LTE 10A Air Interface

STUDENT BOOK
LZT 123 8959 R1A

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This Student Book, LZT 123 8959, R1A supports course number LZU 108 7260 .

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1 LTE/SAE Introduction

OBJECTIVES:

On completion of this chapter the students will be able to:

- **Explain the LTE Radio Interface general principles**
  - Describe the evolution of cellular networks
  - Summarize the evolution of 3GPP releases, from release 99 to release 8
  - Describe the radio interface techniques
  - Explain the difference between the FDD and TDD mode
  - Describe the flexible spectrum usage
  - Explain the concepts of channel coding and FEC (Forward Error Correction)
  - Describe the principle for OFDM
  - Describe the principle for SC-FDMA

Figure 1-1. Objectives.

Most of the channels (e.g, DPSCH, DPCCH, PBCH etc) is for carrying a special information (a sequence of bits) and they have some higher layer channel connected to them, but Reference Signal is a special signal that exists only at PHY layer. This is not for delivering any specific information. The purpose of this Reference Signal is to deliver the reference point for the downlink power.

When UE try to figure out DL power (i.e, the power of the signal from a eNode B), it measure the power of this reference signal and take it as downlink cell power.

RS is to help the receiver demodulate the received signal.

RS is made up of data known to both transmitter and receiver, the receiver can figure out how the communication channel destort the data by comparing the decoded received reference signal and predefined reference signal, and use the result of this comparison to equalize (post process) the recieved user data.

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INTRODUCTION

This course describes the Long Term Evolution (LTE) and System Architecture Evolution (SAE) for third generation cellular networks as in Release 8 of 3GPP (Third Generation Partnership Project).

The term "generation" regarding cellular network evolution is sometimes misleading and not always accurate. However, many people often refer to "2G", "3G" or even "4G" when it comes to the different generations of the mobile telecommunications systems.

The following historical overview is based on conventional and informal terms in the mobile industry, media and press.

First generation (1G) of modern cellular networks includes e.g. NMT (Nordic Mobile Telephony), AMPS (Advanced Mobile Phone Service) and TACS (Total Access Communication System). These systems all have in common that the user traffic, which is voice, is transmitted with analogue FDMA (Frequency Division Multiple Access) radio techniques. NMT was developed during the seventies and launched 1981.

Second generation (2G) includes systems like GSM (Global System for Mobile communications), D-AMPS (Dual-mode AMPS), PDC (Personal Digital Communications) and IS-95. The new thing with these systems was that they supported both voice and data traffic with digital TDMA (Time Division Multiple Access) or CDMA (Code Division Multiple Access) circuit switched radio techniques. GSM standardization started in 1982 and it was launched 1991.

Enhancements of 2G, like the introduction of packet data GPRS (General Packet Radio Service), is often referred to as 2.5G. Further enhancements, like EDGE (Enhanced Data rates for GSM and TDMA Evolution), is referred to as 2.75G.

In 1986, the ITU (International Telecommunication Union) started to work on the IMT-2000 standard, which is a guideline for every Third generation (3G) standard. In 1992, the World Administrative Radio Conference (WARC) identified the radio frequency bands 1885-2025 and 2110-2200 MHz as the common worldwide spectrum for 3G systems.

In January 1998, European Telecommunications Standards Institute (ETSI) reached a consensus where WCDMA (Wideband Code Division Multiple Access) and TD-CDMA (Time Division- Code Division Multiple Access) were chosen as multiple access methods for the FDD (Frequency Division Duplex) and TDD (Time Division Duplex) mode of UMTS (Universal Mobile Telecommunication System), respectively. UMTS is the term used in Europe for 3G systems. 3G was commercially launched 2001 in Japan and 2003 in Europe.

Figure 1-2 briefly summarizes the history of cellular technologies.

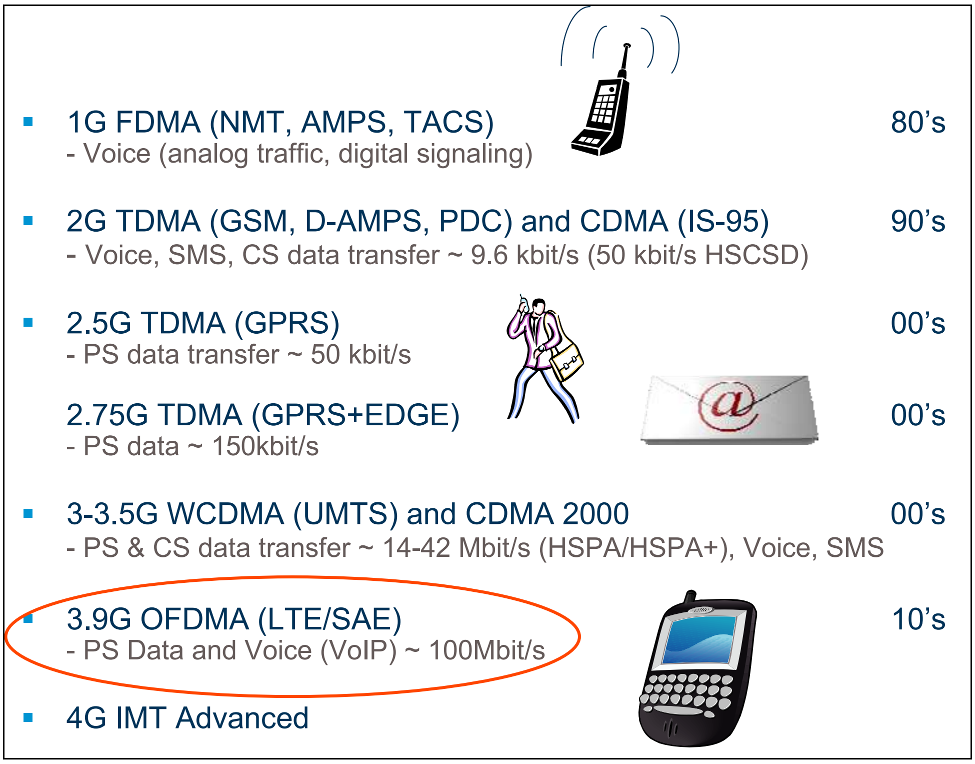


Figure 1-2. History.

The 3rd Generation Partnership Project (3GPP) is a collaboration agreement that was established in December 1998. The collaboration agreement brings together a number of telecommunications standards bodies, e.g. ARIB, CCSA, ETSI, TTA and TTC.

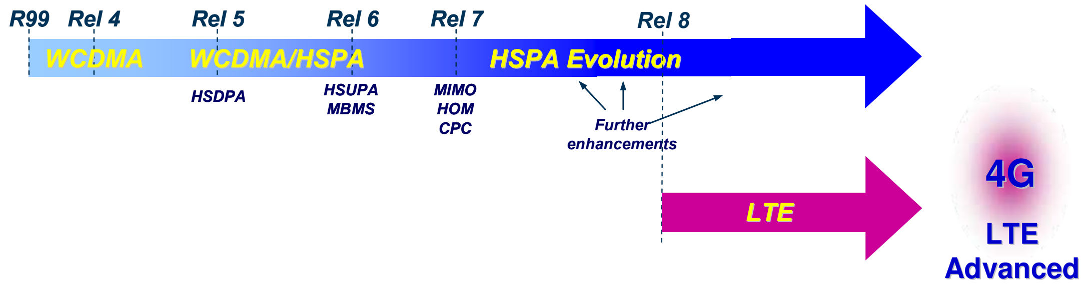
The original scope of 3GPP was to produce globally applicable Technical Specifications and Technical Reports for a 3rd Generation Mobile System based on evolved GSM core networks and the radio access technologies that they support (i.e., Universal Terrestrial Radio Access (UTRA) both Frequency Division Duplex (FDD) and Time Division Duplex (TDD) modes). The scope was subsequently amended to include the maintenance and development of the Global System for Mobile communication (GSM) Technical Specifications and Technical Reports including evolved radio access technologies (e.g. General Packet Radio Service (GPRS) and Enhanced Data rates for GSM Evolution (EDGE)). See www.3gpp.org for further information.

The first practically implemented 3GPP specification for WCDMA was released and frozen 1999 and is called Release 99.

WCDMA Release 99 supports both circuit switched (CS) and packet switched (PS) traffic up to a theoretical rate 2 Mbps.

The evolution of 3G called HSDPA (High Speed Downlink Packet Access, specified in Release 5 - 2002) and HSUPA (High Speed Uplink Packet Access, specified in Release 6 – 2004) increase the maximum downlink (DL) bit rate to 14 Mbps and the uplink (UL) rate to maximum 5.76 Mbps. HSDPA and HSUPA is referred to as HSPA (High Speed Packet Access). HSUPA is also called EUL (Enhanced Uplink).

The next step for WCDMA, called HSPA evolution or HSPA+, is currently ongoing (specified in Release 7 and 8) and aims to increase the maximum bit rates even further (up to 42 Mbps in DL). This is accomplished using e.g. MIMO (Multiple Input Multiple Output) antenna solutions and Higher Order Modulation (HOM).



- HSPA Evolution
  - gradually improved performance at a low additional cost
- LTE
  - improved performance in a wide range of spectrum allocations

Figure 1-3. 3GPP evolution.

In September 2007 the 3GPP family was extended with yet another member, the Evolved UTRAN (E-UTRAN). The work with creating the concept was officially started in the summer of 2006 when the study phase was successfully completed and the 3GPP work item “3G Long Term Evolution – Evolved Packet System RAN” (LTE) commenced. More than 50 companies and research institutes are participating in the largest joint standardization effort ever to specify the new world wide radio access and the evolved core network technology.

Ericsson is playing a key role as an important and visual driver in this process.

The standard development in 3GPP is grouped into two work items, where Long Term Evolution (LTE) targets the radio network evolution and System Architecture Evolution (SAE) targets the evolution of the packet core network. Common to both LTE and SAE is that only a Packet Switched (PS) domain will be specified. The result of these work items are the Evolved UTRAN (E-UTRAN) and the Evolved Packet Core (EPC). These together (E-UTRAN+EPC) builds the Evolved Packet System (EPS).

LTE/SAE is specified from 3GPP Release 8.

Note that LTE and SAE refer to the work items in 3GPP. The name of the actual Radio Access Network (RAN) is E-UTRAN and the name of the Core Network (CN) is EPC.

A parallel Partnership Project was also established - "3GPP2," which, quite similar to its sister project 3GPP, also standardizes International Telecommunication Union's (ITU) International Mobile Telecommunications "IMT-2000" based networks. 3GPP2 focuses on the evolution of cdmaOne with cdma2000 and EV-DO (HRPD) while 3GPP focuses on the evolution of GSM, WCDMA, HSPA and LTE. 3GPP2 is divided into four Technical specification groups comprised of representatives from the Project's Individual Member companies. The TSGs are:

- TSG-A for Access Network Interfaces
- TSG-C for cdma2000
- TSG-S Services and Systems Aspects
- TSG-X Core Networks

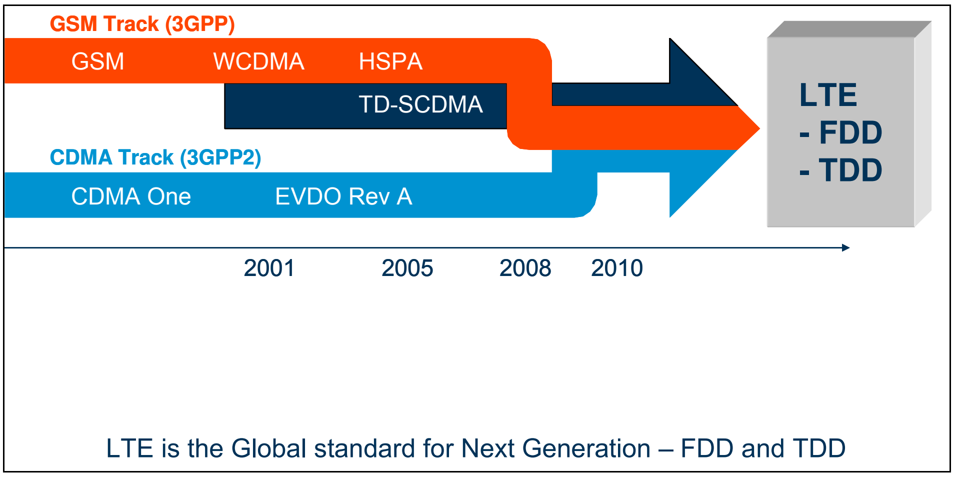


Figure 1-4. Mobile System Evolution.

The E-UTRAN standard is based on Orthogonal Frequency Division Multiplexing (OFDM) and OFDMA (Orthogonal Frequency Division Multiple Access) downlink operation and Single Carrier Frequency Domain Multiple Access (SC-FDMA) uplink operation. These choices support great spectrum flexibility with a number of possible deployments from 1.4 MHz up to 20 MHz spectrum allocations. It will support both FDD and TDD mode of operation and targets both a paired spectrum allocation with uplink and downlink separated in frequency, and unpaired spectrum with uplink and downlink operating on the same frequency.

Furthermore, E-UTRAN supports use of different MIMO (Multiple Input Multiple Output) multiple antenna configurations. This increases the data rates and spectrum efficiency.

LTE is sometimes referred to as 3.9G. Why not 4G? Well, ITU has defined IMT Advanced, which is the follower to IMT2000. IMT Advanced is regarded as 4G and is meant to support theoretical bitrates up to approximately 1Gbit/s and may be deployed with LTE Release 10 (also referred to as LTE Advanced).

LTE Release 10 will probably fulfill the IMT Advanced requirements. LTE Release 10 will simply be called LTE in Release 10, since it is built on the same solutions as LTE in Release 8 but with some extra features like simultaneous communication with different base stations (COMP) and spectrum aggregation.

The first LTE networks based on 3GPP Release 8 are expected to be implemented in 2009.

EPS in 3GPP Release 8 is based on a simplified network architecture compared to Release 6. The number of user-plane nodes is reduced from four in Release 6 (NodeB, RNC, SGSN and GGSN) to only two (e-NodeB and S-GW) in EPS.

Only a Packet Switched (PS) domain is defined in LTE. This means that the traditionally Circuit Switched (CS) services will be carried by PS bearers.

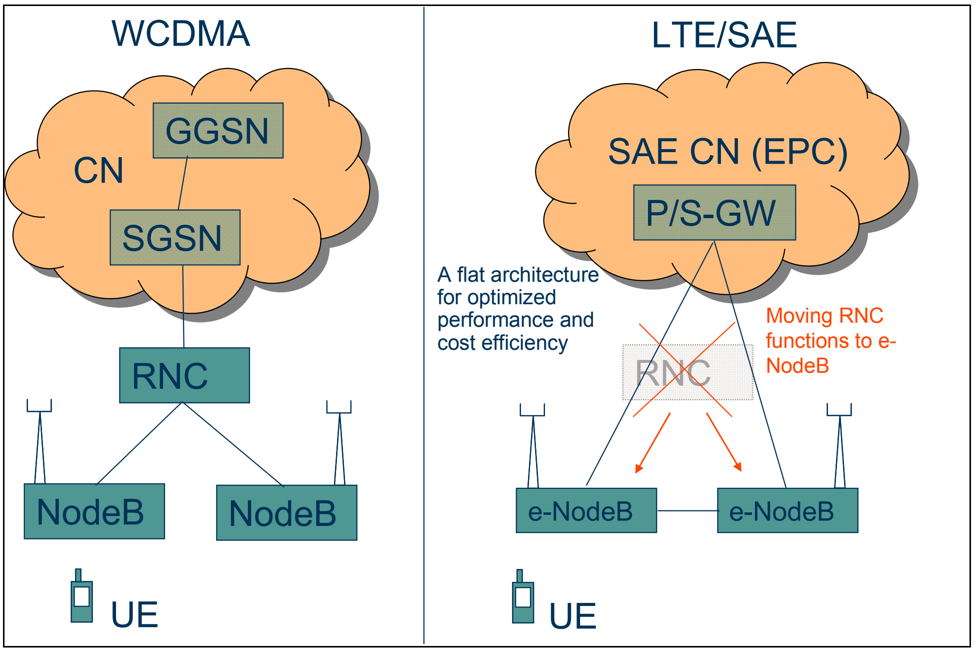


Figure 1-5. Simplified network architecture.

LTE Requirements

The performance of LTE as specified in 3GPP Release 8 shall fulfill a number of requirements regarding throughput and latency listed below. This seems to be quite easily achieved, thanks to, among other improvements, the simplified network architecture. Data rates of more than 300 Mbps in DL seems to be possible to reach.

Also, it is a requirement that E-UTRAN architecture should reduce the cost of future network deployment whilst enabling the usage of existing site locations. It is expected that the reduction of the number of nodes and interfaces contributes to this overall goal.

Furthermore, should all specified interfaces be open for multi-vendor equipment interoperability. There are two identified interfaces that will be standardized, S1 and X2. For them no major problems regarding multi-vendor interoperability have been identified during the study item phase.

E-UTRA should support significantly increased instantaneous peak data rates. The supported peak data rate should scale according to size of the spectrum allocation.

Note that the peak data rates may depend on the numbers of transmit and receive antennas (MIMO configuration) at the UE (User Equipment). The targets for DL and UL peak data rates are specified in terms of a reference UE configuration comprising:

a) Downlink capability: 2 receive antennas at UE

b) Uplink capability: 1 transmit antenna at UE

For this baseline configuration, the system should support an instantaneous downlink peak data rate of 100Mbps within a 20 MHz downlink spectrum allocation (5 bps/Hz) and an instantaneous uplink peak data rate of 50Mbps (2.5 bps/Hz) within a 20MHz uplink spectrum allocation. The peak data rates should then scale linearly with the size of the spectrum allocation.

In case of spectrum shared between downlink and uplink transmission, E-UTRA does not need to support the above instantaneous peak data rates simultaneously.

The control plane latency should be lower than 100ms. The control plane latency is here defined as the transition time from ECM-IDLE to ECM-CONNECTED state (see later next chapter for definition of these states).

Also, the one-way user plane latency shall not exceed 5 ms in an unloaded situation for small IP-packets.

but bandwidth refers to capacity, while throughput details how much data actually transmits.

Target rates for user throughput

Downlink

- Target for user throughput per MHz at the 5 % point of the C.D.F., 2 to 3 times Release 6 HSDPA.

- Target for averaged user throughput per MHz, 3 to 4 times Release 6 HSDPA. Both targets should be achieved assuming Release 6 reference performance is based on a single Tx antenna at the Node B with enhanced performance type 1 (Rx diversity) receiver in UE whilst the E-UTRA may use a maximum of 2 Tx antennas at the Node B and 2 Rx antennas at the UE.

- The supported user throughput should scale with the spectrum bandwidth.

Uplink

- Target for user throughput per MHz at the 5 % point of the C.D.F., 2 to 3 times Release 6 Enhanced Uplink (deployed with a single Tx antenna at the UE and 2 Rx antennas at the Node B).

- Target for averaged user throughput per MHz, 2 to 3 times Release 6 Enhanced Uplink (deployed with a single Tx antenna at the UE and 2 Rx antennas at the Node B).

- Both should be achievable by the E-UTRA using a maximum of a single Tx antenna at the UE and 2 Rx antennas at the Node B. Greater user throughput should be achievable using multiple Tx antennas at the UE.

- The user throughput should scale with the spectrum bandwidth provided that the maximum transmit power is also scaled.

Targets for spectrum efficiency

E-UTRA should deliver significantly improved spectrum efficiency and increased cell edge bit rate whilst maintaining the same site locations as deployed today.

Spectrum efficiency needs to be significantly increased as followings:

Downlink

In a loaded network, target for spectrum efficiency (bits/sec/Hz/site), 3 to 4 times Release 6 HSDPA This should be achieved assuming Release 6 reference performance is based on a single Tx antenna at the Node B with enhanced performance type 1 receiver in UE whilst the E-UTRA may use a maximum of 2 Tx antennas at the Node B and 2 Rx antennas at the UE.

Uplink

In a loaded network, target for spectrum efficiency (bits/sec/Hz/site), 2 to 3 times Release 6 Enhanced Uplink (deployed with a single Tx antenna at the UE and 2 Rx antennas at the Node B). This should be achievable by the E-UTRA using a maximum of a single Tx antenna at the UE and 2Rx antennas at the Node B.

- High data rates
  - Downlink: >100 Mbps
  - Uplink: >50 Mbps
  - Cell-edge data rates 2-3 x HSPA Rel. 6 (@ 2006)

- Low delay/latency   ROUND TRIP TIME
  - User plane RTT: < 10 ms RAN RTT (fewer nodes, shorter TTI)
  - Channel set-up: < 100 ms idle-to-active (fewer nodes, shorter messages, quicker node resp.)

