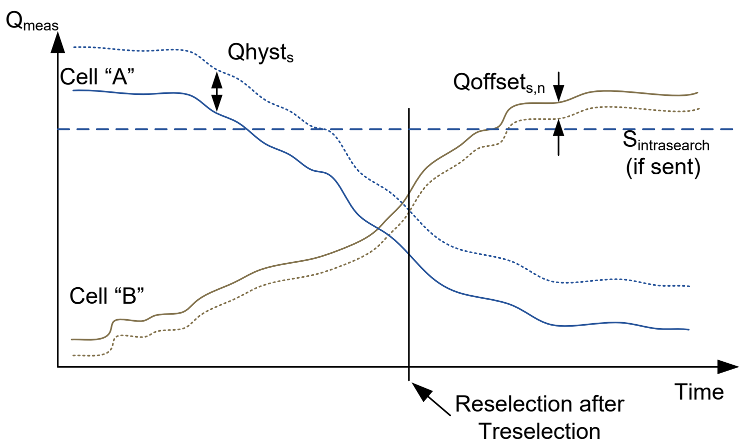


Figure 17-4 NR Reselection

17.1.3 Priority Based Inter-RAT Cell Reselection

NR, like LTE, includes priority mechanisms for Inter-Frequency and Inter-RAT operation. In so doing, absolute priorities of different NR frequencies or inter-RAT frequencies may be provided to the device in:

- System Information.
- RRC Release message.
- Inherited from another RAT at inter-RAT cell (re)selection.
- The priority parameter ranges from 0 to 7 (0 is the lowest).

It is also worth noting that in the case of system information, a NR frequency or inter-RAT frequency may be listed without providing a priority, i.e. the field "cellReselectionPriority" is absent.

There are various aspects to the priorities, more detail can be found in 3GPP 38.304 "User Equipment (UE) procedures in idle mode and RRC Inactive state".

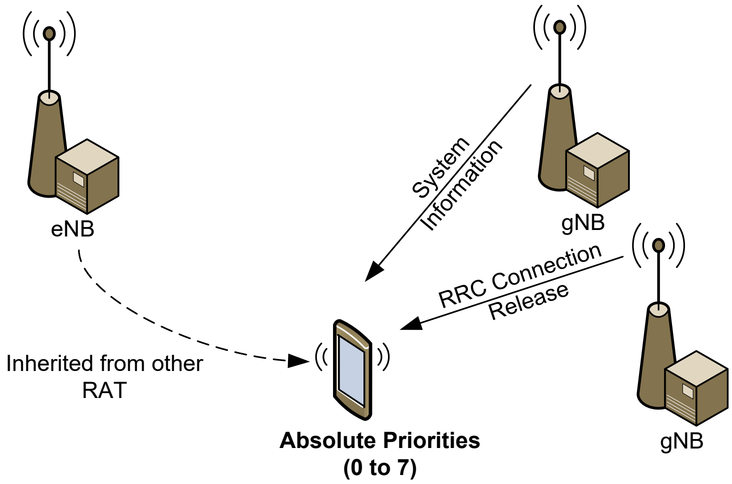


Figure 17-5 Absolute Priorities

17.1.4 NR System Information Messages

The specific cell priority parameter is included in various NR System Information Blocks, as illustrated in Figure 17-6.

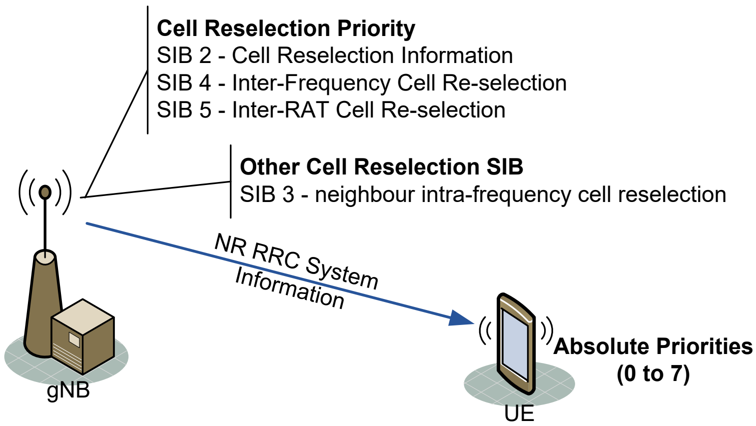


Figure 17-6 Location of Cell Reselection Priority Parameter

17.1.5 Reselection to a Higher Priority Frequency or RAT Cell

When a device detects a higher priority RAT cell it will reselect to that cell if the relevant threshold, $Thresh_{X,HighQ}$ or $Thresh_{X,HighP}$, is exceeded.

Figure 17-7 illustrates the concept of higher priority RAT cell reselection. In this example, the serving cell level is good however the higher priority RAT cell (NR Cell) has met the criteria, i.e. the signal has exceeded the $Thresh_{X,HighQ}$ or $Thresh_{X,HighP}$.

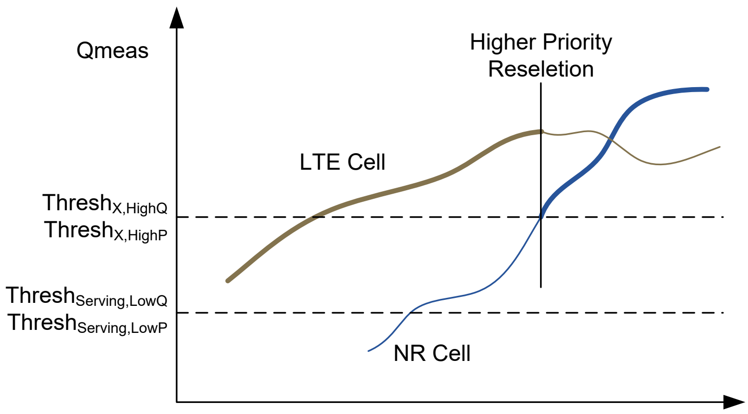


Figure 17-7 Example of the Higher Priority RAT Cell Reselection to NR

17.1.6 Reselection to a Lower Priority Frequency or RAT Cell

The specifications also enable reselection to a lower priority RAT cell.