- High spectral efficiency
  - Targeting 3 X HSPA Rel. 6 (@ 2006)
- Spectrum flexibility
  - Operation in a wide-range of spectrum allocations, new and existing
  - Wide range of Bandwidth: 1.4, 3, 5, 10, 15 and 20 MHz, FDD and TDD
- Simplicity – Less signaling, Auto Configuration e-NodeB
  – ”PnP”, ”Simple as an Apple”
- Cost-effective migration from current/future 3G systems
- State-of-the-art towards 4G
- Focus on services from the packet-switched domain

Figure 1-6. LTE requirements

eNB functionality

eNB is the RAN node in the EPS architecture that is responsible for radio transmission to and reception from UEs in one or more cells. The eNB is connected to EPC nodes by means of an S1 interface. The eNB is also connected to its neighbor eNBs by means of the X2 interface. Some significant changes have been made to the eNB functional allocation compared to UTRAN. Most Rel-6 RNC functionality has been moved to the E-UTRAN eNB. Below follows a description of the functionality provided by eNB.

- **Cell control and MME pool support**
  eNB owns and controls the radio resources of its own cells. Cell resources are requested by and granted to MMEs in an ordered fashion. This arrangement supports the MME pooling concept. S-GW pooling is managed by the MMEs and is not really seen in the eNB.

- **Mobility control**
  The eNB is responsible for controlling the mobility for terminals in active state. This is done by ordering the UE to perform measurement and then performing handover when necessary.

- **Control and User Plane security**
  The ciphering of user plane data over the radio interface is terminated in the eNB. Also the ciphering and integrity protection of RRC signaling is terminated in the eNB.

- **Shared Channel handling**
  Since the eNB owns the cell resources, the eNB also handles the shared and random access channels used for signaling and initial access.

- **Segmentation/Concatenation**
  Radio Link Control (RLC) Service Data Units (SDUs) received from the Packet Data Convergence Protocol (PDCP) layer consist of whole IP packets and may be larger than the transport block size provided by the physical layer. Thus, the RLC layer must support segmentation and concatenation to adapt the payload to the transport block size.

- **HARQ**
  A Medium Access Control (MAC) Hybrid Automatic Repeat reQuest (HARQ) layer with fast feedback provides a means for quickly correcting most errors from the radio channel. To achieve low delay and efficient use of radio resources, the HARQ operates with a native error rate which is sufficient only for services with moderate error rate requirements such as for instance VoIP. Lower error rates are achieved by letting an outer Automatic Repeat reQuest (ARQ) layer in the eNB handle the HARQ errors.

- **Scheduling**
  A scheduling with support for QoS provides for efficient scheduling of UP and CP data.

- **Multiplexing and Mapping**
  The eNB performs mapping of logical channels onto transport channels.

- **Physical layer functionality**
  The eNB handles the physical layer such as scrambling, Tx diversity, beamforming processing and OFDM modulation. The eNB also handles layer one functions like link adaptation and power control.

- **Measurements and reporting**
  eNB provides functions for configuring and making measurements on the radio environment and eNB-internal variables and conditions. The collected data is used internally for Radio Resource Management (RRM) but can be reported for the purpose of multi-cell RRM.

- **Automated operation and maintenance**.
  eNB provides functions for Automated Neighbor Relations (ANR) and Automatic Integration of RBS.

- Cell control and MME pool support
- Mobility control
- Control and User Plane security
- Shared Channel handling
- Segmentation/Concatenation
- HARQ
- Scheduling
- Multiplexing and Mapping
- Physical layer functionality
- Measurements and reporting
- Automated operation and maintenance

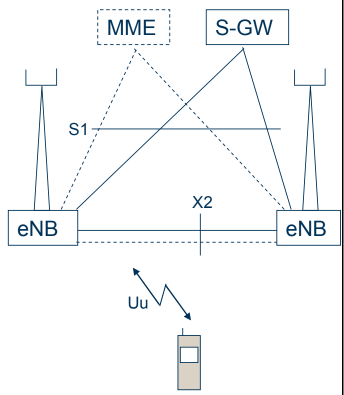


Figure 1-7. eNodeB functionality.

LTE RADIO INTERFACE

The LTE radio interface is based on OFDM (Orthogonal Frequency Division Multiplex) and OFDMA (Orthogonal Frequency Division Multiple Access) in DL and SC-FDMA (Single Carrier Frequency Division Multiple Access) in UL. These techniques are well suited for flexible bandwidth operation. This enables operators to deploy LTE in different regions with different frequency bands and bandwidths available.

OFDM also shows very good performance in highly time dispersive radio environments (i.e. many delayed and strong multipath reflections). That is because the data stream is distributed over many subcarriers. Each subcarrier will thus have a slow symbol rate and correspondingly, a long symbol time. This means that the Inter Symbol Interference (ISI) is reduced.

SC-FDMA--> for UL transmission
DFTS-OFDM--> for DL transmission

The users in DL are separated with OFDMA, which means that each user has its own time- and frequency resources.

The uplink transmission technique, SC-FDMA, is realized in a similar manner as for the downlink (OFDM) and is also called DFTS-OFDM (Discrete Fourier Transform Spread – OFDM). The time domain structure is also similar in uplink and downlink. SC-FDMA has much lower PAPR (Peak to Average Power Ratio) than OFDM. This is one of the reasons for the choice of SC-OFDM for the uplink since the power amplifier in the UE can be made more power efficient and manufactured at a lower cost.

In addition to that, both FDD (Frequency Division Duplex) and TDD (Time Division Duplex) is supported, which opens up for deployment in both paired and unpaired spectrum. In FDD, different frequency bands are used for UL and DL. In TDD the UL and DL transmissions are separated in time. There are pros and cons with both methods. TDD has some more overhead and latency, due to the frequent switching in time. On the other hand, the TDD mode enables radio channel reciprocity, which means that UL measurements can be used for DL transmissions, and vice versa. The TTD mode is also simpler to deploy in areas with limited available spectrum since it can utilize unpaired frequency bands.

A half duplex FDD mode (HD-FDD) is also defined, where the UE does not have to transmit at the same time as it receives. Therefore, more cost effective UEs can be manufactured since a duplex filter is not needed.

Orthogonal Frequency Division Multiplexing (OFDM) is another widely used modulation method used to achieve high data rates and spectral efficiency.

The radio resources are defined in the time- and frequency domain and divided into so called resource blocks. Dynamic channel dependent scheduling allocates a number of these time- and frequency resources to different users at different times.

Link adaptation adapts the modulation scheme and coding rate to the varying radio channel condition.

HARQ (Hybrid Automatic Repeat and Request) caters for very quick layer 2 retransmission functionality. In addition, ordinary ARQ is implemented in the RLC layer.

The LTE radio transmissions are based on a very short TTI (Transmission Time Interval) of 1ms, which speeds up the operation of all of the above functions. The short TTI also reduces the radio interface latency, which is one of the main concerns in the LTE development.

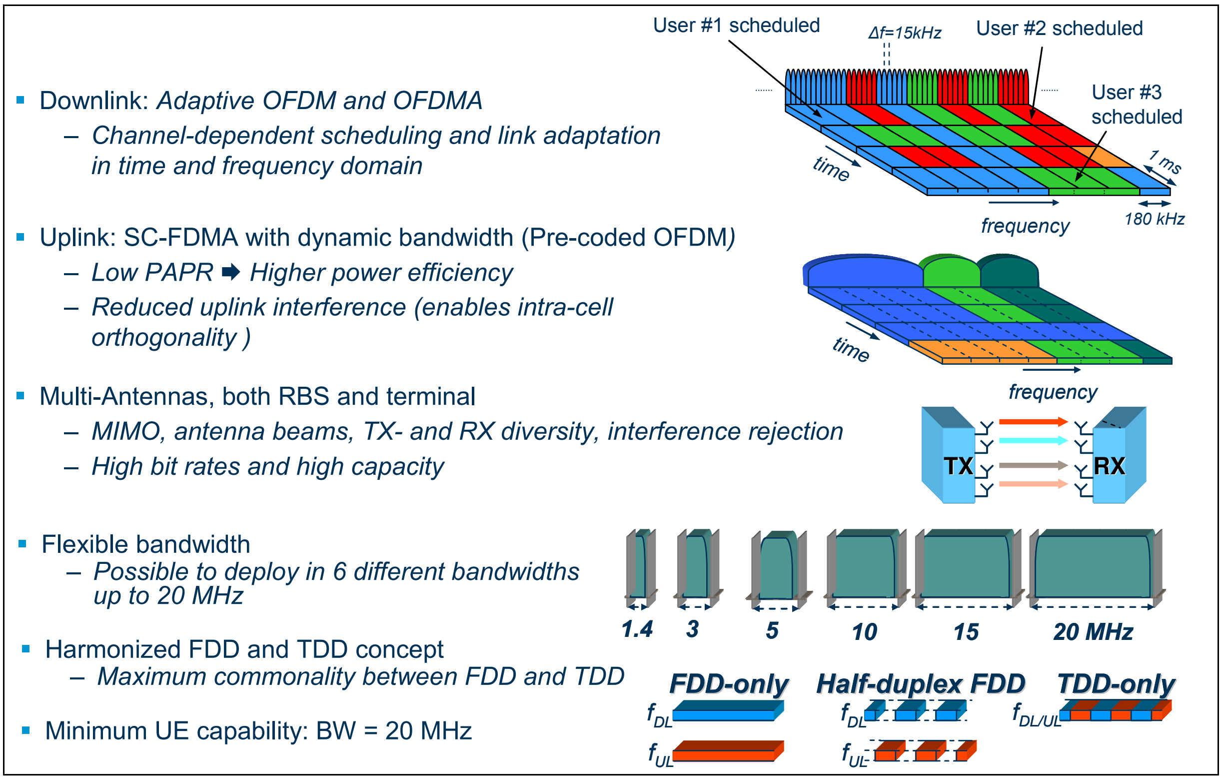


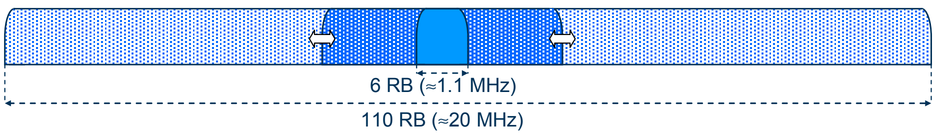
Figure 1-8. LTE Physical layer.

In contrary to WCDMA, the uplink transmissions in LTE are, thanks to the SC-FDMA solution, well separated within a cell (intra-cell orthogonality). This leads to a less extensive power control operation.

In order to increase the spectrum efficiency, capacity and overall data rates the use of multiple antennas, MIMO (Multiple Input Multiple Output) is included in the standard. With these multiple antennas and advanced signal processing such as spatial multiplexing, the radio channel can be separated into several layers, or “data pipes”. Up to four layers can be utilized. This corresponds to up to four times higher data rates for a given bandwidth.

The maximum number of Resource Blocks that can be allocated is 100. The 10 remaining RBs (since 20 MHz corresponds to 110 RBs) are needed as guard bands.

- LTE physical-layer specification supports any bandwidth in the range 6 RBs to 110 RBs in steps of one RB



- Radio requirements only specified for a limited set of bandwidths
  - Can be different for different frequency bands
- Relatively straighforward to extend to additional bandwidths
  - e.g. for new frequency bands
- All UEs must support the maximum bandwidth of each supported band
- The maximum number of RBs that can be allocated is 100

Figure 1-9. Bandwidth flexibility.

UE states and area concepts

LTE is developed to have a simpler architecture (fewer nodes) and less signaling (fewer messages) than UTRAN. Also, the number of states which the UE can be in (corresponding to RRC states) are reduced from 5 in UTRAN (DETACHED, IDLE, URA_PCH, CELL_FACH, CELL_DCH) to only 3 in E-UTRAN (DETACHED, IDLE and CONNECTED).

Furthermore, the area concept is somewhat simplified in LTE compared to UTRAN. In LTE only one area for idle mode mobility is defined; the Tracking Area (TA). In UTRAN, Routing Area (RA) and UTRAN Registration Area (URA) is defined for PS traffic and Location Area (LA) for CS traffic.

In ECM-IDLE (EPS Connection Management IDLE) the UE position is only known by the network on TA level, whereas in ECM-CONNECTED, the UE location is known on cell level by the eNB.

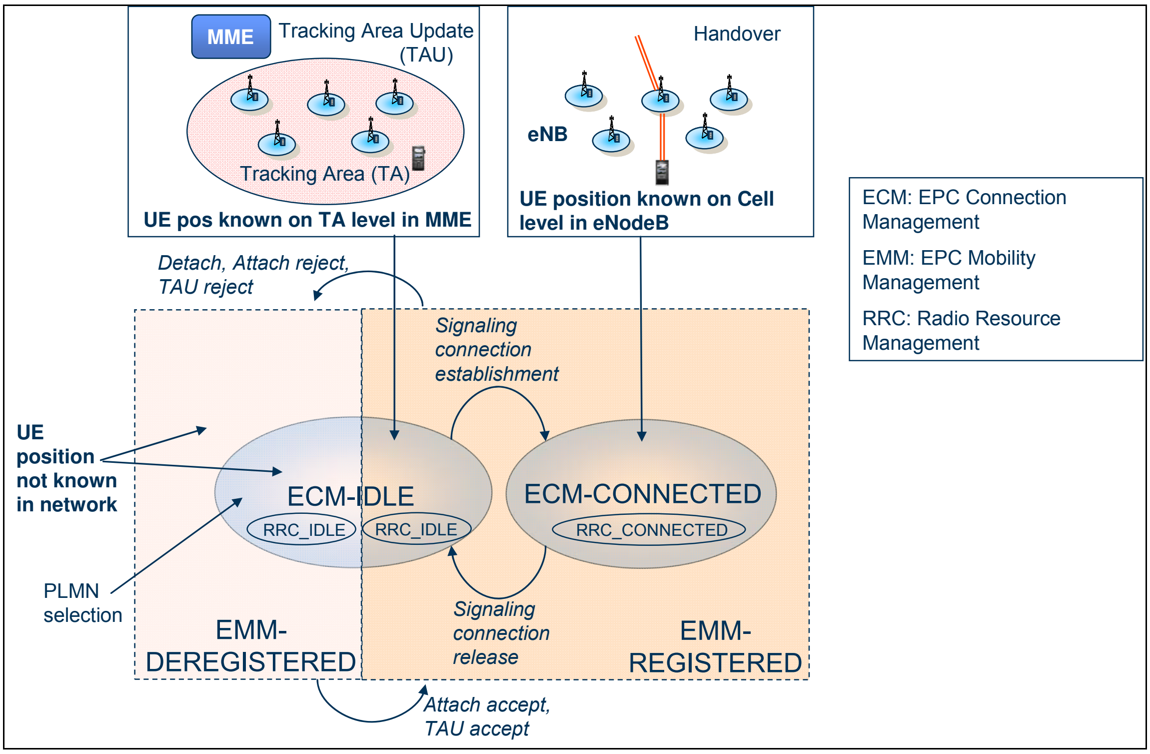


Figure 1-10. Protocol states and Mobility

When a UE attaches to the network it is assigned an IP address from a P-GW. The IP-address is kept regardless of if the UE enters idle mode or not as long as it is attached to the network, but is released if the UE detaches from the network.

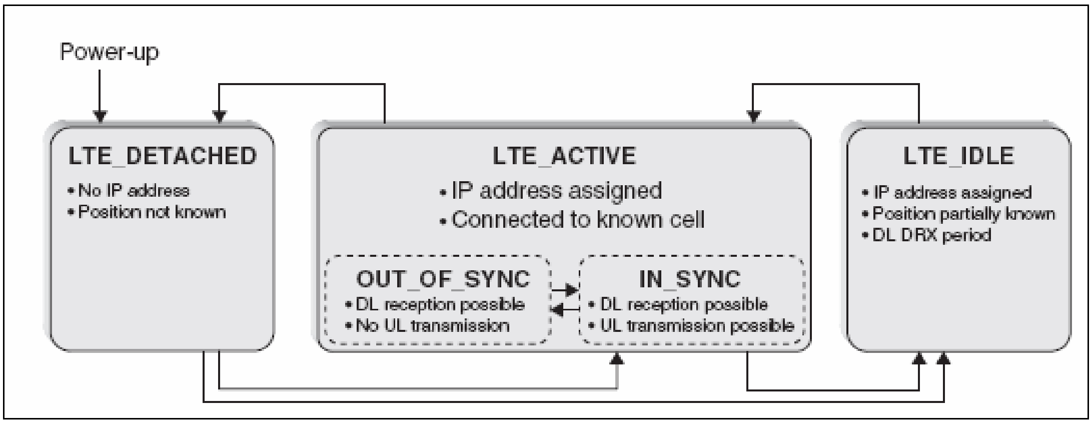


Figure 1-11 LTE states.

In Figure 1-12, the UE categories are shown.

Category	1	2	3	4	5
DL peak rate	10	50	100	150	300
UL peak rate	5	25	50	50	75
Max DL mod	64QAM				
Max UL mod	16QAM				64QAM
Layers for DL spatial mux.	1	2			4

- All UEs support 4 Tx antennas at eNodeB
- Soft buffer sizes under discussion
- MBMS is a separate capability
- FDD, HD-FDD and TDD are independent capabilities

Figure 1-12 UE Categories

RADIO CHANNEL AND CHANNEL CODING

This part describes the general principles of the radio channel behavior and the physical layer processing done to mitigate the errors introduced by the radio channel.

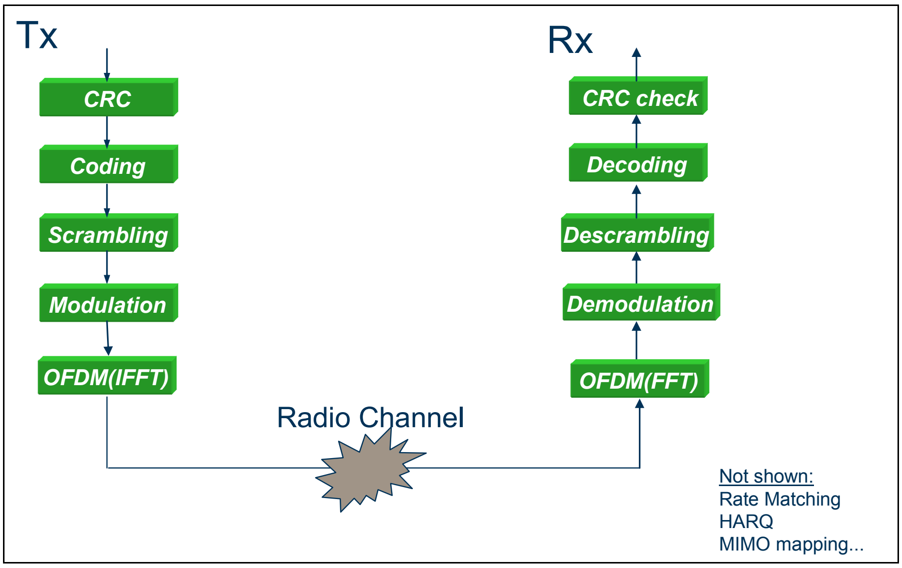


Figure 1-13 Tx & Rx physical layer processing.

Error detection and Correction - CRC and FEC Coding

In all radio systems the air interface will add noise to the signal (Figure 1-14). This will produce a distortion in the received signal. In the case of an analogue cellular system the human ear perform error correction of this received signal and noise. However in digital systems we do not have this luxury.

This noise will result in bit errors, that is what left the transmitter as a logic 1 could be interpreted as a logic 0 if the level of noise lowers the amplitude below the threshold for a logic 0. The same could be the case for a transmitted logic 0 being interpreted as a logic 1.

All digital systems must have some method of overcoming these errors.

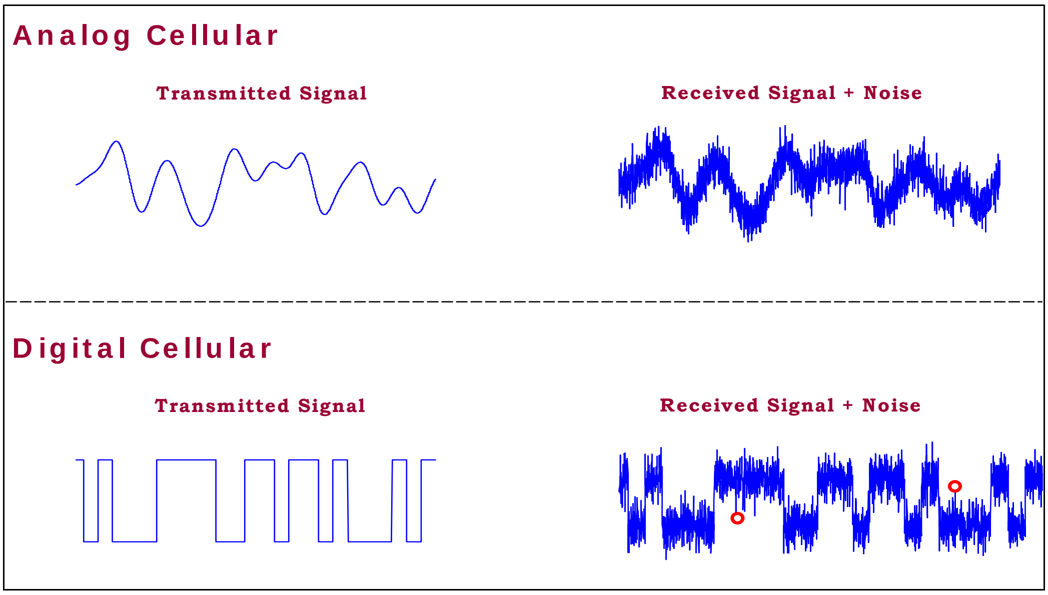


Figure 1-14: Digital Cellular Error Correction

This concept can be related to addressing envelopes. The address on the left (Figure 1-15) contains just enough information to get to the destination. The envelope on the right contains some unnecessary or redundant data.

If both envelopes were subjected to the same amount of errors the one on the left would be undeliverable. However the redundant data in the right hand one would allow it to be delivered.

A process that produces this error protection without increasing the bandwidth too much is required for cellular transmissions.

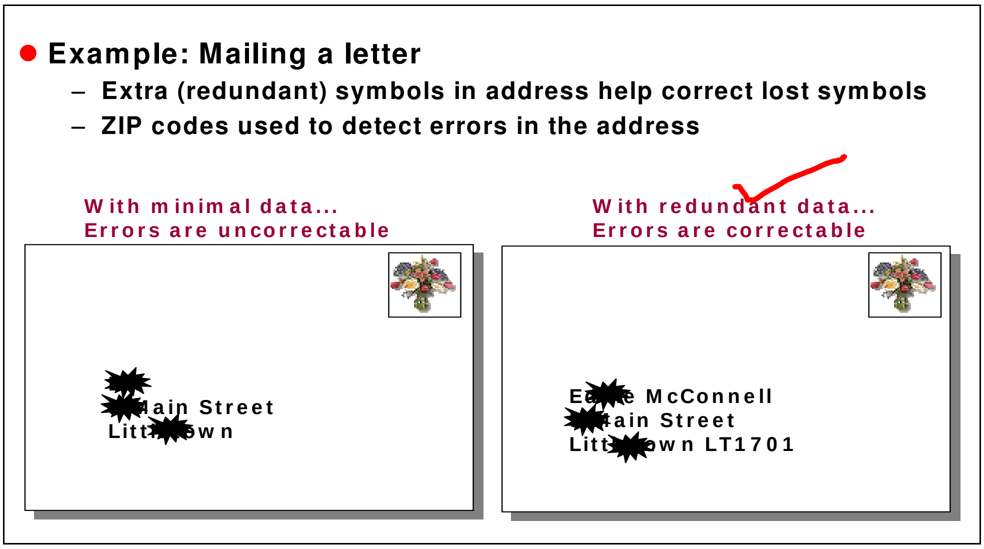


Figure 1-15: Digital Cellular Error Correction; Example: Mailing a letter in the US. Extra redundant symbols in address help correct symbols. ZIP codes are used to detect errors in the address.

CRC

Cyclic Redundancy Check (CRC) is used to detect if there are any uncorrected errors left after error correction.

Blocks of data are passed through a CRC generator (Figure 1-16), which will perform a mathematical division on the data producing a remainder or checksum. This is added to the block of data and transmitted.

The same division is performed on the data block in the receiver. If a different checksum is produced the receiver will know that there is an error in the block of data (alternatively there is an error in the received checksum). This knowledge can be used to calculate Block Error Ratio (BLER) used in the outer loop power control.

The longer the checksum, the greater is the accuracy of the process. In the example the checksum is twelve bits long. 24 bits of binary information represents 16 777 216 (2^{24}) different combinations. It could be imagined that various combinations of errors on the data and the checksum would produce the same checksum. The longer the checksum the less likely it is for this to happen. LTE uses a 24 bit CRC for the user data channels.

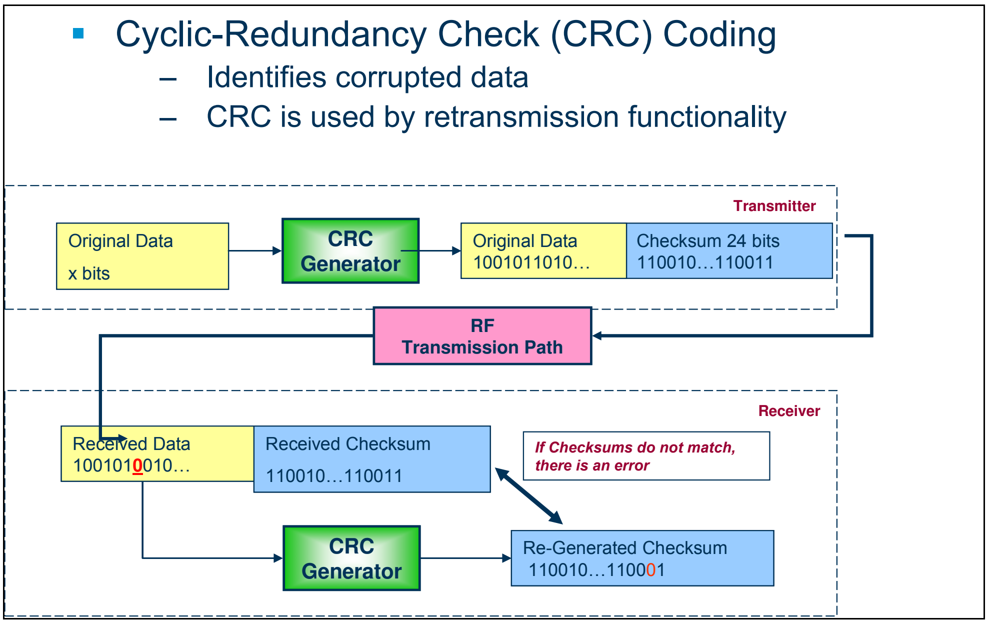


Figure 1-16: CRC Coding

FEC

The next part in the transmitter is Forward Error Correction (FEC). The function of this block is to help the receiver correct bit errors caused by the air interface.

One method for correcting these errors would be to send the information a number of times (Figure 1-17). Provided this is more than twice, the receiver could select which message is most correct by a "best out of three" decision. The more times the data is transmitted the better is the error protection. However the bandwidth is also increased proportionally

What is required is a system that provides forward error correction with minimal increase in the bandwidth.

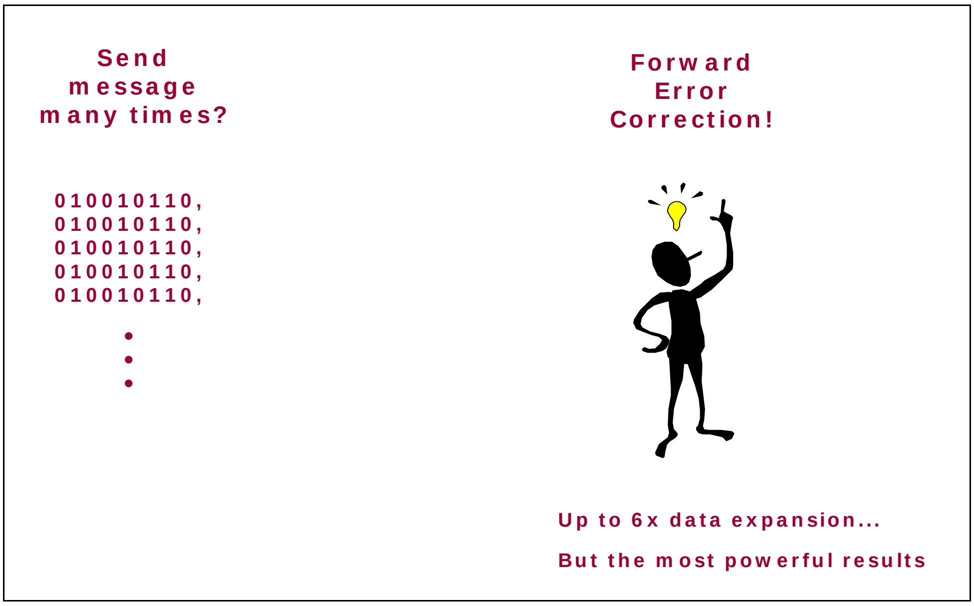


Figure 1-17: FEC Coding. How do you correct errors at the receiver?

There are two basic types of FEC available, block or continuous codes.

- Block Codes (Hamming Codes, BCH Codes, Reed-Solomon Codes)
- Continuous Codes (Convolutional Codes, Turbo Codes)
  - Data is processed continuously through FEC generator
  - Resulting data stream has built-in redundancy that can be extracted to correct bit errors.
- LTE uses Turbo codes with rate 1/3 for DL-SCH transmissions.
- Convolutional coding used for BCH

Figure 1-18. FEC coding approaches.

Continuous codes, such as convolutional codes and turbo codes are continuously produced as the data is fed to the FEC. The result will contain redundant bits that help to correct errors.

LTE utilizes turbo coding for the user data, regardless of if a low latency and real time processing are required or not. This type of coding gives a much better error correction performance than traditional methods, as for example convolutional coding. Some signaling, however, uses convolutional coding.

In LTE the turbo coding is quite similar to the coding in WCDMA, but improved with a QPP interleaver (Quadrature Permutation Polynomial interleaver).

Convolutional coding

Figure 1-19 gives a high level overview of the operation of the Convolutional coder.

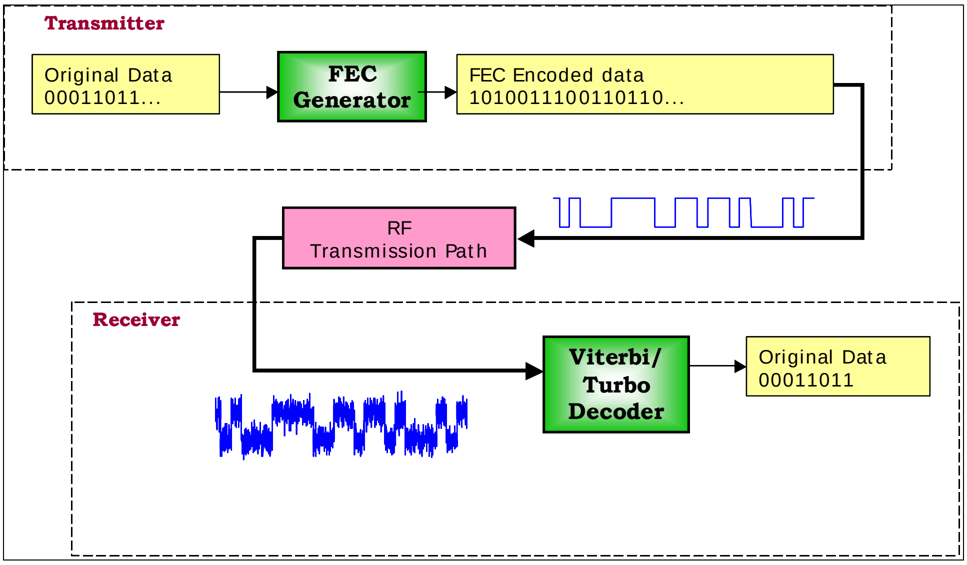


Figure 1-19: FEC Coding: The Convolutional Coder.

The original data is fed to the FEC generator, which in this case produces twice as much data. A coder that produces this increase, that is, two bits out for one bit in is known as a 1/2 rate coder. One that produces three bits of information for one input is known as a 1/3 rate coder. This output is not simply the input data repeated; it will be subjected to noise superimposed by the RF transmission path.

In the receiver, a device known as a ‘Viterbi Decoder’ can be used to correct these errors and recover the original data. This device works by taking the actual level of the data and estimating whether this was a 1 or a 0 when it left the transmitter, rather than use thresholds for 1 and 0.

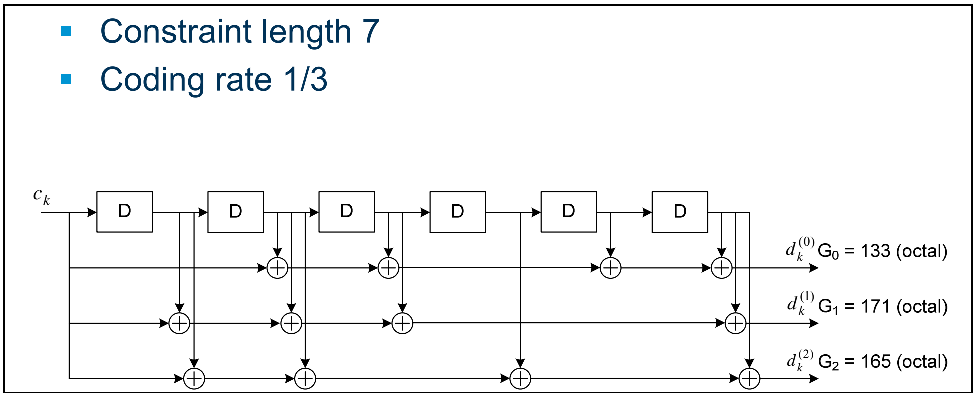


Figure 1-20: Tail Biting Convolutional Encoder.

Figure 1-20 shows how the convolutional encoder in E-UTRAN is structured using a shift register and twelwe XOR gates. For every input data bit there will be three output bits produced.

Multipath propagation and channel coding

Many radio propagation effects such as reflections can attenuate the transmitted radio signal Figure 1-21.

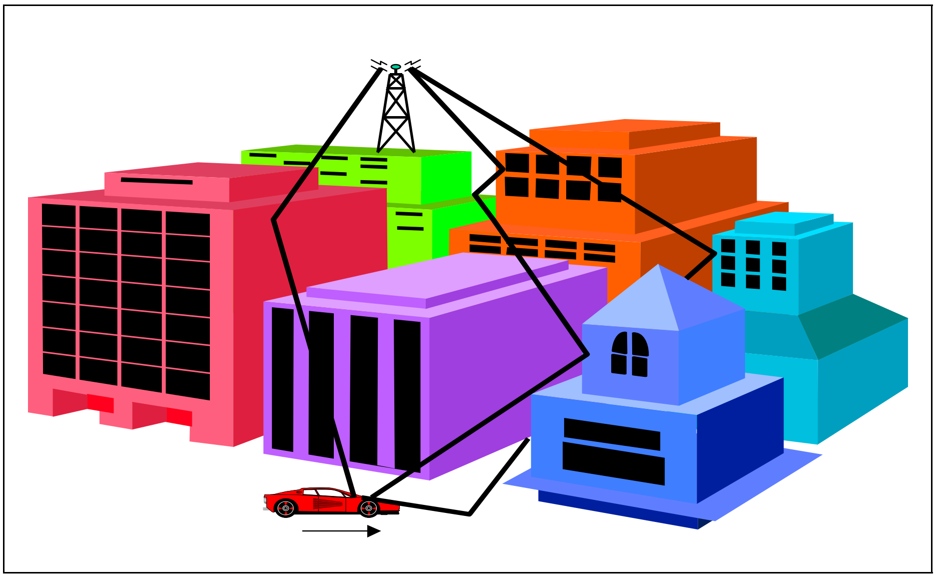


Figure 1-21: Multipath Propagation. The received signal contains many time-delayed replicas.

Multipath Propagation gives rise to:

1. InterSymbol Interference (ISI)
2. Fast fading (Rayleigh fading)

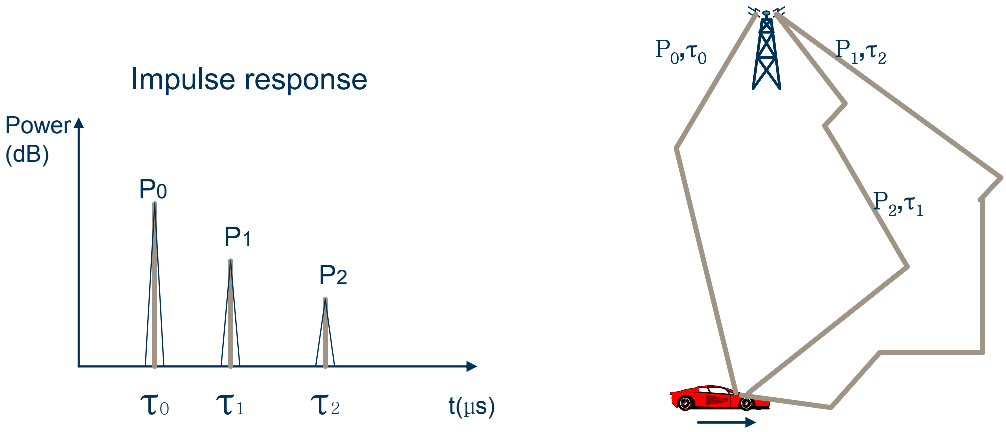


Figure 1-22. Multipath propagation and the resulting impulse response.

This occurs when the propagation wave reflects on an object, which is large compared to the wavelength, for example, the surface of the earth, buildings, walls, etc. This phenomenon is called multipath propagation and it has several effects, these are:

- Rapid changes in signal strength over a small area or time interval
- Random frequency modulation due to varying Doppler shifts on different multipath signals.
- Time dispersion caused by multipath propagation delays

- Previous symbol leaks into current symbol due to the different path delays
- When the amount of ISI exceeds a certain level (~10%) bit errors occur
- Can be reduced with equalizers, rake receivers or the use of OFDM

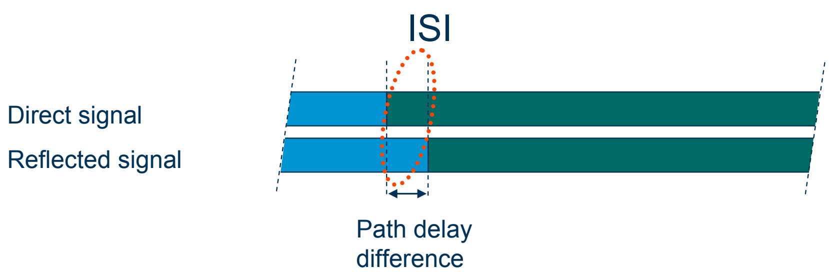


Figure 1-23 Inter Symbol Interference (ISI).

Multipath propagation yields signal paths of different lengths with different times of arrival at the receiver. Typical values of time delays (µs) are 0.2 in Open environment, 0.5 Suburban and 3 in Urban.

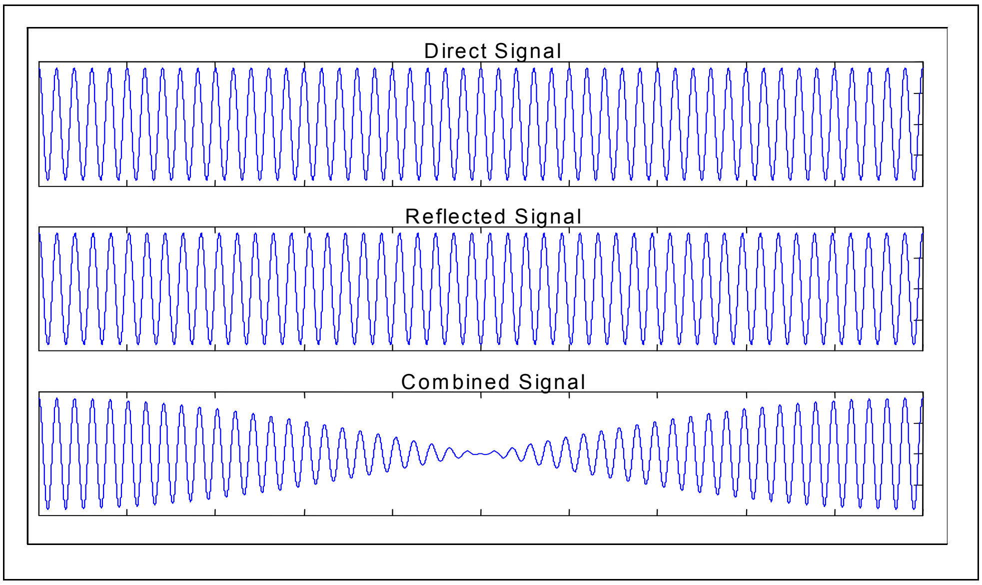


Figure 1-24: Multipath Fading.