Figure 17-8 illustrates the basic concept whereby the serving NR cell has dropped below the $Thresh_{Serving,LowP}$ or $Thresh_{Serving,LowQ}$ level and the lower priority cell (LTE Cell) has exceeded the $Thresh_{X,LowQ}$ or $Thresh_{X,LowP}$ threshold.

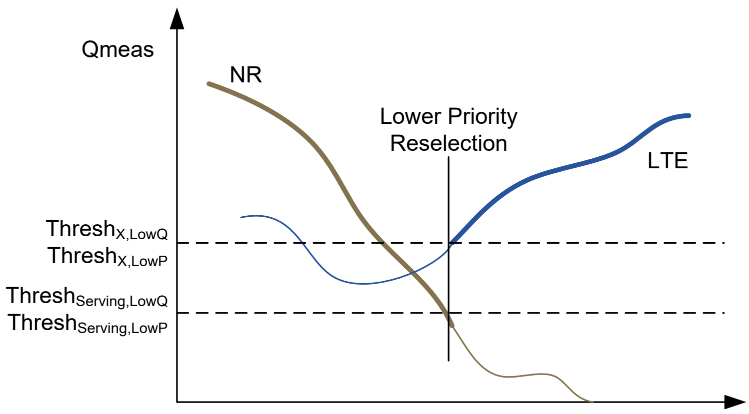


Figure 17-8 Example of the Lower Priority RAT Cell Reselection from NR

17.1.7 Deleting NR Priorities

The device deletes priorities provided by dedicated signalling when:

- The device enters a different RRC state.
- The optional validity time of dedicated priorities (T320) expires.
- A PLMN selection is performed on request by NAS.

17.1.8 Registration Area Update

When in CM Idle mode, the Registration Area Update is designed to keep the network informed as to the location of the device, down to the granularity of a TA (Tracking Area). There are numerous reasons why a Registration Area Update is carried out, such as the procedure being performed periodically, as a result of the device moving into the coverage of a new Tracking Area or due to entering the 5G cell having previously been attached to the 4G network (see Figure 17-9). In addition, the network will also be notified of the device's Tracking Area at any point at which the device moves into a CM Connected state, such as during registration or as part of a Service Request procedure.

Figure 17-9 Triggers for the Registration Update

Figure 17-11 shows the Registration Area Update procedure in which the device is already in a RM Registered state. In this particular example, the device in CM Idle mode has detected that it has moved to a new Tracking Area by decoding the TAI (Tracking Area Identity) broadcast on the serving cell that it has just camped on (as part of cell reselection). Assuming that the TAI is not on the TAI list for the device, the device will initiate an RRC connection to the cell so that it can send the NAS Registration Request to the AMF.

The Registration Request message includes:

- 5G GUTI (Globally Unique Temporary Identity) - the GUTI has two main components; these are the part that uniquely identifies the AMF which allocated the 5G GUTI and the part that uniquely identifies the device within the AMF that allocated the GUTI.
- Registration Type - in the case of Figure 17-11, this will be a Mobility Registration Update. For periodical updates, the type would be Periodic Registration Update.
- PDU Session Status - this lists the PDU Sessions that the device believes currently are active.
- PDU Sessions to be Reactivated - this indicates to the AMF that the device requires active radio resources for one or more PDU Sessions (this would mean a Service Request would not need to be sent immediately after the Registration Area Update).

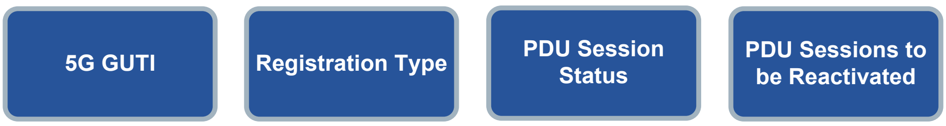


Figure 17-10 Components of the Registration Request (Mobility)

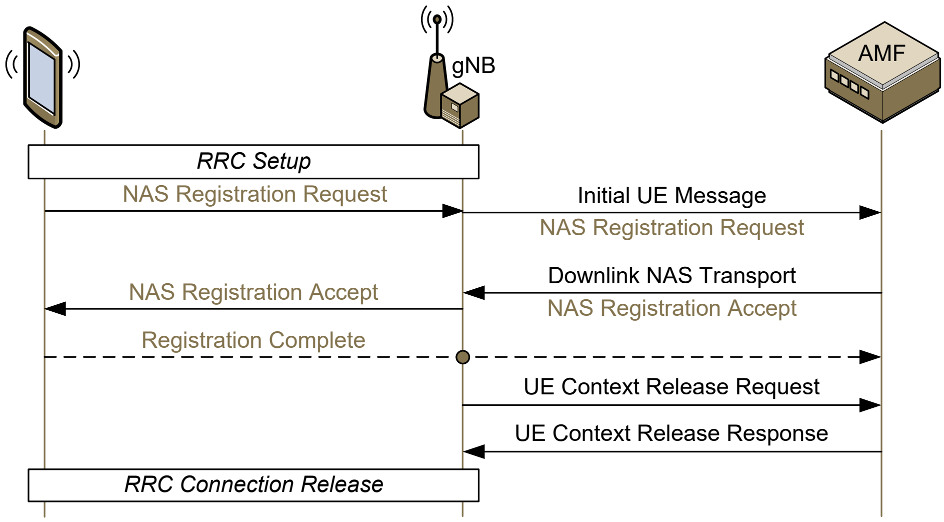


Figure 17-11 Registration Update Procedure (Mobility)

The gNB derives the AMF from the 5G-S-TMSI obtained during the RRC Connection Establishment and forwards the NAS message along with the Cell ID and TAI to the respective AMF. This NAS-MM (Mobility Management) message, viewed as NAS (Non Access Stratum) information by the gNB, is forwarded using RRC (Radio Resource Control) between the device and the gNB and using NGAP between the gNB and the AMF.