The combination of direct and out-of-phase reflected waves at the receiver yields attenuated signals (Figure 1-24). This results in a varying received signal power as illustrated in Figure 1-25.

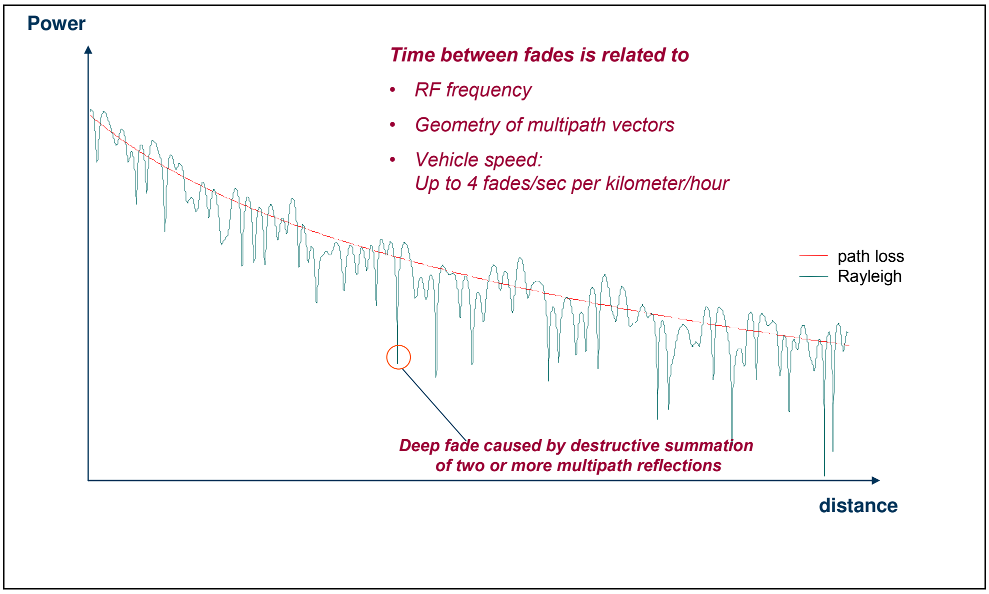


Figure 1-25 Path loss and fast fading.

This attenuation can result in bit errors that occur in consecutive blocks of data (burst errors). As a result the decoder fails to recover such errors.

Interleaving

The solution to overcome the problem with burst errors is to use a block interleaving technique as shown in Figure 1-26.

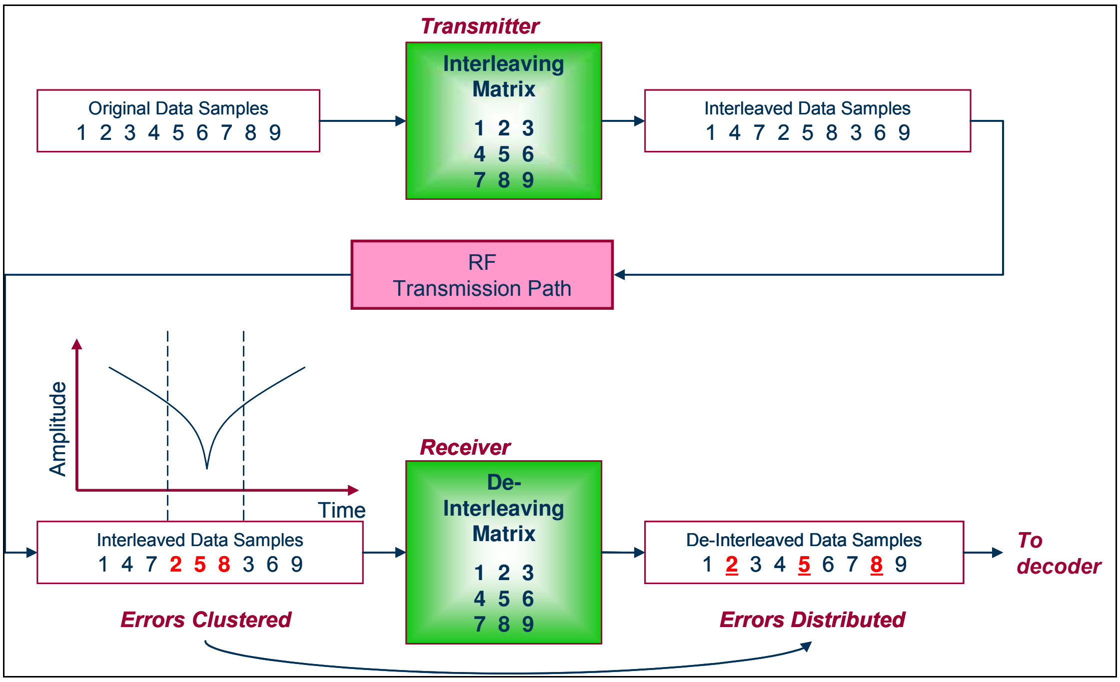


Figure 1-26: Block Interleaving.

A radio channel produces bursty errors. Because continuous codes are most effective against random errors, interleaving is used to randomize the bursty errors. The interleaving scheme can be either block interleaving or convolutional interleaving. Typically, block interleaving is used in cellular applications. The first step of interleaving is determined by the delay requirements of the service.

Turbo Codes

Turbo Codes are newly introduced parallel, recursive, and systematic convolutional codes. These codes are used for channel coding and decoding in order to detect and correct errors occurring in the transmission of digital data through different channels

The iterative method of the decoding scheme helps to achieve the theoretical limit (near Shannon-limit) in error correction performance. Each decoder uses the received data and extrinsic information, which has been delivered by the preceding decoder to give decoded data and new extrinsic information. Interleaving helps the decoders to improve their correction capability by keeping the extrinsic information with the received data un-correlated.

The Turbo code structure is based on a combination of two or more weak error control codes. See Figure 1-27.

- Outperform Convolutional codes
  - Requires much more processing power; data packets may be decoded off-line
  - Used for all DL-SCH transmissions
- Interleaving (time diversity) enhances error correction

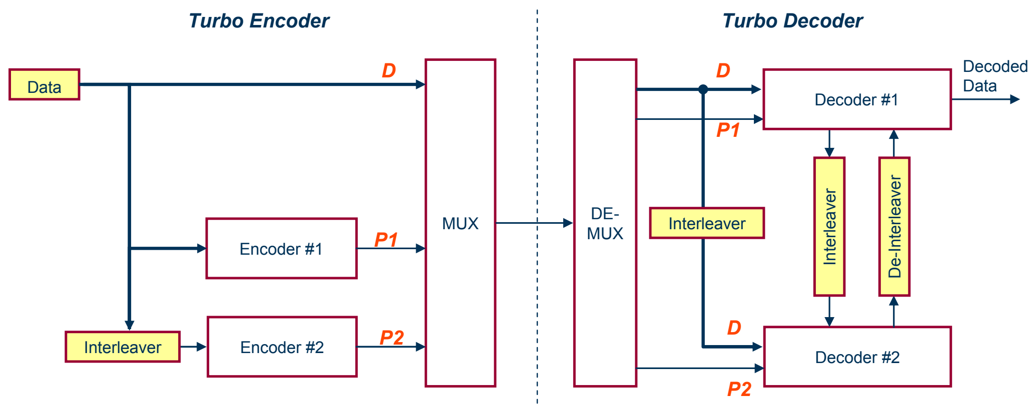


Figure 1-27: Turbo Coding.

The data bits are interleaved between two encoders, generating two parity streams. The whole process results in a code that has powerful error correction properties. A more detailed figure of the turbo coder is shown in Figure 1-28.

- Rate 1/3
- QPP interleaver

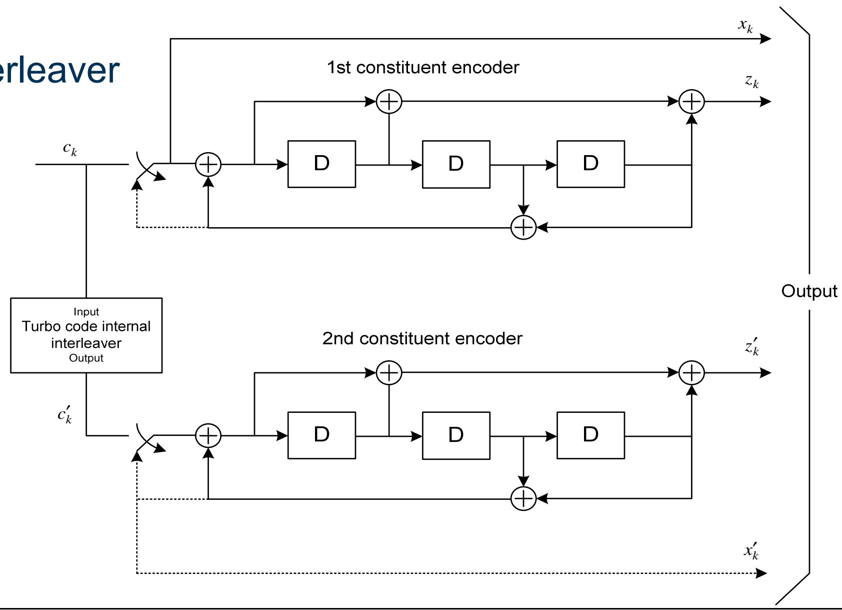


Figure 1-28: Example of Turbo Code Generator

In LTE a QPP (Quadrature Permutation Polynomial) interleaver is used between two rate ½ encoders. The overall coding rate is 1/3.

Rate matching

Rate matching is performed on the data to change the data rate to one that can be accommodated by the system. It should be noted that this function could not only be used to reduce the data rate (by puncturing bits) but also to increase the data rate (by padding it with extra bits).

- Rate Matching is used to equalize the data rates to fit the transport format
- Rate Matching may be performed by:
  - Padding with extra bits
  - Puncturing of bits

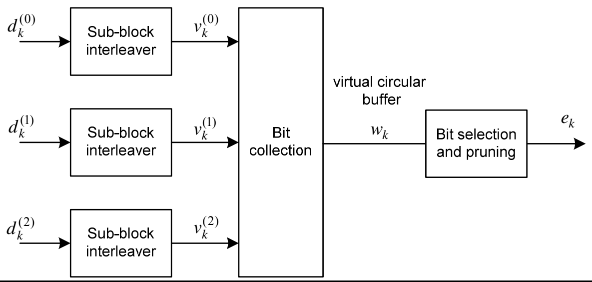


Figure 1-29:Rate Matching

SCRAMBLING

In LTE, a frequency reuse of 1 will typically be used. This means that all cells use the same frequency band(s). For UEs close to the cell border, this will lead to massive interference in both UL and DL.

In order to reduce this inter cell interference, a cell specific bit-level scrambling is applied for all transmissions in both UL and DL.

Other solutions for mitigating the inter-cell interference includes e.g. Inter Cell Interference Co-ordination (ICIC). ICIC co-ordinates the radio resource allocations (scheduling) between neighboring cells that experience problems.

- Cell specific bit-level scrambling used in LTE for all datastreams in UL and DL
  - used in order to achieve interference randomization between cells
- No frequency planning (freq reuse 1)
  - massive inter-cell interference mitigated by scrambling and interference co-ordination techniques (e.g. ICIC)
- Common scrambling used for cells in broadcast/multicast service transmissions (MBMS)

Figure 1-30. Scrambling in LTE.

MODULATION

The next step after channel coding and scrambling is modulation. The modulation process maps blocks of scrambled bits onto symbols. The different symbols correspond to a specific amplitude and/or phase shift of the carrier wave. Three different modulation schemes are supported in E-UTRAN;

- QPSK (Quadrature Phase shift keying)
- 16-QAM (16 Quadrature Amplitude Modulation)
- 64-QAM (64 Quadrature Amplitude Modulation)

QPSK is theoretically a pure phase modulation, i.e. it has constant amplitude, while 16-QAM and 64-QAM both uses a combination of phase and amplitude.

The acknowledgements in DL are transmitted with BPSK (Binary Phase Shift Keying), which only has one bit per symbol.

The different modulation schemes are produced by an IQ-modulator. The IQ modulator splits the data stream (pairs of 1's and 0's) into on I-branch (Inphase) and one Q-branch (Quadrature phase). The In-phase part corresponds to the real part and the Quadrature phase corresponds to the imaginary part in the mathematical expression I+jQ.

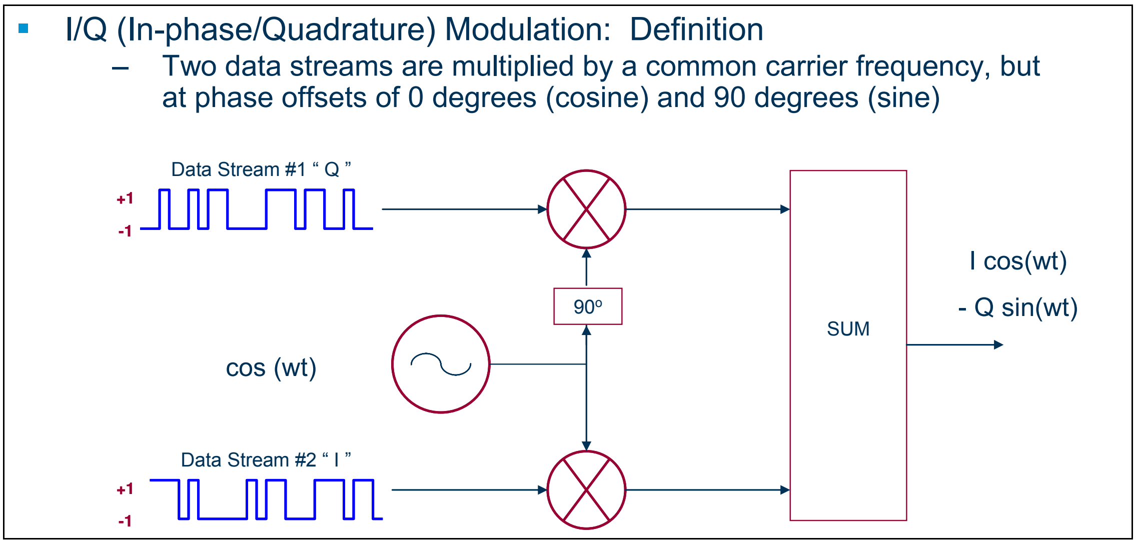


Figure 1-31. IQ-modulation.

For QPSK, this results in a constellation diagram as shown in Figure 1-32.

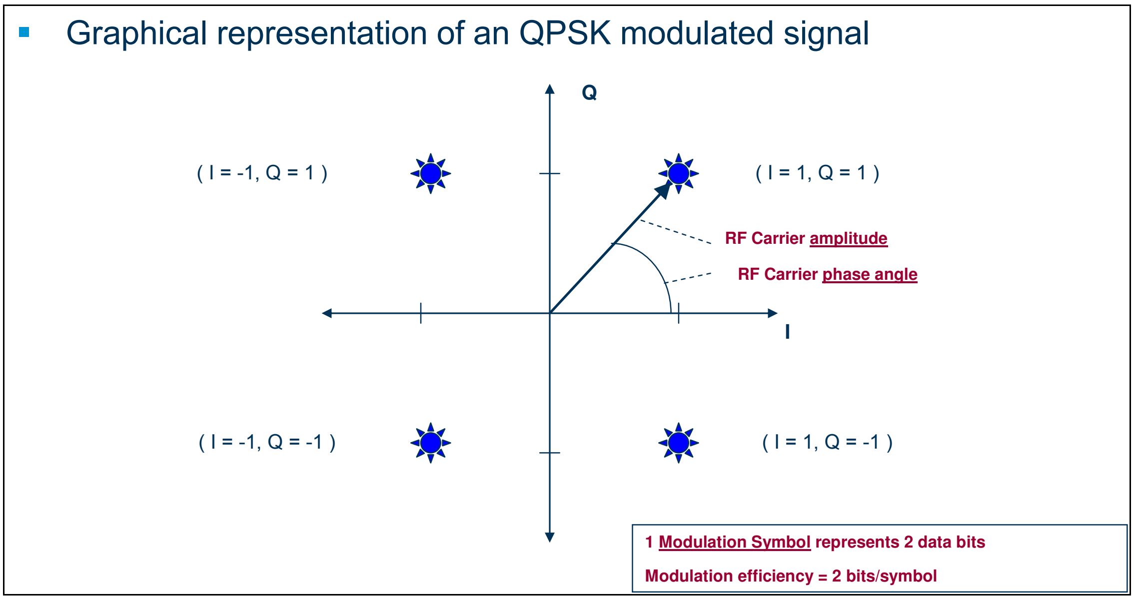


Figure 1-32 QPSK constellation.

The 1's and 0's are actually converted the to different amplitude levels depending on the modulation scheme (e.g. ±1/√2 for QPSK) according to:

$b(i), b(i+1)$	***I***	***Q***
00	$1/\sqrt{2}$	$1/\sqrt{2}$
01	$1/\sqrt{2}$	$-1/\sqrt{2}$
10	$-1/\sqrt{2}$	$1/\sqrt{2}$
11	$-1/\sqrt{2}$	$-1/\sqrt{2}$

At the receiver side, a corresponding IQ-demodulation takes place. Here the I and Q data streams are recovered as illustrated in Figure 1-33.

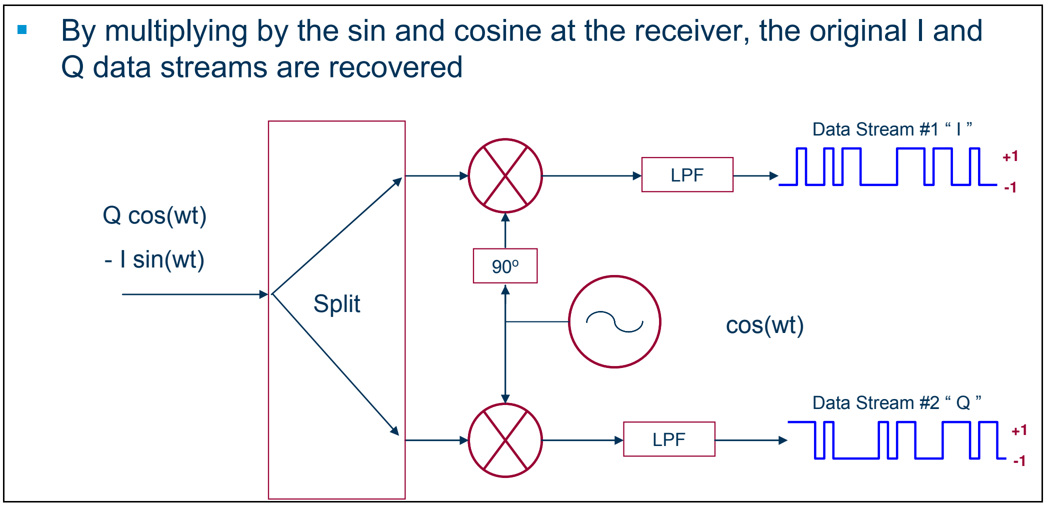


Figure 1-33 IQ-demodulation

The three different modulation schemes and constellation diagrams are illustrated in Figure 1-34.

- The sub-carriers are modulated with a certain modulation scheme
  - maps the data bits into a carrier phase and amplitude (symbols)
- E-UTRAN user data channels supports QPSK, 16QAM and 64QAM
- 16QAM allows for twice the peak data rate compared to QPSK
- 64QAM allows for three times the data rate compared to QPSK
- Higher order modulation more sensitive to interference
  - Useful mainly in good radio channel conditions (high C/I, Little or no dispersion, Low speed) e.g. Close to cell site & Micro/Indoor cells
- BPSK is used for some signaling (PHICH)

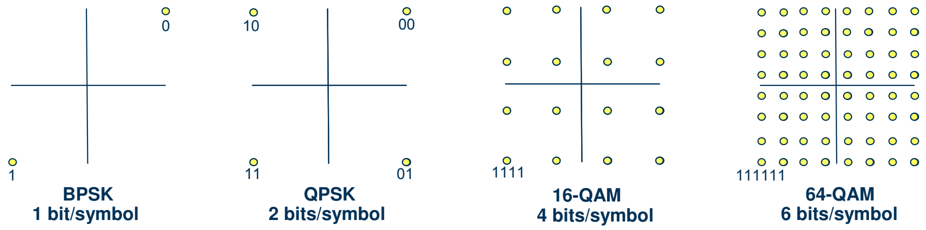


Figure 1-34. Modulation.

In E-UTRAN, the modulation is carried out per sub-carrier in the OFDM signal. This means that each 15 kHz subcarrier is modulated with either QPSK, 16-QAM or 64-QAM.