Upon receipt of the Registration Request, the AMF will record the current TAI for the device (if necessary, the TAI list may need to be updated). The procedure would then conclude with the AMF sending the Registration Accept, which would include the new TAI List if applicable. It is also possible that the AMF allocates a new GUTI. If this is the case, the device must confirm receipt of the new GUTI using the Registration Complete message. Following this, the UE Context information at the gNB, as well as the RRC connection, can be torn down (assuming a User Plane data session is not required).

17.2 Xn Based Handover

NR supports both Xn and N2 based handovers, however the device is unaware since it received a NR RRC Reconfiguration message which include the new Master Cell Group parameter with the “reconfigurationWithSync” included, i.e. indicating the resources and methodology for accessing the target cell.

17.2.1 Handover Procedure

Figure 17-12 outlines the process of an Xn Handover procedure. The handover process starts when, upon analysis of the measurement report sent by the device, the Source gNB issues a XnAP (Xn Application Protocol) Handover Request message to the Target gNB. This includes the necessary information to prepare the handover at the Target gNB, such as the identity of the AMF serving the device, the Target cell ID, security keys, UE and RRC Context information, PDU Session information and associated QoS Flow information.

Admission Control may be performed by the Target gNB (which is dependent upon the received PDU Session QoS Flow information) to increase the likelihood of a successful handover. If the resources can be granted, the Target gNB reserves the required cell resources. Generally, restrictions will occur if the Target Cell is heavily congested and the subscriber has a number of GBR (Guaranteed Bit Rate) QoS Flows which must be supported. That said, there may be other reasons as to why a Handover Request may not be accepted. Once the Target gNB has prepared, it sends the Handover Request Acknowledge message to the Source gNB. This message includes a transparent container (CG-Config) which carriers the NR RRC Reconfiguration message.

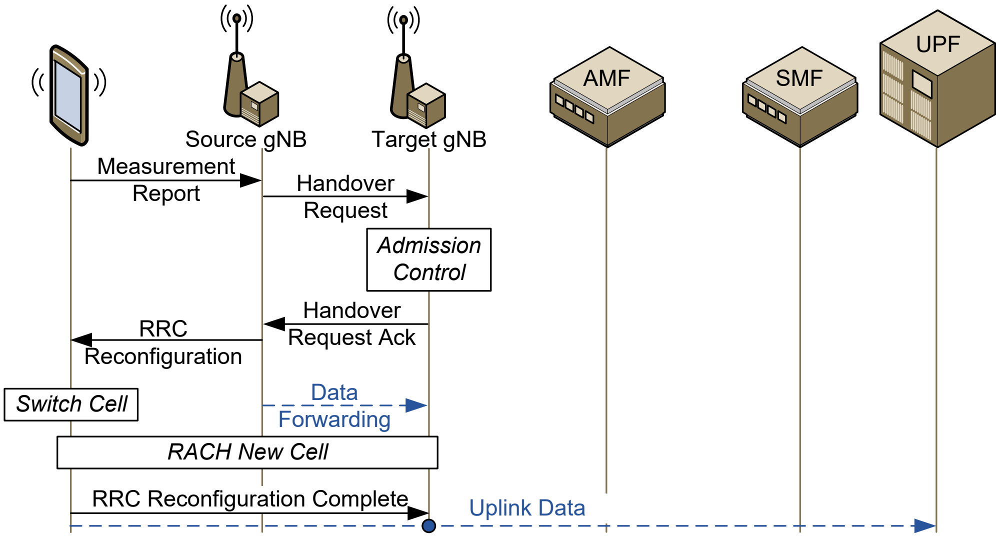


Figure 17-12 Xn Based Handover (Part 1)

The Handover Request Acknowledge may also carry a GTP TEID (Tunnel Endpoint ID) relative to the Target gNB. During the handover process execution, there will be a small period of time in which the UPF is sending downlink User Plane data to the Source instead of the Target gNB (the time from the device leaving the Source gNB to the point at which the path switch takes place). To ensure that data is not lost, the Source gNB will use the GTP TEID as a forwarding tunnel for this data.

17.2.2 RRC Connection Reconfiguration

The device will receive the RRC Reconfiguration message.

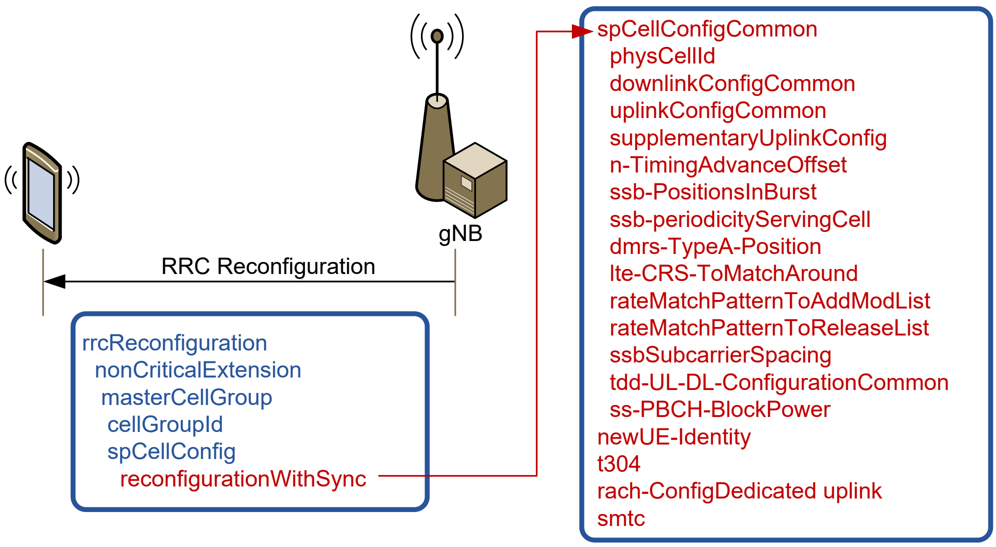


Figure 17-13 RRC Reconfiguration message

The ReconfigurationWithSync parameters includes:

- spCellConfigCommon - this includes various parameters relating to the target cell configuration. As such, it defines the RACH configuration as part of the UplinkConfigCommon parameter.
- New UE Identity - this is the UEs C-RNTI on the new cell.
- T304 - this is the handover timer.
- Rach-Config Dedicated - this can assign a dedicated preamble as part of SSB or CSI-RS resources.
- SMTC - this provides detail of the SSB location, i.e. periodicity, offset and duration.

17.2.3 Path Switch Procedure

Figure 17-14 outlines the key aspects of the Path Switch operation, which takes place following the receipt of the RRC Reconfiguration Complete message at the Target (now Serving) gNB.

The first part of the procedure is the exchange of the XnAP SN Status Transfer message, sent from the Source gNB to the Target gNB. This message is designed to provide the PDCP (Packet Data Convergence Protocol) SDN (Signalling Data Unit Number) for the Uplink and Downlink DRBs (Data Radio Bearers) that the device has in place. Essentially, this provides the current sequence number for the Uplink and Downlink data from the source gNB perspective. In addition, the device will also provide PDCP status from its perspective. This enables the Target gNB to inform the device which packets are still outstanding from both the uplink and downlink perspective, which may trigger re-transmissions.

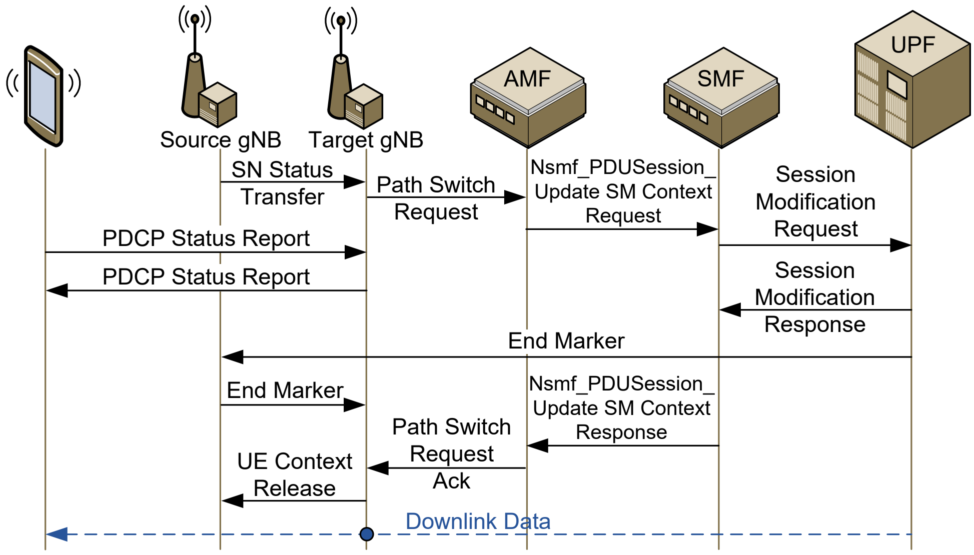


Figure 17-14 Xn Based Handover – Part 2

The Target gNB now sends an NGAP Path Switch message to the AMF to inform it that the device has changed cell and to provide its identity to the AMF. In addition, the Path Switch Request will identify the GTP TEID of the new Serving gNB, which must ultimately be conveyed to the UPF(s) serving the device.

As such, the AMF will send new TEID information in the Nsmf_PDUSession_Update SM Context Request to the SMF. In turn, the SMF will take this information and supply it to the UPF using the PFCP Session Modification Request message. The UPF, on receipt of the Session Modification Request, will redirect the User Plane data away from the Source gNB and towards the now Serving gNB. In addition, the UPF will send the GTPv1-U End Marker message to the Source gNB, which signifies that the UPF has no further data to send. This causes the Source gNB to send the same message to the Target gNB, effectively shutting down traffic flow on the Xn forwarding tunnel.

The UPF will send a Session Modification Response message to the SMF, confirming that the User Plane tunnels have been switched as instructed. The SMF will then send the Nsmf_PDUSession_Update SM Context Response message to the AMF, confirming the same. This path switch confirmation continues with the AMF sending the Path Switch Request Acknowledge message to the Target gNB. It is at this point that the AMF supplies the Target gNB will all of the Core Network tunnel information for the UPFs involved in the PDU Session(s) that the device has active.

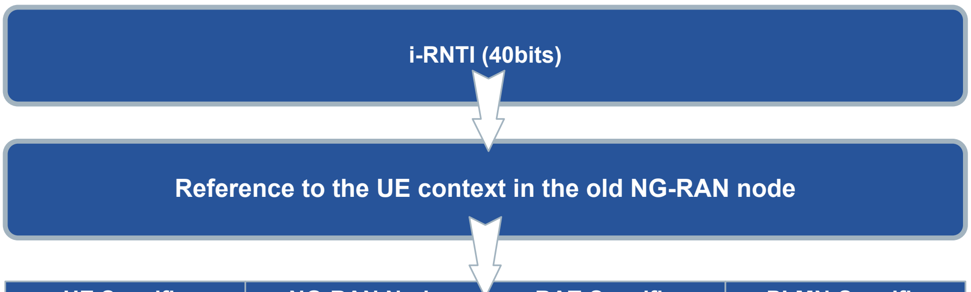
Finally, knowing that the Source gNB is no longer required, the Target gNB will send the XnAP UE Context Release message, causing the UE Context to be deleted at the Source gNB. This will conclude the Xn Handover procedure.