OFDM

At the transmitter the coded and modulated data stream is split up to a number of sub-streams. The number of sub-streams can range from typically 12 (one resource block) and up to 1200 (100 resource blocks at 20MHz bandwidth). Each stream is fed into the IFFT block and transformed into a corresponding subcarrier. This is the principle of OFDM. The number of subcarriers thus ranges from 12 to 1200.

At the receiver a reverse process is performed. The OFDM signal is fed into a FFT block. The output of the FFT block corresponds to the input of the IFFT block at the transmitter side. This parallel data stream output is converted into a serial stream, demodulated, and decoded.

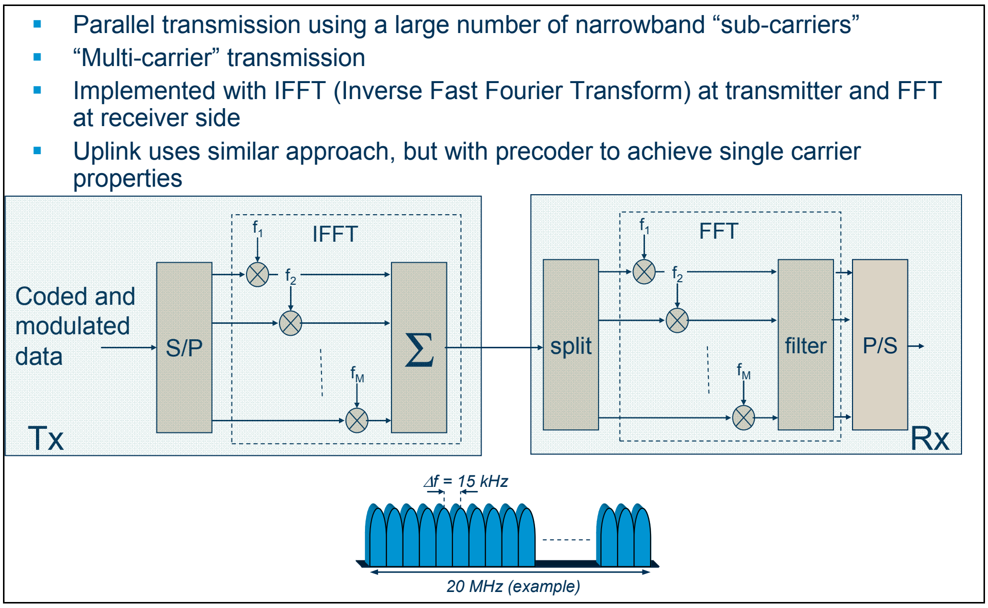


Figure 1-35 OFDM principle

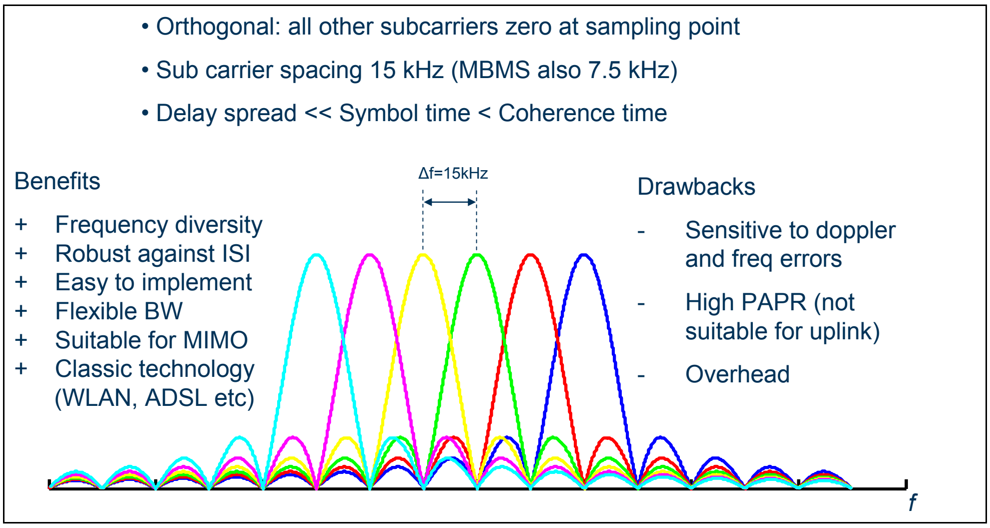


Figure 1-36 OFDM - Orthogonal Frequency Multiple Multiplexing

OFDMA

OFDMA (Orthogonal Frequency Multiple Access) is the multiple access method that separates the users and channels in frequency and time. The different users and/or different channels are orthogonal within one cell. This means that they do not interfere with each other in the same cell. This is valid for both uplink and downlink in LTE.

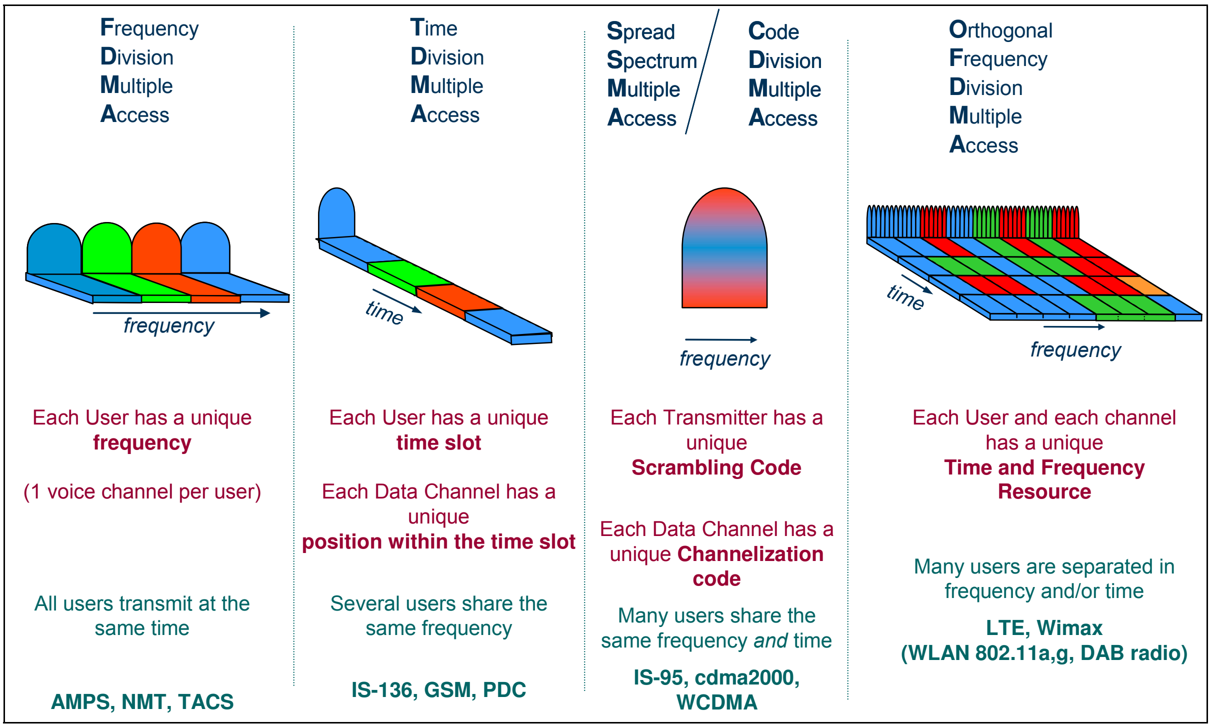


Figure 1-37 Multiple Access approaches.

OFDMA is used by LTE and Wimax. WLAN 802.11 a,g, ADSL, VDSL and DAB radio uses OFDM.

In WCDMA, the users/channels are not orthogonal in uplink within the cell. This leads to a high interference level and a need for an extensive and accurate power control.

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2 Radio Interface

OBJECTIVES:

On completion of this chapter the students will be able to:

- **Explain the Radio Interface Structure**
  - –Detail the channel structure of the radio interface
  - –Describe the physical signals in UL and DL
  - –Detail the time-domain structure in the radio interface in UL and DL for both FDD and TDD mode
  - –Detail the downlink transmission technique
  - –Have a good understanding of the OFDM principle, signal generation and processing
  - –Detail the reference symbols in DL
  - –Detail the control signaling in DL
  - –Explain the paging procedure
  - –Explain cell search procedure
  - –Explain HARQ
  - –Detail the uplink transmission technique
  - –Have a good understanding of the SC-FDMA principle, signal generation and processing
  - –Explain the pros and cons with OFDM and SC-FDMA
  - –Detail the control signaling in UL
  - –Detail the random access procedure
  - –Describe the Power Control in UL and DL
  - –Describe the concepts of layers, channel rank, spatial multiplexing, open and closed loop spatial multiplexing, TX diversity, beamforming, SU-MIMO and MU-MIMO

Figure 2-1. Objectives.

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INTRODUCTION

The radio interface in LTE is developed according to the requirements of spectrum flexibility, spectrum efficiency, cost effectiveness etc. Robustness against time dispersion has influenced the choice of transmission technique in both UL and DL.

Spectrum flexibility incorporates the possibility to use both paired and unpaired spectrum, i.e. LTE should support both FDD- and TDD-based duplex arrangements, respectively. Also, the support for operation in six different bandwidths, 1.4, 3, 5, 10, 15 and 20 MHz, plays an important role of the spectrum flexibility part in the standardization of the radio interface. Actually, the LTE radio interface implementation supports operation in any bandwidth between 1.4 and 20 MHz in steps of one resource block, which corresponds to 12 subcarriers or 180 kHz.

A high spectrum efficiency is achieved by the use of higher order modulation schemes, like 16-QAM and 64-QAM and advanced antenna solutions, including transmit- and receiver diversity, beamforming and spatial multiplexing (MIMO).

Beamforming is a type of radio frequency used to send strong, focused signals to a targeted device.

Beamforming is also widely used in radar, sonar, medical imaging, and audio applications

Furthermore, the Inter-symbol Interference (ISI) is reduced by the choice of OFDM in the DL and SC-FDMA in UL. Both of these methods results in a long symbol time and thus a reduced ISI, which increases the performance in highly time dispersive radio environments.

The UL and DL have a similar time-domain structure.

The radio interface is structured in a layered model, similar to WCDMA, with a layer 2 bearer (here called EPS Bearer Service), which corresponds to a PDP-context in Rel. 6, carrying layer 3 data and the end-to-end service. The EPS bearer is carried by the E-UTRA Radio Bearer Service in the radio interface. The E-UTRA radio bearer is carried by the radio channels. The radio channel structure is divided into logical, transport and physical channels. The logical channels are carried by transport channels, which in turn are carried by the physical channels as illustrated in Figure 2-2.

Also known as spectral efficiency or bandwidth efficiency, a cellular network's spectral efficiency is equivalent to the maximum number of bits of data that can be transmitted to a specified number of users per second while maintaining an acceptable quality of service.

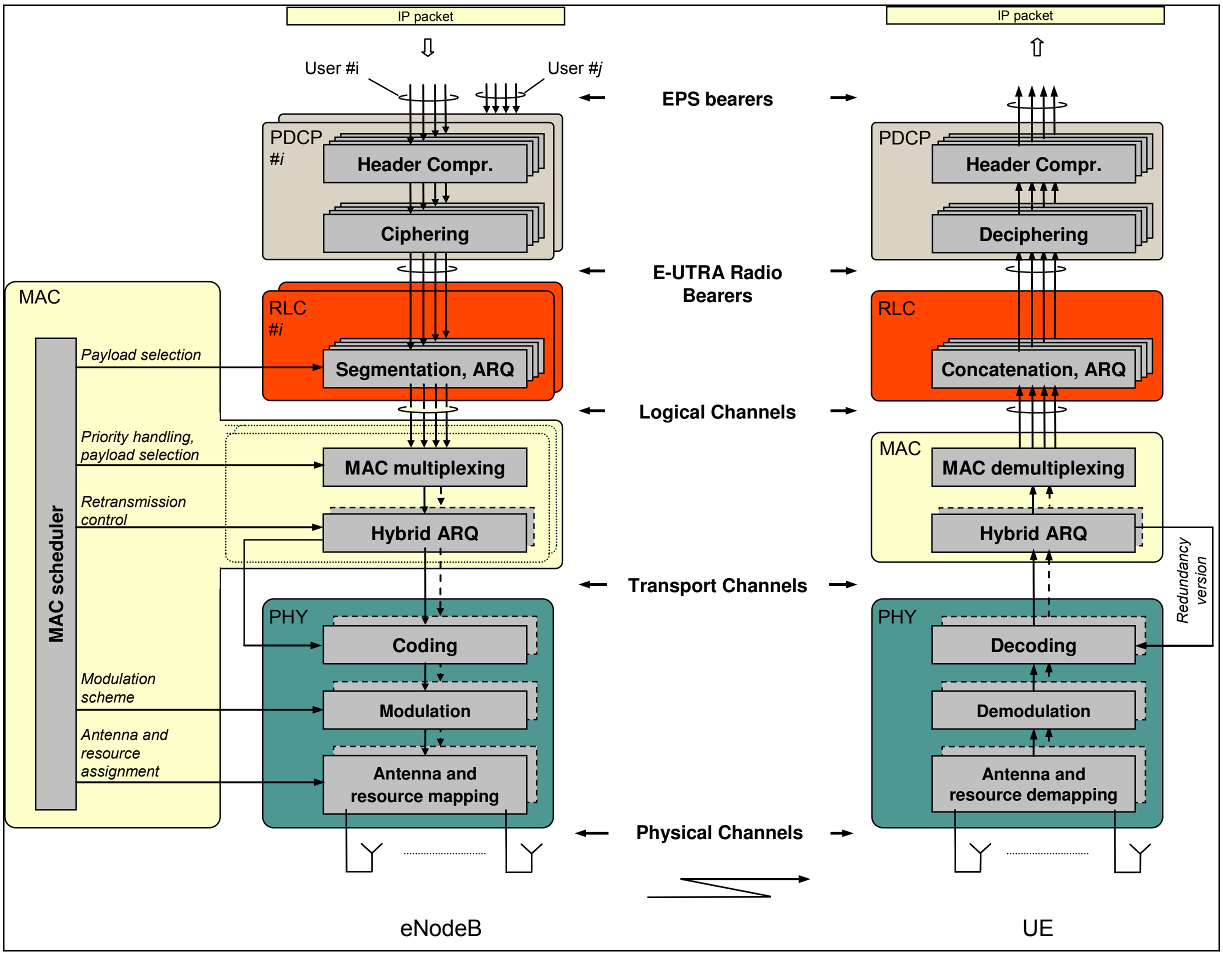


Figure 2-2. Radio interface structure.

The protocols performing the functions in the radio interface are: PDCP (Packet Data Convergence Protocol), RLC (Radio Link Protocol), MAC (Medium Access Control) and the physical layer. For control signaling the RRC (Radio Resource Control) protocol is used to transfer the NAS (Non Access Stratum) information over the radio interface.

The PDCP protocol maps the EPS bearer onto the E-UTRA Radio Bearer and performs Robust Header Compression (ROHC). The RLC protocol maps the E-UTRA Radio Bearer to a logical channel and performs segmentation, in-sequence delivery and retransmissions. The MAC protocol maps the logical channel to a transport channel and is responsible for Hybrid ARQ (HARQ) and scheduling. The physical layer maps the transport channel onto a physical channel and performs channel coding, modulation etc.

The radio interface protocol architecture is shown in Figure 2-3 for both Control Plane and User Plane.

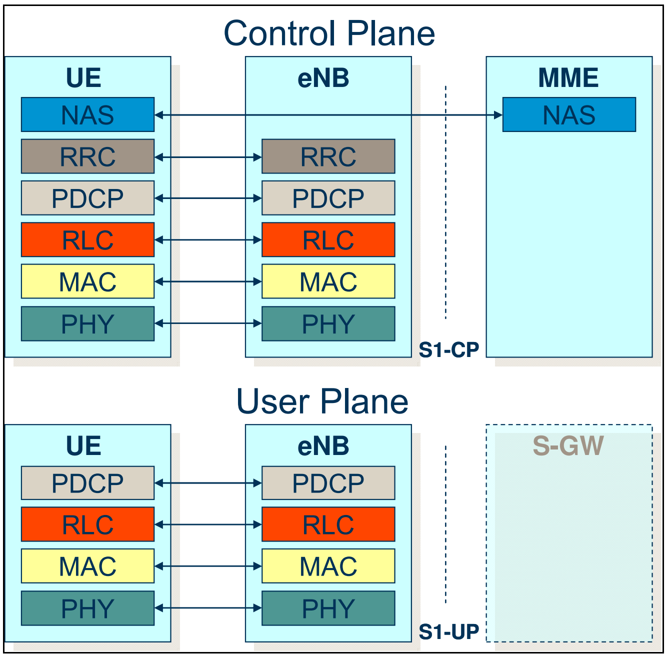


Figure 2-3. Radio interface protocol architecture.

MEDIUM ACCESS CONTROL (MAC)

The MAC layer for the LTE access can be compared to the Rel-6 MAC-hs/MAC-e and covers mainly similar functionality: HARQ, priority handling (scheduling), transport format selection and DRX control (not part of MAC in Rel-6).

The Hybrid ARQ (HARQ) protocol is very similar to the solution adopted for HSDPA, i.e., the protocol uses multiple stop-and-wait hybrid ARQ processes. The motivation for this type of protocol is to allow continuous transmission, which cannot be achieved with a single stop-and-wait scheme, while at the same time having some of the simplicity of a stop-and-wait protocol. The functionality and performance is similar to that of a window based selective repeat protocol but only single-bit HARQ feedback is required.

The protocol is modeled as a number of parallel HARQ processes, where each process uses a simple stop-and-wait protocol. By using N_{HARQ} parallel HARQ processes, where N_{HARQ} > Round trip time / subframe length, a continuous transmission is achieved. The maximum UE processing time before sending a HARQ feedback has been specified such that 8 HARQ process are needed for continuous transmission in FDD with a typical eNB implementation.

In 3GPP, the current working assumption is to use a synchronous HARQ for the uplink and an asynchronous HARQ for the downlink. That is, for the uplink, the subframe when the retransmission occurs is known at the receiver, while for the downlink the scheduler has the freedom to choose the subframe for the retransmission dynamically. For both up- and downlink a synchronous, single-bit HARQ feedback (ACK/NACK) is sent providing feedback about the success of the previous transmission. The HARQ protocol is adaptive in both uplink and downlink meaning that the scheduler can decide to use a different resource for a retransmission compared to for the previous (re)transmission.

The redundancy version of a (re)transmission needs to be known by the receiver. Thus, the redundancy version and an indication whether the transmission contains a first transmission or a retransmission is indicated on the PDCCH.

In case the data is a retransmission of previously stored data, the received data is soft combined with the data stored in the soft buffer. In case the received data is not a retransmission or a retransmission of data that has not been stored, the soft buffer is cleared and only the latest received data is placed in the buffer.

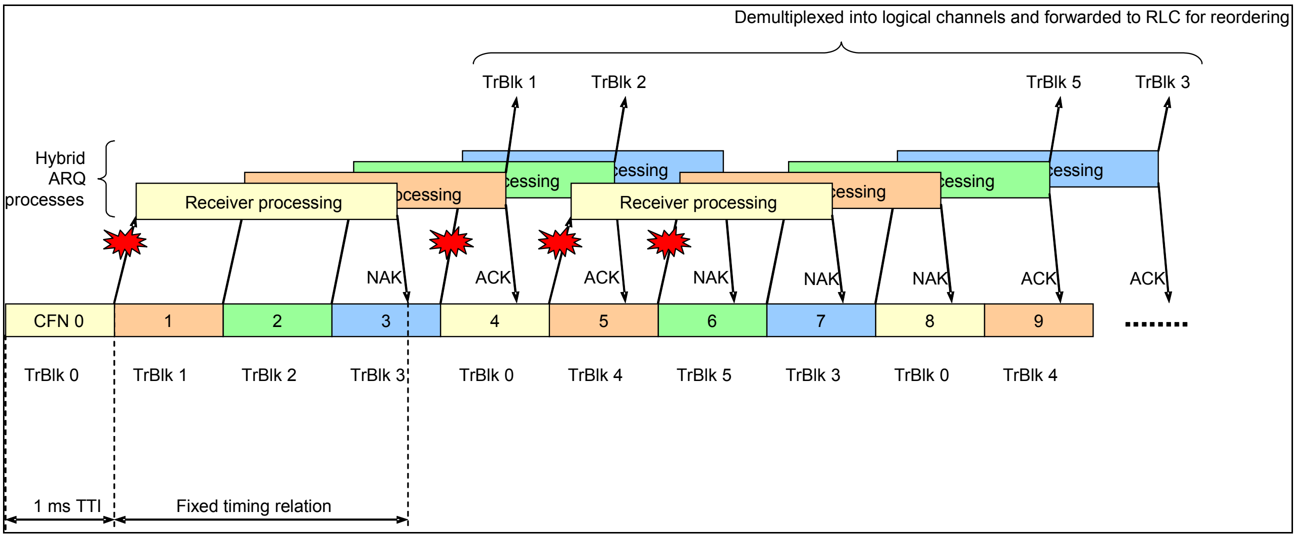


Figure 2-4 HARQ principle – four multiple HARQ processes

The MAC layer does not support in-order delivery to RLC. HARQ retransmissions will lead to that MAC Protocol Data Units (PDUs) are received in a different order than they were sent. Due to the lack of MAC sequence numbers it is up to the RLC receivers to restore the original sequence and to provide in-order delivery to higher layers.