17.3 RRC Inactive Mobility

When the device is RRC Inactive, the device can perform cell reselection to different cells, without informing the network. The only limitation is that the cells that the device considers for reselection must all be in the same RNA (RAN based Notification Area), identified by a RANAC (RAN Area Code).

17.3.1 I-RNTI

The I-RNTI (Inactive RNTI) provides the new NG-RAN node a reference to the UE context in the old NG-RAN node. How the new NG-RAN node is able to resolve the old NG-RAN ID from the I-RNTI is a matter of proper configuration in the old and new NG-RAN node. The implementation of the I-RNTI 40bits is also flexible, as illustrated in Figure 13-15. This shows three example profiles.



UE Specific Reference	NG-RAN Node Address Index	RAT-Specific Information	PLMN-Specific Information
20bits	20bits	N/A	N/A
20bits	16bits	N/A	4bits
24bits	16bits	N/A	N/A

Figure 17-15 I-RNTI

The system will also inform the device of a Short I-RNTI. This is 24bits and is indicated separately, as shown in Figure 13-16.

17.3.2 RAN Notification Area

The device will be informed about the RAN notification area, this will either be a “celllList” or a “ran-AreaConfigList”.

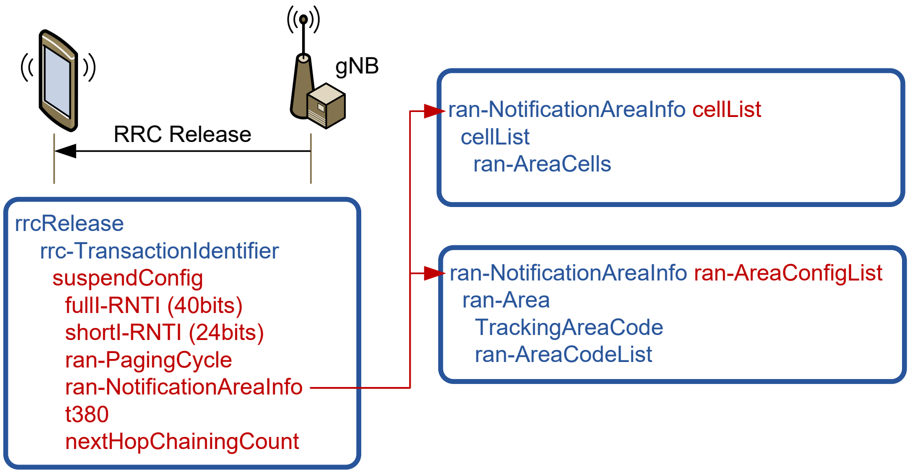


Figure 17-16 Suspend Configuration

Figure 13-14 illustrates the location of the RAN Area Code in SIB1 (System Information Block 1), as well as the indication to the device to use the Full I-RNTI or not. As such, the device will utilize an RRC Resume Request message for the Short I-RNTI and an RRC Resume Request1 messages for the Full I-RNTI.

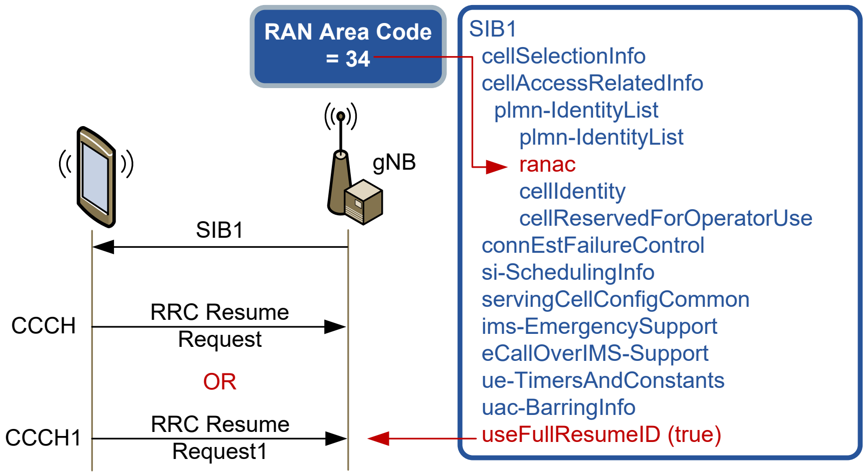


Figure 17-17 RRC Inactive Mobility Concept

17.3.3 RRC Resume Procedure

The RRC Resume procedure (using the Short I-RNTI) is illustrated in Figure 13-18. The gNB utilizes an RRC Resume message to provide the MCG configuration.