The MAC layer supports the ARQ in the RLC layer with certain triggers if residual HARQ errors are detected, e.g., if the maximum number of HARQ transmissions has been reached.

Finally, MAC also allows flows from a single user to be multiplexed. Correspondingly, the MAC header carries multiplexing information used to de-multiplex RLC PDUs to different flows.

CHANNEL STRUCTURE

Physical L provides transport ch.
MAC L provides logic ch

transport ch. describe how data transmitted
logical ch. describe kind of data conveyed

The physical layer provides transport channels to the L2. These transport channels differ in their characteristics how data is transmitted and are mapped to different logical channels provided by the MAC layer. Logical channels describe which type of data is conveyed.

LOGICAL CHANNELS

The logical channels can be divided into control channels and traffic channels. The control channels are used for transfer of control plane information and the traffic channels are used for the transfer of user plane information. The following logical channels are supported for LTE:

Control Channels

- **Broadcast Control Channel (BCCH):** A downlink channel for broadcasting system control information.
- **Paging Control Channel (PCCH):** A downlink channel that transfers paging information. This channel is used when the network does not know the location cell of the UE.
- **Common Control Channel (CCCH):** This channel is used by the UEs having no RRC connection with the network. CCCH would be used by the UEs when accessing a new cell or after cell reselection.

LTE MBMS is a point-to-multipoint interface that delivers broadcast and multicast services, both within a cell and the core network

- **Multicast Control Channel (MCCH):** A point-to-multipoint downlink channel used for transmitting MBMS scheduling and control information from the network to the UE, for one or several MTCHs. After establishing an RRC connection this channel is only used by UEs that receive MBMS.
- **Dedicated Control Channel (DCCH):** A point-to-point bi-directional channel that transmits dedicated control information between a UE and the network. Used by UEs having an RRC connection.

LTE MBMS is a point-to-multipoint interface that delivers broadcast and multicast services, both within a cell and the core network

- **Broadcast Control Channel (BCCH)**
  - DL broadcast of system control information.
- **Paging Control Channel (PCCH)**
  - DL paging information. UE position not known on cell level
- **Common Control Channel (CCCH)**
  - UL/DL. When no RRC connection exists.
- **Multicast Control Channel (MCCH)**
  - DL point-to-multipoint for MBMS scheduling and control, for one or several MTCHs.
- **Dedicated Control Channel (DCCH)**
  - UL/DL dedicated control information. Used by UEs having an RRC connection.

Figure 2-5. Logical channels - control.

Traffic Channels

- **Dedicated Traffic Channel (DTCH):** A Dedicated Traffic Channel (DTCH) is a point-to-point channel, dedicated to one UE, for the transfer of user information. A DTCH can exist in both uplink and downlink.

- **Multicast Traffic Channel (MTCH):** A point-to-multipoint downlink channel for transmitting traffic data from the network to the UEs using MBMS.

- **Dedicated Traffic Channel (DTCH)**
  - UL/DL Dedicated Traffic to one UE, user information.
- **Multicast Traffic Channel (MTCH)**
  - DL point-to-multipoint. MBMS user data.

Figure 2-6. Logical channels - traffic.

TRANSPORT CHANNELS

An effort has been made to keep a low number of transport channels in order to avoid unnecessary switches between different channel types, which are found to be time consuming in UMTS. In fact there is currently only one transport channel in downlink and one in uplink carrying user data, i.e., channel switching is not needed.

For LTE, the following transport channels are provided by the physical layer:

Downlink:

- **Broadcast Channel (BCH):** A low fixed bit rate channel broadcast in the entire coverage area of the cell. Beamforming is not applied.

- **Downlink Shared Channel (DL-SCH):** A channel with possibility to use HARQ and link adaptation by varying the modulation, coding and transmit power. The channel is possible to broadcast in the entire cell and beamforming may be applied. UE power saving (DRX) is supported to reduce the UE power consumption. MBMS transmission is also supported.
- **Paging Channel (PCH):** A channel that is broadcasted in the entire cell. DRX is supported to enable power saving.
- **Multicast channel (MCH):** A separate transport channel for multicast (MBMS). This channel is broadcast in the entire coverage area of the cell. Combining of MBMS transmissions from multiple cells (MBSFN) is supported.

- **Broadcast Channel (BCH)**
  - System Information broadcasted in the entire coverage area of the cell. Beamforming is not applied.
- **Downlink Shared Channel (DL-SCH)**
  - User data, control signaling and System Info. HARQ and link adaptation. Broadcast in the entire cell or beamforming. DRX and MBMS supported.
- **Paging Channel (PCH)**
  - Paging Info broadcasted in the entire cell. DRX
- **Multicast Channel (MCH)**
  - MBMS traffic broadcasted in entire cell. MBSFN is supported.

Figure 2-7. Transport channels DL.

Uplink:

- **Uplink Shared channel (UL-SCH):** A channel with possibility to use HARQ and link adaptation by varying the transmit power, modulation and coding. Beamforming may be applied.
- **Random Access Channel (RACH):** A channel used to obtain timing synchronization (asynchronous random access) and to transmit information needed to obtain scheduling grants (synchronous random access). The transmission is typically contention based. For UEs having an RRC connection there is some limited support for contention free access.

- **Uplink Shared channel (UL-SCH)**
  - User data and control signaling. HARQ and link adaptation. Beamforming may be applied.
- **Random Access Channel (RACH)**
  - Random Access transmissions (asynchronous and synchronous). The transmission is typically contention based. For UEs having an RRC connection there is some limited support for contention free access.

Figure 2-8. Transport channels UL.

PHYSICAL CHANNELS

The physical layer offers services to the MAC layer in the form of transport channels. User data to be transmitted is delivered to the physical layer from the MAC layer in the form of transport blocks. The MAC layer at the transmitter side also provides the physical layer with control information necessary for transmission and/or reception of the user data.

The physical layer defines *physical channels* and *physical signals*. A physical channel corresponds to a set of physical resources used for transmission of data and/or control information from the MAC layer. A physical signal, which also corresponds to a set of physical resources, is used to support physical-layer functionality but do not carry any information from the MAC layer. From a specification perspective, the interface between 3GPP TS 36.211 and 36.212 is defined in terms of physical channels, while physical signals are generated inside 36.211.

The following physical channels and physical signals are defined:

Physical channels

- **Physical Downlink Shared Channel (PDSCH)**
  - transmission of the DL-SCH transport channel
- **Physical Uplink Shared Channel (PUSCH)**
  - transmission of the UL-SCH transport channel
- **Physical Control Format Indicator Channel (PCFICH)**
  - indicates the PDCCH format in DL
- **Physical Downlink Control Channel (PDCCH)**
  - DL L1/L2 control signaling
- **Physical Uplink Control Channel (PUCCH)**
  - UL L1/L2 control signaling
- **Physical Hybrid ARQ Indicator Channel (PHICH)**
  - DL HARQ info
- **Physical Broadcast Channel (PBCH)**
  - DL transmission of the BCH transport channel.
- **Physical Multicast Channel (PMCH)**
  - DL transmission of the MCH transport channel.
- **Physical Random Access Channel (PRACH)**
  - UL transmission of the random access preamble as given by the RACH transport channel.

Physical signals

- **Reference Signals (RS)**
  - support measurements and coherent demodulation in uplink and downlink.
- **Primary and Secondary Synchronization signals (P-SCH and S-SCH)**
  - DL only and used in the cell search procedure.
- **Sounding Reference Signal (SRS)**
  - supports UL scheduling measurements

Figure 2-9. Physical channels and signals.

Figure 2-10 illustrates the logical channels and the mapping to transport channels and physical channels.

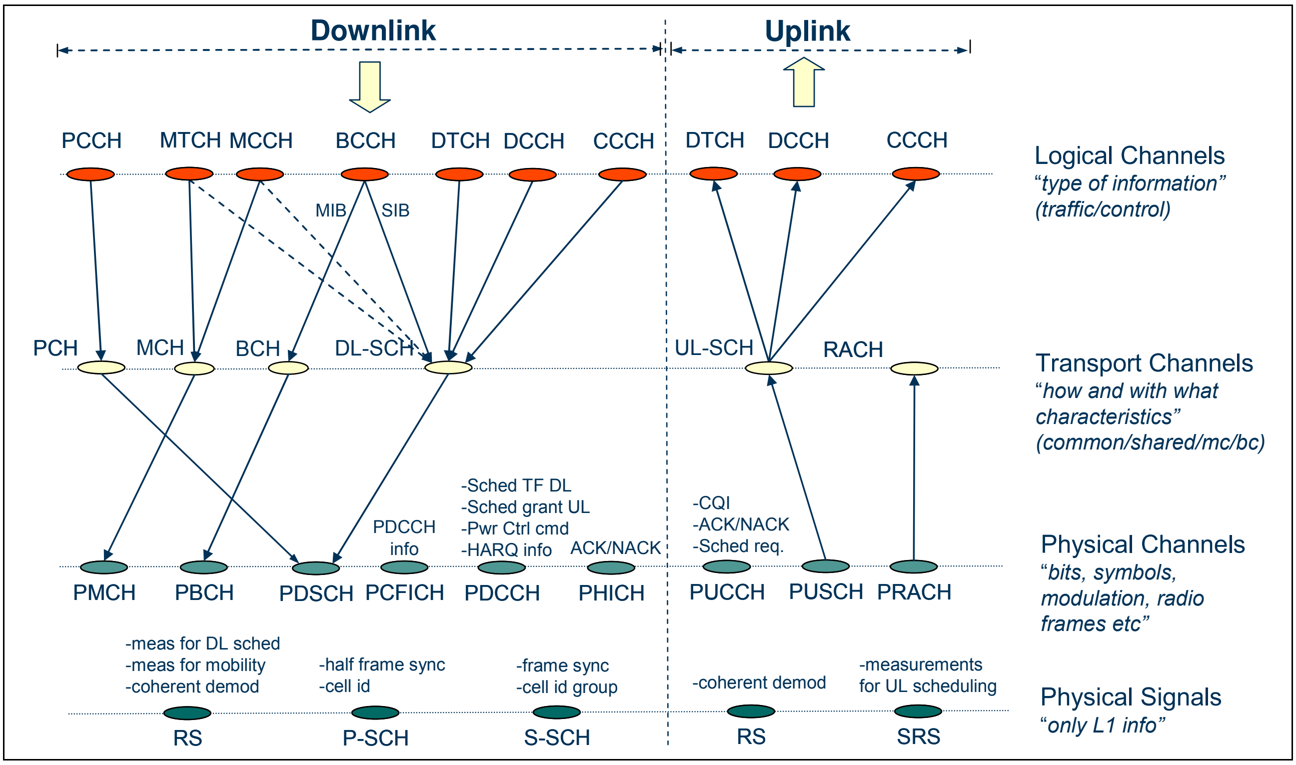


Figure 2-10 Channel mapping

TIME-DOMAIN STRUCTURE

Figure 2-11 illustrates the high-level time-domain structure for LTE transmission in case of FDD mode-of-operation. The figure is valid for both the downlink and uplink transmission direction (except that PBCH and SCH are only for DL and in uplink the symbols are called DFTS-OFDM symbols). Each (radio) *frame* of length T_f = 10 ms consists of ten equally-sized *subframes* of length $T_{subframe}$ = 1 ms. Each subframe, in turn, consists of two equally-sized *slots* of length T_{slot} = 0.5 ms. The subframe is the typical scheduling unit of LTE while the slots are relevant in case of frequency hopping.

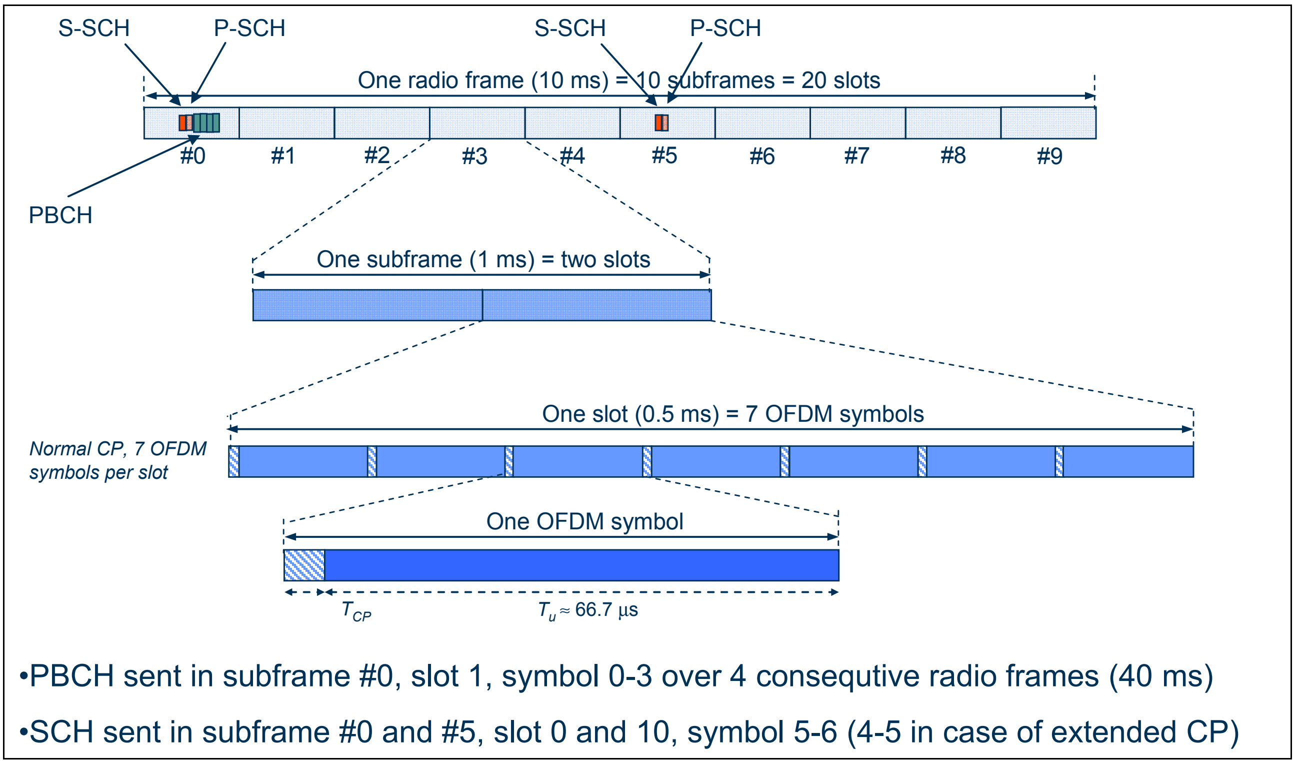
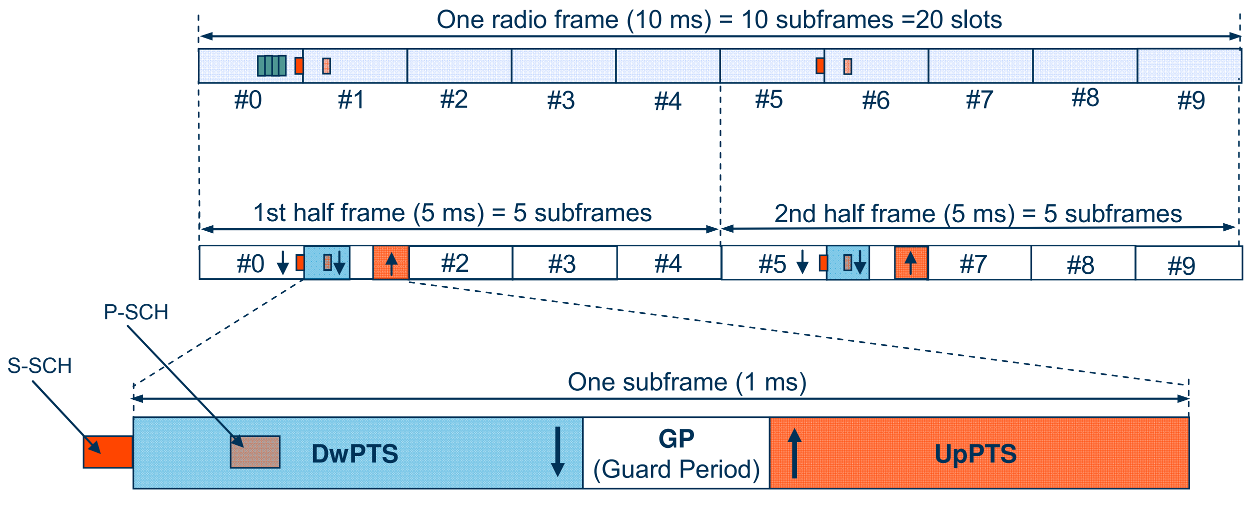


Figure 2-11 Time-domain structure FDD

In the general FDD case, all slots of a carrier are available for downlink transmission (in case of a downlink carrier) or uplink transmission (in case of an uplink carrier). However, LTE should allow for half-duplex terminals in case of FDD operation, implying that, from a terminal point-of-view, downlink reception and uplink transmission do not coincide for such terminals. The assumption is that this is ensured by means of scheduling restrictions.

As illustrated in Figure 2-12, the LTE time-domain structure in case of TDD operation is similar to that of FDD with the following exceptions:

- The 10 ms frame is assumed to consist of two equal-sized half-frames, each of length 5 ms and each consisting of five subframes of length 1 ms.
- The second subframe within each half-frame (subframe #1 and #6 within the frame) has a special structure. More specifically, it consists of a downlink part (DwPTS), a guard period (GP), and an uplink part (UpPTS). The downlink-to-uplink switching point thus takes place within the second subframe of each half-frame, i.e. there can be two downlink-to-uplink switching points within each frame.[1] The corresponding uplink-to-downlink switching point can take place at any sub-sequent subframe boundary within the half-frame. Thus, the first subframe of each half frame is always a downlink subframe.



- DL to UL switch point in special subframe #1 and #6 only
- Other subframes allocated to UL or DL
- Sum of DwPTS, GP and UpPTS always 1 ms
- Subframe #0 and #5 always DL
  - Used for cell search signals (S-SCH)

Figure 2-12 Time-domain structure TDD.

[1] In case of only a single downlink-to-uplink switching within a 10 ms frame, the second subframe of the second half-frame consists of DwPTS only.

Figure 2-13 shows the TDD UL/DL configurations. Configuration 1 is the configuration that is most compatible with TD-SCDMA.

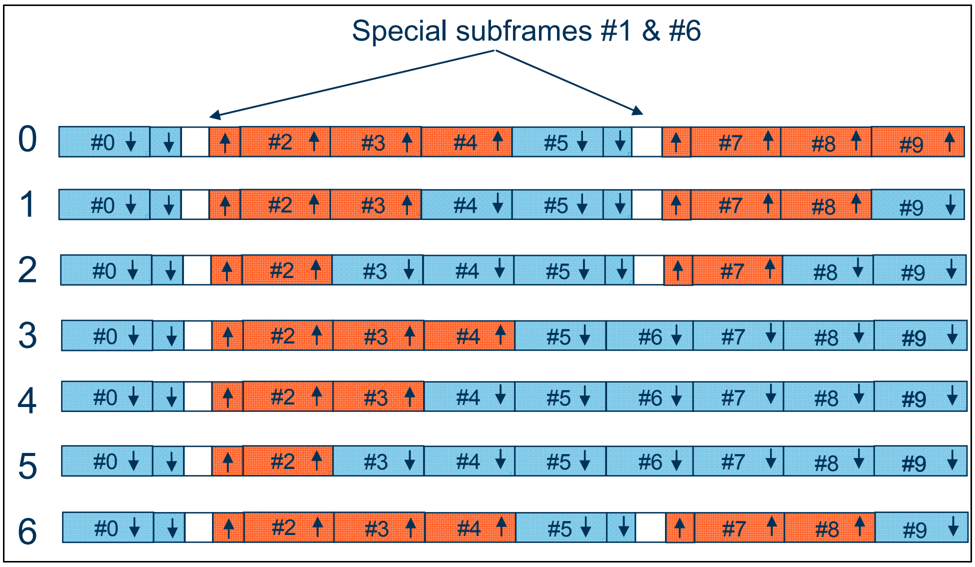


Figure 2-13. TDD UL/DL configurations.

Figure 2-14 shows the different configurations of the DwPTS, GP and UpPTS lengths (in terms of symbols), for normal CP.

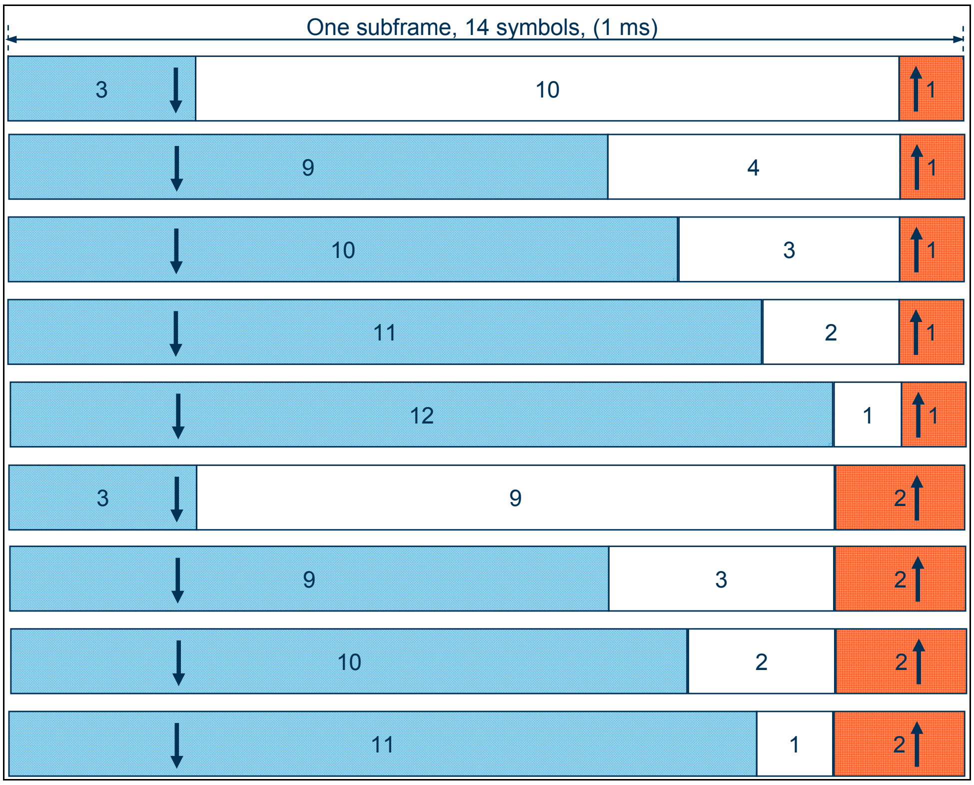


Figure 2-14. TDD special subframe configurations.

In the special subframe, the first one or two symbols are used for DL control signaling. The P-SCH is transmitted in the third symbol. The UpPTS contains RACH preamble or the sounding reference signal (SRS).

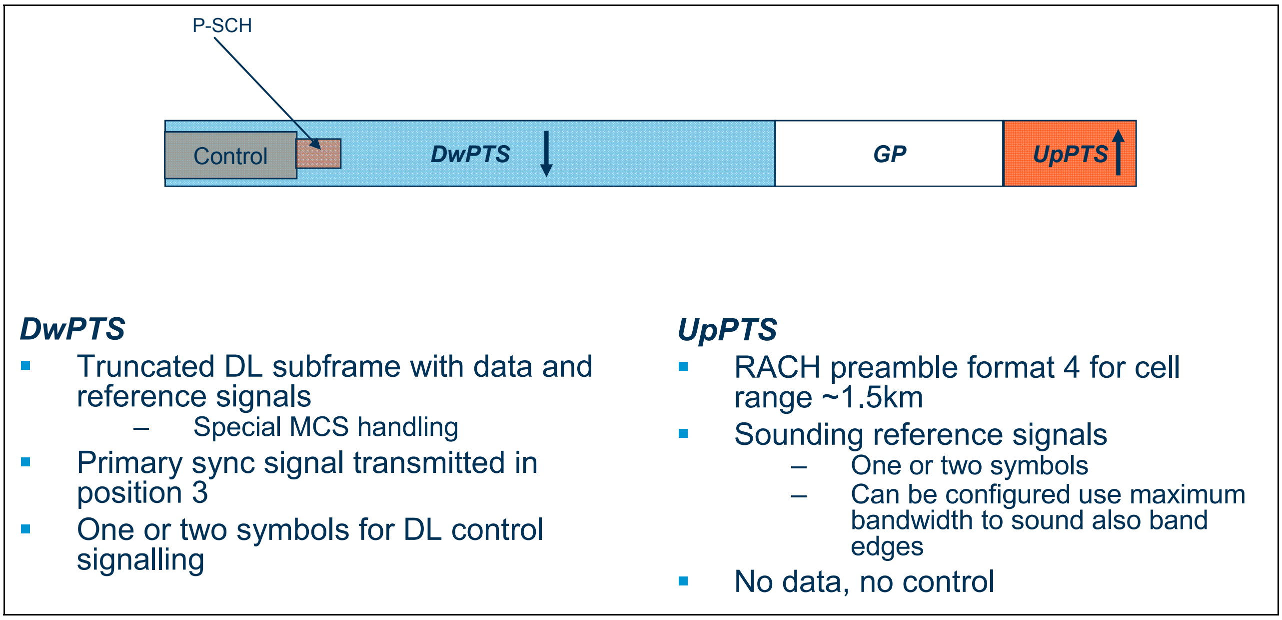


Figure 2-15. TDD special subframe fields.

FDD RACH can be sent in normal uplink subframes. UpPTS can be used for short RACH and sounding signal simultaneously.

DOWNLINK TRANSMISSION TECHNIQUE

LTE downlink transmission is based on Orthogonal Frequency Division Multiplex (OFDM). The basic LTE downlink physical resource can thus be seen as a time-frequency grid as illustrated in Figure 2-16, where each resource element corresponds to one OFDM subcarrier during one OFDM symbol interval. A Resource Block corresponds to twelve OFDM sub-carriers during one 0.5 ms slot. The smallest unit that can be allocated by the scheduler is two consecutive Resource Blocks (12 sub-carriers during 1ms). This is sometimes referred to as a Scheduling Block (SB) and is equal to the TTI (Transmission Time Interval) of 1 ms.

- One Resource Block is 12 sub-carriers during one 0.5 ms slot
- The basic TTI (Transmission Time Interval) for DL-SCH is 1 ms
  - TTI is a *transport channel property*
  - Subframe is a *physical channel property*
  - One (or two) transport blocks per TTI sent to L1

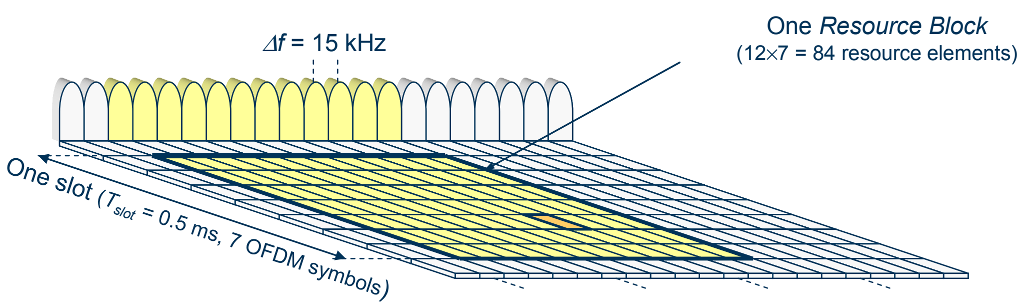


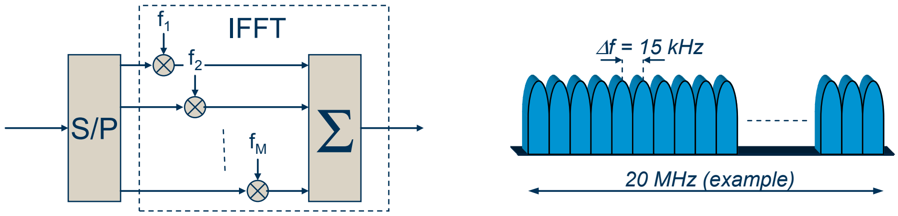
Figure 2-16 The LTE downlink physical resource

For LTE, the downlink subcarrier spacing is $\Delta f = 15$ kHz. Assuming an FFT-based (Fast Fourier Transform) transmitter/receiver implementation, this corresponds to a sampling rate

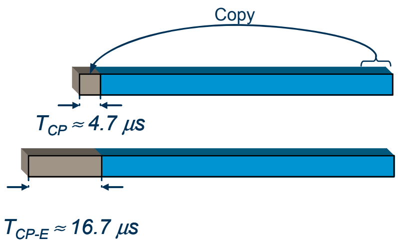
$$f_s = 15000 \cdot N_{FFT} \qquad (1)$$

where N_{FFT} is the FFT size equal to 2048.

- Parallel transmission using a large number of narrowband “sub-carriers”
- “Multi-carrier” transmission
  - Typically implemented with FFT (Fast Fourier Transform) and Inverse FFT



- Insertion of cyclic prefix prior to transmission
  - Improved robustness in time-dispersive channels – *requires CP > delay spread*
  - Spectral efficiency loss



Configuration, Δf		CP length	Symbols per slot
Normal	15 kHz	≈4.7 µs*	7
Extended	15 kHz	≈16.7 µs	6
	7.5 kHz	≈33.3 µs	3

* First symbol of each slot has a CP length of 5.2 µs

Figure 2-17 DL OFDM with Cyclic Prefix.

In addition to the 15 kHz subcarrier spacing, a reduced subcarrier spacing Δf_{low} = 7.5 kHz is also defined for LTE. This reduced subcarrier spacing specifically targets MBSFN-based multicast/broadcast transmission. The cyclic prefix is then extended to 33.3µs in order to better cope with the timing differences that may occur when several base-stations are involved the transmission of the same MBMS data.

The remaining discussions within this and the following chapters will focus on the 15 kHz subcarrier spacing unless explicitly stated otherwise.

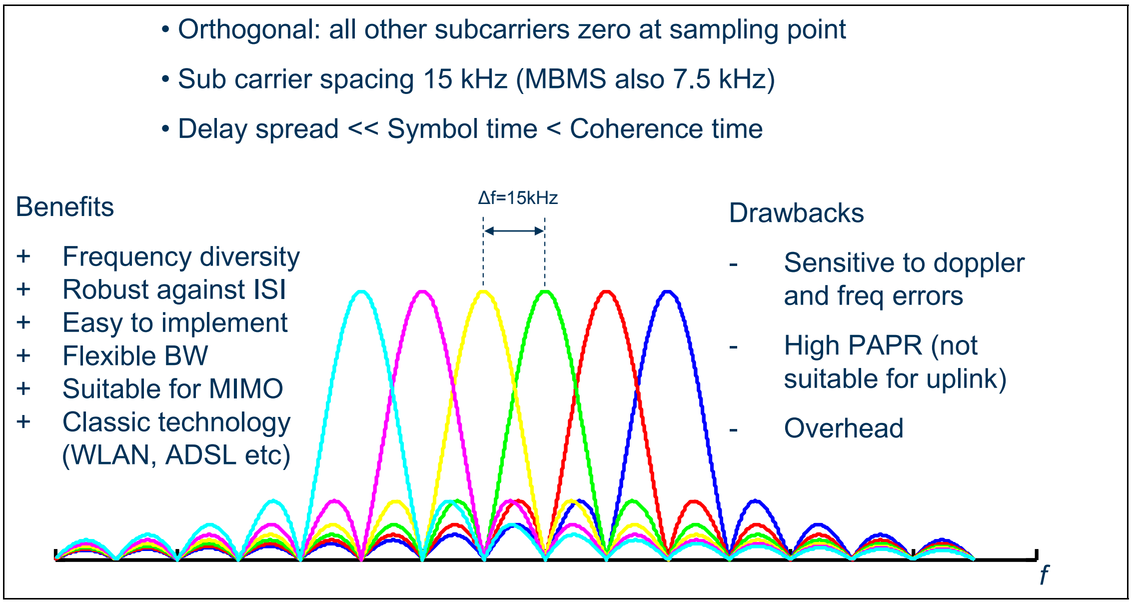


Figure 2-18. Downlink: OFDM - Orthogonal Frequency Division Multiplexing.

The symbol time in LTE is chosen to 66.7μs. This choice is based on the average radio channel delay spread (a measure of the radio channel time dispersion) and the coherence time (a measure of how slow the radio channel changes). The symbol time should be much longer than the delay spread in order to keep the ISI (Inter Symbol Interference) low. Also, the cyclic prefix should be longer than the expected delay spread in order to completely remove ISI.

However, if the symbol time is too long (i.e. longer than the coherence time), the radio channel will change considerably during one symbol. This would lead to inter carrier interference (ICI).

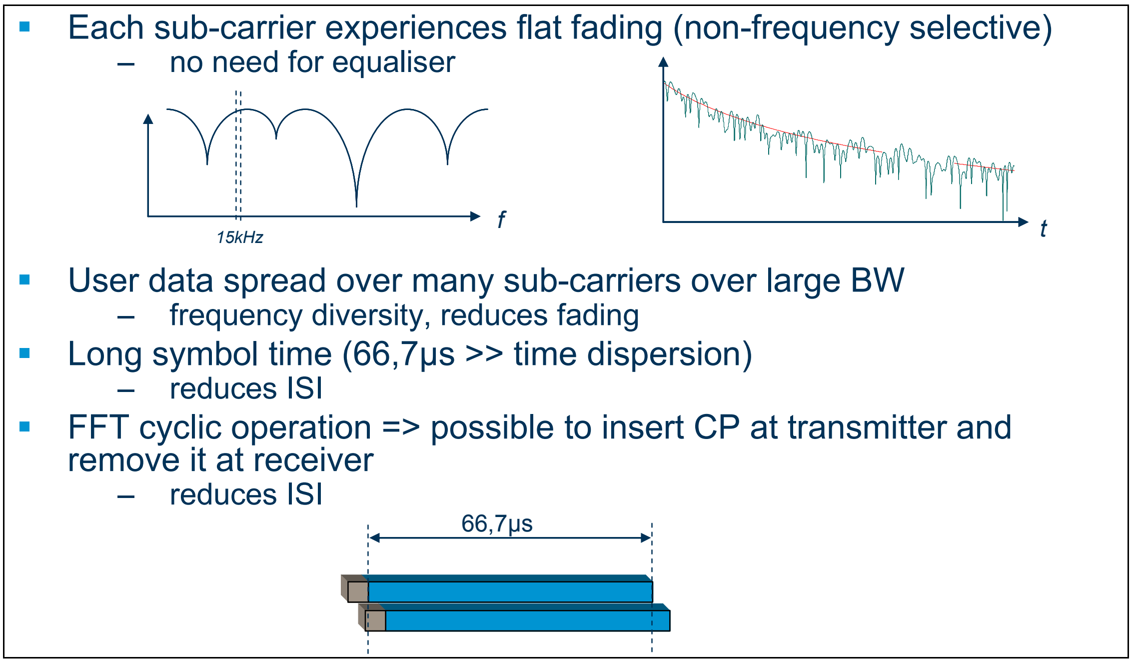


Figure 2-19. OFDM properties.

As mentioned above, in addition to the 15 kHz subcarrier spacing, a reduced subcarrier spacing Δf_{low} = 7.5 kHz is also defined for LTE and specifically targeting MBSFN transmission. The use of the reduced subcarrier spacing also scales the OFDM symbol time, including the cyclic-prefix length, by a factor of two, thus providing a twice as long cyclic prefix (≈ 33.3 µs). In the case of the 7.5 kHz subcarrier spacing, the resource block consists of 24 subcarriers, i.e. the resource-block “bandwidth” is still 180 kHz.

In Figure 2-20 the downlink transmission and receiving scheme is illustrated. The coded and modulated symbols are converted from serial to parallel and transformed by an inverse fourier transform (typically implemented with an Inverse Fast Fourier Transform - IFFT). Now each parallel symbol stream is modulating a 15 kHz subcarrier and the symbol time is 1/Δf = 1/15kHz = 66.7 µs. A cyclic prefix (CP) of 4.7µs is inserted. This is the normal CP, there are also extended CP of 16.7 and 33.3 µs. In the first symbol, however, the normal CP is 5.2 µs, in order to fit the seven symbols per slot.

The CP is copy of the last part of the symbol in order to preserve the subcarrier orthogonality. This is possible since the FFT is a cyclic operation, but it is required that the time dispersion of the radio channel is shorter than the CP length.

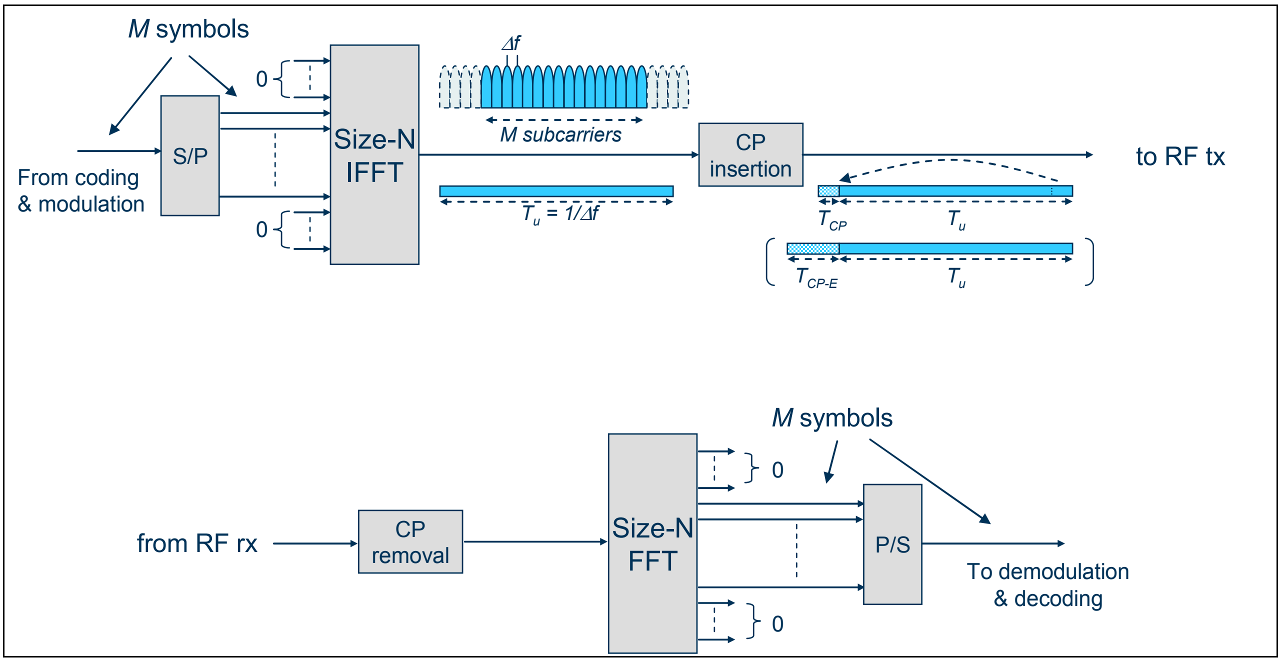


Figure 2-20. Downlink Tx and Rx scheme - OFDM.

DOWNLINK REFERENCE SIGNALS

The *downlink reference signals* consist of so-called *reference symbols* which are known symbols inserted within in the OFDM time/frequency grid. The reference signals can be used by the UE for downlink channel estimation to enable coherent detection. Three types of reference signals are defined for the LTE downlink.

- Up to four *cell-specific* reference signals, each corresponding to one downlink antenna port.
- MBSFN reference signals within MBSFN subframes
- UE-specific reference signals, sometimes also referred to as dedicated reference signals. The detailed structure of the dedicated reference signals is still to be determined and is thus not further discussed.

In case of a single antenna port (a single transmit antenna), a single cell-specific unicast reference signal is inserted into the time/frequency grid according to Figure 2-21. As can be seen, the reference symbols are inserted within the first and the third last[2] OFDM symbol of each slot and with a frequency-domain spacing of six subcarriers. Furthermore, there is a frequency-domain staggering of three subcarriers between the first and second reference symbols. Within each resource block there is thus a total of four reference symbols.