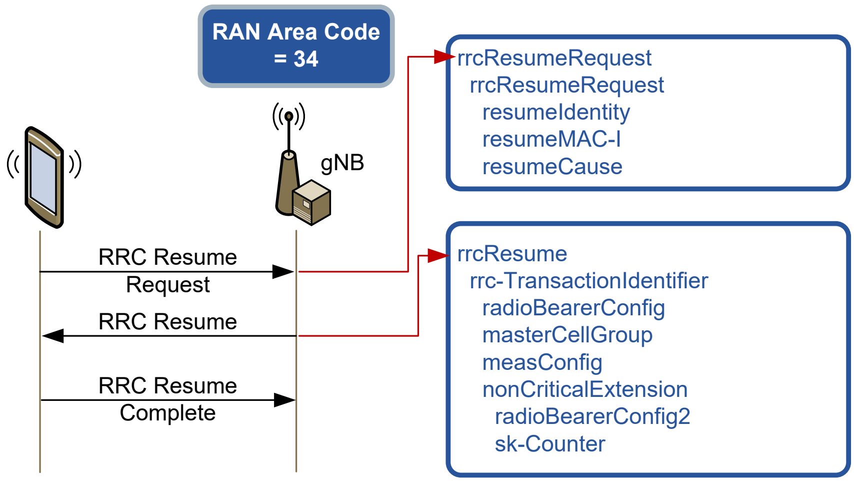


Figure 17-18 RRC Resume Procedure

17.4 Inter MeNB Handover with EN-DC

When EN-DC is in operation, handovers between MeNBs will routinely occur as the device moves around the network. This handover may or may not trigger a secondary node change, depending on the configuration and coverage of the network.

17.4.1 MeNB Handover Procedure

Figure 17-19 outlines how an X2 handover occurs between eNBs when EN-DC is in operation. In terms of the message flow, the overall procedure is very similar, regardless of whether a secondary node change does or does not occur.

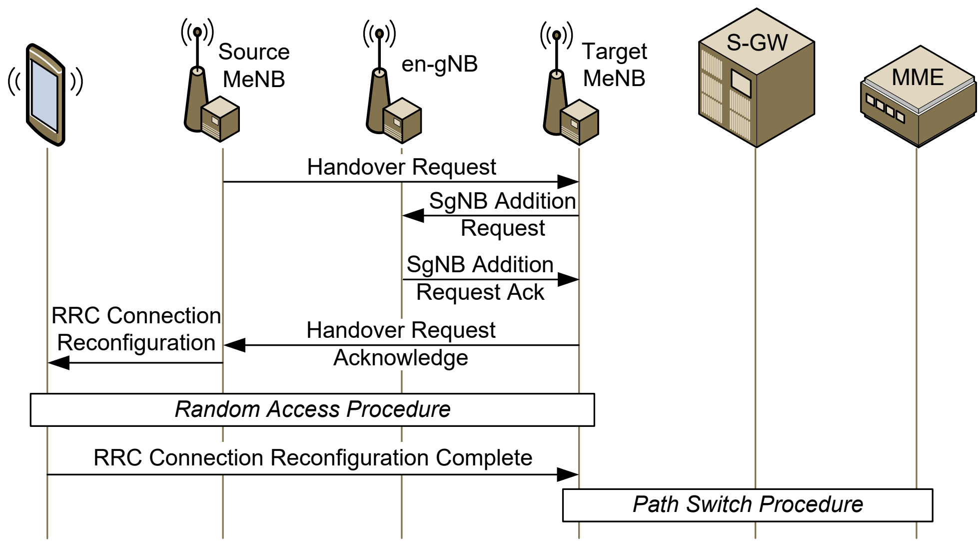


Figure 17-19 Inter MeNB Handover with EN-DC

As with any X2 handover, the procedure begins with the Source MeNB sending the Handover Request to the Target MeNB. This message will include all of the information that the target MeNB requires to support the subscriber, such as EPS bearer configuration, security information and also EPC node information (MME S1AP ID, S-GW Uplink TEID). When EN-DC is in operation, the Handover Request will also contain the SgNB UE X2AP ID, en-gNB ID and the UE context that is currently installed in the en-gNB (the current E-RAB configuration of SCG and SCG Split Bearers that is active in the en-gNB).

At this stage, the Target MeNB will determine whether or not the secondary node should change.

- If a secondary node change is required, the Target MeNB will send the SgNB Addition Request to the new en-gNB which contains the UE Context provided by the Source MeNB. As such, the new en-gNB will know the exact E-RAN configurations it must support.
- If a secondary node change is not required, the Target MeNB will send the SgNB Addition Request to the existing en-gNB. This message will include the SgNB UE X2AP ID as a reference, as well as any new tunnel information required for split bearer operation between the existing en-gNB and the Target MeNB.

The en-gNB will send the SgNB Addition Request Acknowledge in response to the MeNB, providing confirmation that the E-RAB configurations are active and also supplying TEID information where necessary. Consequently, the Target MeNB will then send the Handover Request Acknowledge message back to the Source MeNB, confirming that the handover has been accepted. This message will contain information which will allow the device to successfully access the new target cell. As such, this information is relayed to the device in the RRC Connection Reconfiguration Request and may include information related to a new secondary en-gNB, if applicable (this information would be provided by the Target MeNB).

Upon receipt of the RRC Connection Reconfiguration Request, the device will conduct the RACH procedure with the target cell, sending the RRC Connection Reconfiguration Complete message when signalling resources have been assigned by the Target MeNB. If a new secondary en-gNB has been assigned, the device will also conduct a RACH procedure with this en-gNB also.

In conclusion, the Target MeNB will conduct the Path Switch procedure with the core network, ensuring that the S-GW is sending downlink data to the correct MeNB and en-gNB (depending on E-RAB configuration in use).

17.4.2 RRC Connection Reconfiguration

The E-UTRA RRC Connection Reconfiguration message in Figure 17-19 is used to trigger a MeNB change, as well as providing the en-gNB information, i.e. configuring a SCG. Figure 17-20 illustrates an example of this message. Firstly, the highlighted green “mobilityControlInfo” parameter will trigger the decision to handover to the target eNB. The messages also include the nr-Config-r15 parameter with NR RRC Reconfiguration message being carried. This includes RLC bearer information which indicates whether the SRB(s) or/and DRB(s) are present on the en-gNB. Finally, the reconfigurationWithSync parameter is also included. This configures the device to RACH into the SPCell.

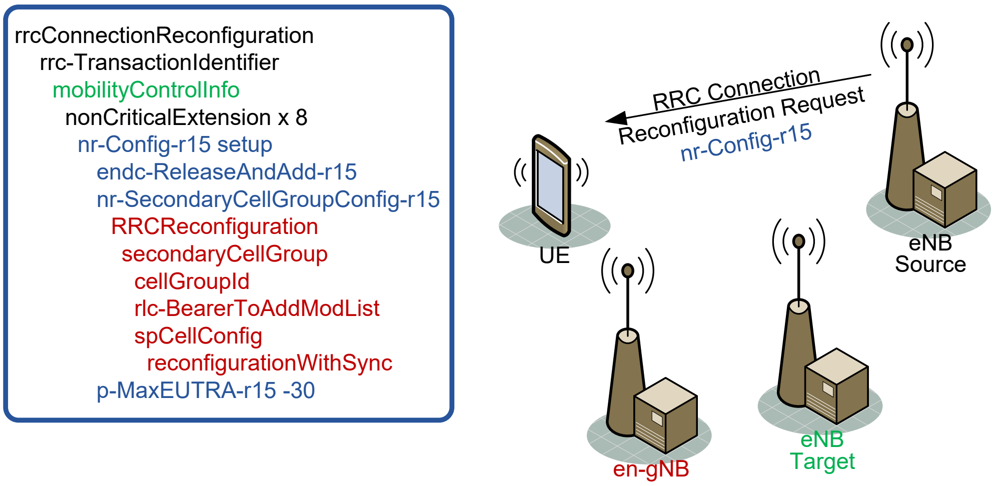


Figure 17-20 E-UTRA RRC Connection Reconfiguration (MN Change with SCG)

18 Glossary

μ (Numerology)
5GC (5G Core)
AM (Acknowledged Mode)
AMBR (Aggregate Maximum Bit Rate)
AMD (Acknowledged Mode Data)
ARP (Allocation and Retention Priority)
AS (Access Stratum)
ASN.1 (Abstract Syntax Notation version 1)
BA (Bandwidth Adaptation)
BCCH (Broadcast Control Channel)
BCH (Broadcast Channel)
BFI (Beam Failure Instance)
BLER (Block Error Rate)
BPC (Baseband Processing Combination)
BSR (Buffer Status Report)
BWP (Bandwidth Part)
BWP-ID (BWP Identity)
CA (Carrier Aggregation)
CAPEX (Capital Expenditure)
CB (Code Block)
CBG (Code Block Group)
CC (Component Carrier)
CCCH (Common Control Channel)
CCE (Control Channel Elements)
CDM (Code Division Multiplexing)
CE (Control Element)
CORESET (Control Resource Set)
CP (Cyclic Prefix)
CPE (Common Phase Error)
CQI (Channel Quality Indicator)
C-RAN (Centralized RAN)
CRB (Common Resource Blocks)
CRC (Cyclic Redundancy Check)
CRI (CSI-RS Resource Indicator)
C-RNTI (Cell RNTI)
CS (Cyclic Shift)
CSI (Channel State Information)
CSI-RS (Channel State Information RS)
CS-RNTI (Configured Scheduling RNTI)
CU (Central Unit)
DC (Dual Connectivity)
DCCH (Dedicated Control Channel)
DCI (Downlink Control Information)
DFT-s-OFDM (Discrete Fourier Transform - spread - Orthogonal Frequency Division Multiplexing)
DL (Downlink)
DL-SCH (Downlink - Shared Channel)
DMRS (Demodulation Reference Signals)
DRB (Data Radio Bearer)
DRX (Discontinuous Reception)
DTCH (Dedicated Traffic Channel)
DTX (Discontinuous Transmission)
DU (Distributed Unit)
eMBB (Enhanced Mobile Broadband)
EMM (EPS Mobility Management)
EN-DC (E-UTRA-NR Dual Connectivity)
EPC (Evolved Packet Core)
EPRE (Energy Per Resource Element)
F1AP (F1 Application Protocol)
FDD (Frequency Division Duplexing)
FDM (Frequency Division Multiplexing)
FD-MIMO (Fully Dimension MIMO)
FEC (Forward Error Correction)
FMC (First Missing Count)
FR (Frequency Range)
FR1 (Frequency Range 1)
FR2 (Frequency Range 2)
GBR (Guaranteed Bit Rate)
gNB (New Radio Node B)
GNSS (Global Navigation Satellite System)
GP (Guard Period)

GSCN (Global Synchronization Channel Number)
GUTI (Globally Unique Temporary Identity)
HARQ (Hybrid Automatic Repeat Request)
HSS (Home Subscriber Sever)
Hys (Hysteresis)
I_{MCS} (MCS Index)
IMS (IP Multimedia Subsystem)
IMT (International Mobile Telecommunications)
INT-RNTI (Interruption RNTI)
IR (Incremental Redundancy)
ISI (Inter Symbol Interference)
ITU-R (International Telecommunication Union – Radiocommunication)
L (Location)
LCG (Logical Channel Group)
LCID (Logical Channel Identity)
LDPC (Low-Density Parity Check)
LSB (Least Significant Bits)
MAC (Medium Access Control)
MCG (Master Cell Group)
MCS (Modulation and Coding Scheme)
MeNB (Master eNB)
MIB (Master Information Block)
MIMO (Multiple Input Multiple Output)
MIoT (Massive Internet of Things)
MM (Mobility Management)
MME (Mobility Management Entity)
mmWAVE (Millimetre Wave)
MN (Master Node)
MR (Measurement Report)
MR-DC (Multi-RAT Dual Connectivity)
MSB (Most Significant Bit)
MTC (Measurement Timing Configuration)
MU-MIMO (Multi-User MIMO)
NACK_SN (Negative Acknowledgement SN)
NAS (Non Access Stratum)
NEA (NR Encryption Algorithms)
NE-DC (NR - E-UTRA Dual Connectivity)
ng-eNB (next generation eNB)
NGEN-DC (NG-RAN - E-UTRA-NR Dual Connectivity)
NIA (NR Integrity Algorithms)
N_{info} (Intermediate Number of Information Bits)
NR (New Radio)
NR-ARFCN (NR Absolute Radio Frequency Channel Number)
NRB (Transmission Bandwidth Configuration)
NR-DC (New Radio Dual Connectivity)
NSA (Non-Standalone)
NZP (Non-Zero Power)
OFDM (Orthogonal Frequency Division Multiplexing)
Ofn (Frequency Specific Offset)
OPEX (Operational Expenditure)
P (Polling)
PAPR (Peak-to-Average Power Ratio)
PBCH (Physical Broadcast Channel)
PCCH (Paging Control Channel)
PCell (Primary Cell)
PCH (Paging Channel)
PCI (Physical Cell Identity)
PDCCH (Physical Downlink Control Channel)
PDCP (Packet Data Convergence Protocol)
PDR (Packet Detection Rule)
PDSCH (Physical Downlink Shared Channel)
PDU (Protocol Data Unit)
PH (Power Headroom)
PHR (Power Headroom Report)
PHY (Physical)
PL (Pathloss)
PLMN (Public Land Mobile Network)
PMI (Precoding Matrix Indicator)
PRACH (Physical Random Access Channel)
PRB (Physical Resource Block)
P-RNTI (Paging RNTI)
PSCell (Primary SCell)
PSS (Primary Synchronization Signal)
PTAG (Primary Timing Advance Group)
PTRS (Phase Tracking RS)
PUCCH (Physical Uplink Control Channel)
PUSCH (Physical Uplink Shared Channel)
QCI (Quality Class Identifier)
QCL (Quasi Co-Location)
QFI (QoS Flow Identifier)
Q_m (Modulation Order)
RA (Random Access)
RACH (Random Access Channel)
RAN (Radio Access Network)
RAPID (Random Access Preamble Identifier)

RAR (Random Access Response)
RA-RNTI (Random Access RNTI)
RB (Resource Blocks)
RBG (Resource Block Group)
RE (Resource Element)
REG (Resource Element Groups)
RF (Radio Frequency)
RIV (Resource Indication Value)
RLC (Radio Link Control)
RLF (Radio Link Failure)
RMSI (Remaining Minimum System Information)
RNA (RAN based Notification Area)
RNTI (Radio Network Temporary Identifier)
RRC (Radio Resource Control)
RS (Reference Signal)
RSRP (Reference Signal Received Power)
RTD (Round Trip Delay)
S/N (Signal to Noise)
SA (Standalone)
SCell (Secondary Cell)
SCG (Secondary Cell Group)
SCS (Subcarrier Spacing)
SDAP (Service Data Adaptation Protocol)
SDF (Service Data Flow)
SDL (Supplementary Downlink)
SDN (Signalling Data Unit Number)
SDU (Service Data Unit)
SFI (Slot Format Indication)
SFI-RNTI (Slot Format Indication RNTI)
SFN (System Frame Number)
SgNB (Secondary gNB)
SI (Segment Information)
SI (System Information)
SI-RNTI (System Information RNTI)
SLIV (Start Symbol and Length Indicator Value)
SMTC (SS/PBCH Block Measurement Timing Configuration)
SN (Sequence Number)
SO (Segment Offset)
SpCell (Special Cell)
SP-CSI-RNTI (Semi-Persistent CSI RNTI)
SPS (Semi-Persistent Scheduling)
SR (Scheduling Request)
SRB (Signalling Radio Bearer)
SRB1 (Signalling Radio Bearer 1)
SRI (Sounding Reference Signal Resource Indicator)
SRS (Sounding RS)
SS (Synchronization Signal)
SSB (Synchronization Signal Block)
SS-RSRP (Synchronization Signal based Reference Signal Received Power)
SS-RSRQ (Synchronization Signal based Reference Signal Received Quality)
SSS (Secondary Synchronization Signal)
SS-SINR (Synchronization Signal based Signal to Interference and Noise Ratio)
STAG (Secondary Timing Advance Group)
SUL (Supplementary Uplink)
SU-MIMO (Single-User MIMO)
TA (Timing Advance)
TAG (Timing Advance Group)
TAI (Tracking Area Identity)
TAU (Tracking Area Update)
TB (Transport Blocks)
TBS (Transport Block Size)
TCI (Transmission Configuration Indicator)
T_{CP} (Cyclic Prefix Duration)
TDD (Time Division Duplexing)
TEIDs (Tunnel Endpoint Identities)
Thresh1 (Threshold1)
Thresh2 (Threshold2)
TM (Transparent Mode)
TMD (Transparent Mode Data)
TPC (Transmit Power Control)
TPC-PUCCH-RNTI (Transmit Power Control PUCCH RNTI)
TPC-PUSCH-RNTI (Transmit Power Control PUSCH RNTI)
TPC-SRS-RNTI (Transmit Power Control Sounding Reference Symbols RNTI)
TR (Technical Reports)
TRxP (Transmission Reception Point)
TTT (Time to Trigger)
UCI (Uplink Control Information)
UL (Uplink)
UL-SCH (Uplink - Shared Channel)
UM (Unacknowledged Mode)
UMD (Unacknowledged Mode Data)
URLLC (Ultra Reliable Low Latency Communications)
V2X (Vehicle to Everything)
VoIP (Voice over IP)
VRB (Virtual Resource Blocks)
WRC-15 (World Radio Conference 15)
XnAP (Xn Application Protocol)

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