[2] The fifth and fourth OFDM symbol in case of normal and extended cyclic prefix respectively

- Cell-specific reference signals
  - Sequence is a product of
    - 1 of 3 orthogonal sequences
    - 1 of 168 pseudo-random sequences
  - 3×168=504 different sequences ➡ 504 different cell identities
- Used for
  - coherent demodulation in the UE
  - channel-quality measurements for scheduling
  - measurements for mobility

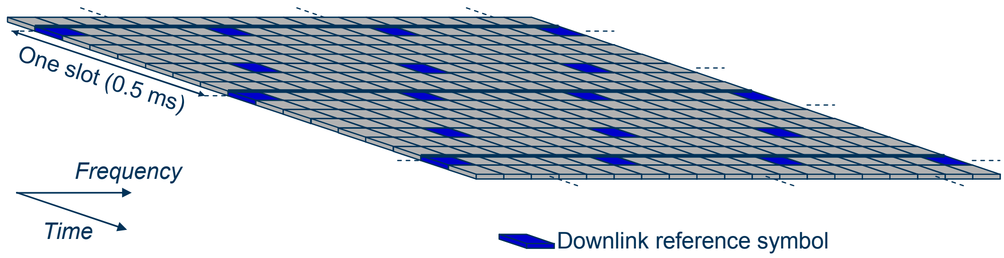


Figure 2-21. Cell-specific reference signals.

The actual complex values of different reference symbols are cell specific and directly given by the cell ID.

In case of normal cyclic prefix, the set of reference symbols can be seen as a combination of a (2-dimensional) pseudo-random sequence and a (2-dimensional) orthogonal sequence, where each cell-ID group (168 groups) corresponds to one out of 168 pseudo-random sequence and each of the three cell IDs within each cell ID group corresponds to one out of three orthogonal sequence.

In case of extended cyclic prefix, there is no orthogonal sequence and each cell ID (504 cell IDs) correspond to one out of 504 pseudo-random sequences.

In case of downlink multi-antenna transmission (transmit diversity and spatial multiplexing) the mobile terminal must be able to identify and estimate the channel corresponding of each transmit antenna port. In order to enable this, there is one downlink reference signal transmitted from each antenna port, as illustrated in Figure 2-22.

- In case of two transmit antennas ports (left part of Figure 2-22) the position of the reference signal of the second antenna port is frequency-shifted 3 subcarriers, relative to the reference signal of the first antenna.

- In case of four antenna ports (right part of Figure 2-22), additional reference signals, corresponding to the third and fourth antennas port, are transmitted within the second OFDM symbol of each slot. Note that this implies that the reference-symbol density on the third and fourth antenna port is lower (one half), compared to that of the first and second antenna port.

As can also be seen from Figure 2-22, in a resource element carrying a reference symbol for a certain antenna port, nothing is being transmitted at the other antenna ports. Thus there is no interference to reference symbols from other antenna ports within the cell. This is because the UE has to be able to separate the antenna ports when it is performing measurements for spatial multiplexing (MIMO).

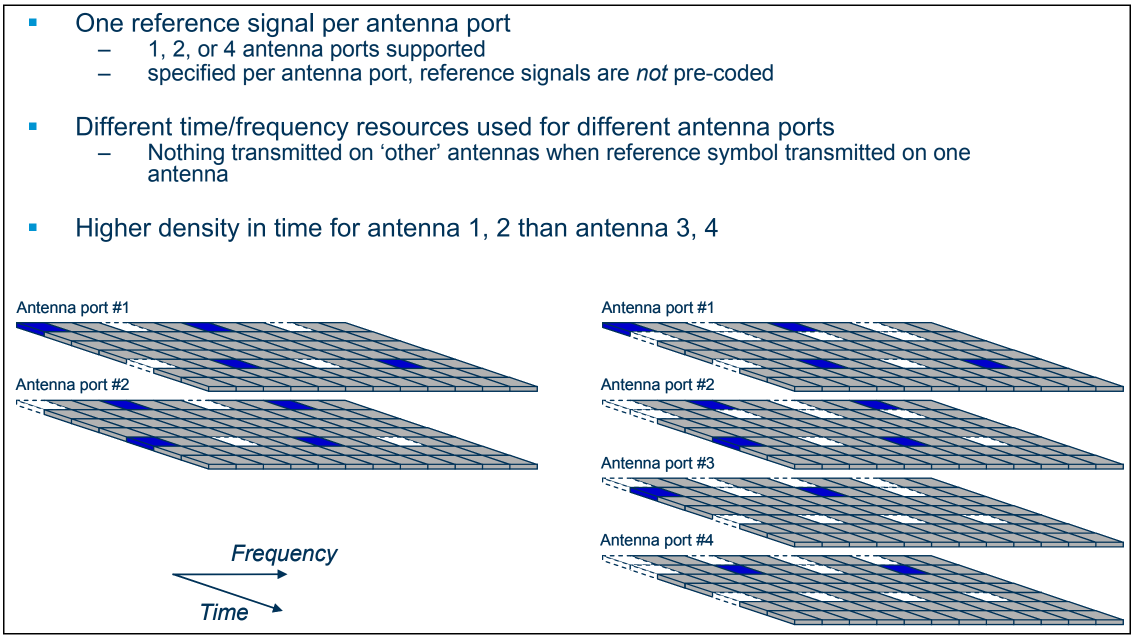


Figure 2-22 Cell-specific reference signals - multiple antennas.

Reference-signal frequency shifting

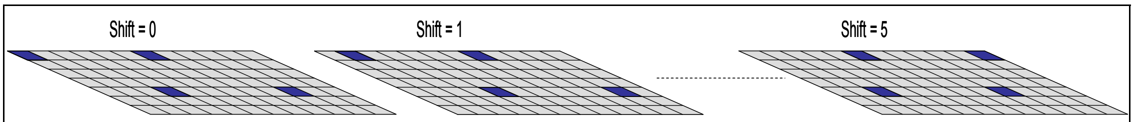
The exact position of the reference symbols can be shifted in the frequency domain between different cells as illustrated in Figure 2-23. This implies that the frequency-domain positions of the reference symbols can expressed as

First reference symbols: $p_k = p_0 + 6 \cdot k$

Second reference symbols: $p_k = (p_0 + 3) \bmod 6 + 6 \cdot k$

where the cell-specific frequency shift p_0 can take values in the range 0 to 5.

The cell-specific frequency shift p_0 is directly given by cell identity (Cell ID) group. Thus, as soon as the cell ID group is found as part of the cell search, the frequency shift of the downlink reference signals of that cell is known.



First reference symbols:
$p_k = p_0 + 6 \cdot k$

Second reference symbols:
$p_k = (p_0 + 3) \bmod 6 + 6 \cdot k$

where the cell-specific frequency shift p_0 is in the range of 0-5.

Figure 2-23 Reference signal frequency shifts

DOWNLINK TRANSPORT-CHANNEL PROCESSING

LTE has inherited the basic principle from WCDMA/HSPA that data is delivered to the physical layer, i.e. on the transport channels, in form of Transport Blocks of a certain size. In terms of the more detailed transport-block structure, LTE has adopted a similar approach as was adopted for HSPA:

- In case of single-antenna transmission, there can be at most one single transport block, of dynamic size, for each TTI
- In case of multi-antenna transmission, there can be up to two transport blocks of dynamic size for each TTI, where each transport block corresponds to one codeword in case of downlink spatial multiplexing.

With this transport-block structure in mind, the LTE downlink transport-channel processing, more specifically the processing of DL-SCH[3], can be outlined according to Figure 2-24 with two, mainly separated, processing chains, each corresponding to the processing of a single transport block.

[3] The processing of other downlink transport channels is similar although typically with some additional constraints

- CRC insertion (24 bit per transport block)
- R=1/3 Turbo coding (with QPP interleaver) + possible code block segmentation and CRC insertion per code block
- Rate matching, redundancy version generation
- Scrambling for inter-cell interference randomization
- Modulation (QPSK, 16QAM, 64QAM)
- Mapping to transmission layers (for multi-layer transmission)
- Pre-coding (for multi-rank transmission)
- Resource block mapping

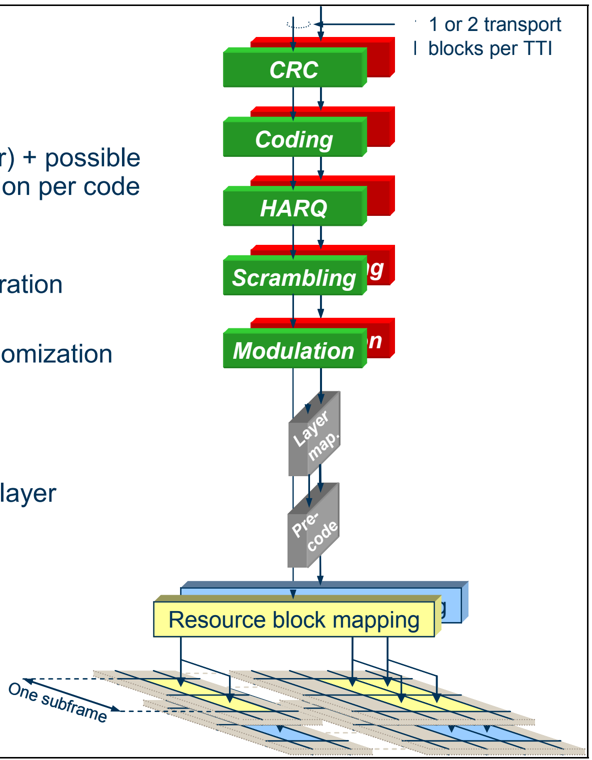


Figure 2-24 DL-SCH processing

CRC insertion

In the first step of the transport-channel processing, a 24 bit Cyclic Redundancy Check (CRC) is calculated and appended to each transport block. Note that, in case of codeblock segmentation into multiple codeblocks as part of the Turbo coding, additional CRCs are calculated and appended to each codeblock, see below,

Channel coding

Only Turbo-coding can be applied in case of DL-SCH transmission. The Turbo coding reuses the two WCDMA/HSPA rate 1/2, eight-state constituent encoders, implying an overall code rate R = 1/3. However, the WCDMA/HSPA Turbo-coder internal interleaver has, for LTE, been replaced by QPP[4]-based interleaving.

[4] QPP = Quadrature Permutation Polynomial

In case of large transport blocks (length > 6120 corresponding to a code block including CRC of 6144 bits), code-block segmentation is applied. The code-block segmentation segments the input to the Turbo coder into smaller code blocks that are separately coded. Furthermore, in case of code-block segmentation a 24 bit CRC is also appended to each codeblock. The use of a per-code-block CRC allows for early termination of each the decoding of each codeblock if the CRC checks at the receiver/decoder side.

Rate matching including physical-layer hybrid-ARQ functionality

The rate matching consists of two parts, sub-block interleaving and bit collection/selection.

The sub-block interleaving, separately interleaves the three output blocks of the Turbo codes, corresponding to the system systematic bits and the two constituent encoders.

The output of the sub-block interleavers are then inserted into a circular buffer such that the systematic bits are inserted at the head, followed by alternative insertion of the bits of the two constituent encoders. Depending on the number of bits that fits into the assigned physical resource (depending on the number of resource blocks and layers, and the selected modulation scheme), a number of consecutive number of consecutive bits are then extracted from the circular buffer where the exact set of extracted bits depends on the redundancy version.

Bit-level scrambling

Downlink scrambling implies that the block of code bits delivered by the hybrid-ARQ functionality is multiplied (exclusive-or operation) by a bit-level scrambling sequence

LTE applies downlink scrambling to the code bits of each transport channel (“bit-level scrambling”). Downlink scrambling is applied to all transport channels as well as to the downlink L1/L2 control signaling. For all downlink transport channels except the MCH, as well as for L1/L2 control, the scrambling sequences should be different between neighbor cells in order to ensure interference randomization between the cells. In contrast, for MBSFN-based multicast/broadcast using the MCH transport channel, the same scrambling should be applied to all cells taking part in the MBSFN transmission.

Data modulation

The downlink data modulation maps blocks of scrambled bits to corresponding blocks of complex modulations symbols. The set of modulation schemes supported for the LTE downlink includes QPSK, 16QAM, and 64QAM, corresponding to two, four, and six bits per modulation symbol respectively.

Multi-antenna processing

The multi-antenna processing maps the modulation symbols corresponding to, in the general case, two transport blocks, and maps the result to the different antennas. LTE specifications support up to four transmit antennas. The first release will, however, only support up to two transmit antennas, thus enabling up to 2x2 MIMO.

Resource-block mapping

The resource-block mapping maps the symbols to be transmitted on each antenna to the resource elements of the set of resource blocks assigned by the MAC scheduler for the transmission of the transport block(s).

Downlink scheduling is carried out on a subframe (1 ms) basis. However, a downlink resource block is defined as a number of subcarriers during one 0.5 ms slot. As a consequence, the downlink resource-block assignment is carried out in terms of pairs of resource blocks, where each pair consists of two consecutive resource blocks within a subframe.

The physical resource to which the DL-SCH is mapped is, in the specification, referred to as the Physical Downlink Shared Channel (PDSCH).

DOWNLINK L1/L2 CONTROL SIGNALING

Downlink L1/L2 control signaling is used for transmitting downlink scheduling assignments required for the terminal to properly receive, demodulate and decode the DL-SCH, uplink scheduling grants informing the terminal about resources and transport format for UL-SCH transmission, and hybrid-ARQ acknowledgements in response to UL-SCH transmission.

As illustrated in Figure 2-25, the downlink L1/L2 control channels are mapped to the first (up to four) OFDM symbols within the subframe (in the figure two symbols are used). Thus, each subframe can be said to be divided into a *control region*, followed by a *data region*. The size of the control region is always equal to an integer number of OFDM symbols (1, 2, 3 or 4 OFDM symbols can be used for control signaling) and can be varied per subframe. This maximizes the spectral efficiency as the control signaling overhead can be adjusted to match the instantaneous traffic situation.

The location of the control signaling at the beginning of the subframe is advantageous as it allows the terminal to decode the downlink scheduling assignment prior to the end of the subframe. Processing of the DL-SCH can therefore begin earlier compared to the case of the control signaling spanning the full subframe duration. This minimizes the delay in the DL-SCH decoding and thus the overall downlink transmission delay.

Furthermore, by transmitting the L1/L2 control channel at the beginning of the sub-frame, i.e. by allowing for early decoding of the L1/L2 control information, mobile terminals that are not scheduled may turn off their receiver circuitry for a large part of the subframe, with reduced terminal power consumption as a consequence.

- Downlink control signaling
  - DL scheduling (transport format and resource assignment)
  - UL scheduling grants
  - ACK/NACK related to UL transmission
- Transmitted in first *n* OFDM symbols, *n*≤4
  - Allows for micro sleep
- DL scheduling assignment, UL scheduling grant
  - Individual per MAC ID
  - Convolutional coding, QPSK, transmitted over the full BW

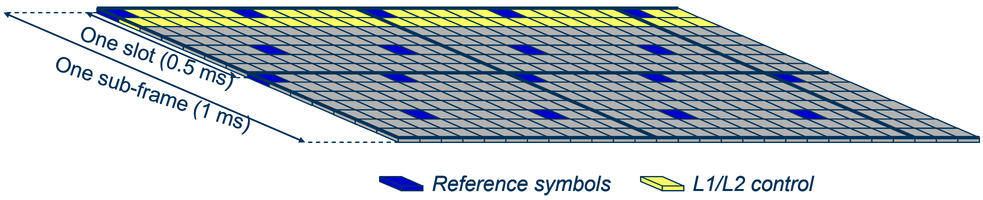


Figure 2-25 DL control signaling

The downlink L1/L2 control signaling consists of three different physical channel types:

- PCFICH (Physical Control Format Indicator Channel), informing the terminal about the number of OFDM symbols (1, 2, 3 or 4) used for L1/l2 control signaling in the current subframe. There is only one PCFICH in a cell.
- PDCCH (Physical Downlink Control Channel), used to carry downlink scheduling assignments and uplink scheduling grants. In addition, it may also be used for power control of a group of terminals. Typically, there are multiple PDCCHs in a cell.
- PHICH (Physical Hybrid-ARQ Indicator Channel), used to transmit ACK/NAK in response to reception of UL-SCH transmissions. Typically, there are multiple PHICH in a cell.

In the following pages, the three channel types are described separately.

PCFICH – Physical Control Format Indicator Channel

The PCFICH is used to indicate the number of OFDM symbols used for L1/L2 control signaling in the current subframe, or, equivalently, where in the subframe the data region starts. Reception of the PCFICH is thus essential to correct operation of the system. If the PCFICH is incorrectly decoded, the terminal will neither know where to find the control channels, nor where the data region starts, and will therefore lose any uplink scheduling grants transmitted as well as any DL-SCH data transmission intended for the terminal. The target error rate of the PCFICH is an implementation issue, but an error rate of one percent is commonly assumed in 3GPP.

Two bits of information, corresponding to a control region size of 1, 2, or 3 OFDM symbols[5], are coded into a 32-bit long sequence using a rate-1/16 simplex code. The coded bits are scrambled, QPSK-modulated and mapped to 16 resource elements. To be compatible with the different Tx diversity schemes, which are specified on groups of 4 symbols, the 16 resource elements are grouped into 4 groups of 4 elements each. The four groups are well-separated in frequency to obtain good diversity. Furthermore, to avoid inter-cell PCFICH collisions, the location of the four groups in the frequency domain depends on the physical-layer cell identity.

- Indicates number of OFDM symbols used for PDCCH (N_{PDCCH})
  - Two bits of information, four alternatives:
    - N_{PDCCH} = 1, 2, 3 when # of RB more than 10
    - N_{PDCCH} = 2, 3, 4 when # of RB less or equal to 10
- Block code + QPSK ⇨ 16 symbols
- Mapping to four groups of resource elements in first OFDM symbol
  - Resource elements not available for PDCCH mapping

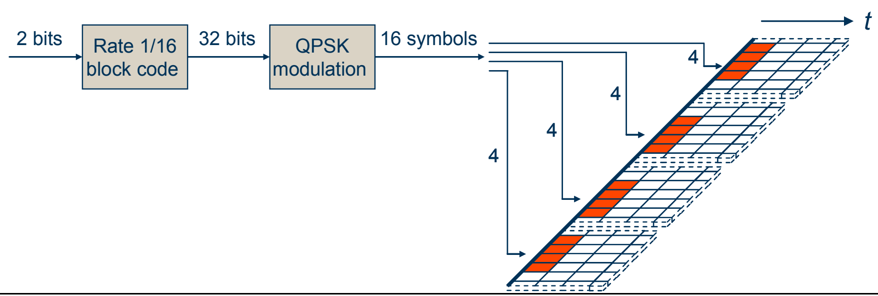


Figure 2-26. PCFICH mapping.

[5] Four symbols are used for low BW allocations.

The transmission power of the PCFICH is under control of the eNB. If necessary for coverage in a certain cell, the power of the PCFICH can be set higher than for other channels by “borrowing” power from e.g. PDCCHs.

PDCCH – Physical Downlink Control Channel

The PDCCHs are used for:

- Downlink scheduling assignments, including PDSCH resource indication, transport format, hybrid-ARQ information, transport block size, MIMO-related control information (if applicable) and PUCCH power control commands
- Uplink scheduling grants, including PUSCH resource indication, transport format, hybrid-ARQ related information, and PUSCH power control commands.
- Power-control commands of groups of terminals (as a complement to the power control commands piggy-backed with the scheduling decisions)

A PDCCH carries one of the above messages. As multiple mobile terminals can be scheduled simultaneously, on both downlink and uplink, there must be a possibility to transmit multiple scheduling messages within each subframe. Each scheduling message is transmitted on a separate PDCCH and consequently there are typically multiple PDCCHs in each cell and each terminal monitors multiple PDCCHs.

The different scheduling messages have different payload sizes. For example, supporting spatial multiplexing with non-contiguous allocation of resource blocks in the frequency domain require a larger scheduling message than an uplink grant supporting frequency-contiguous allocations only. Link adaptation, i.e., to match the code rate of the error-correcting code of the PDCCH to the instantaneous radio conditions, is also supported. Thus, there will be multiple formats for the PDCCH where each format is defined by the payload size and the code rate.

The processing of the PDCCH is illustrated in Figure 2-27. A CRC is attached to each PDCCH payload, where the MAC ID (RNTI) is included in the CRC calculation. Upon reception of a PDCCH, the terminal will check the CRC using its own RNTI. If the CRC checks, the message is declared to be correctly received and intended for the terminal. Thus, the identity of the terminal who is supposed to receive the PDCCH message is implicitly encoded in the CRC and not explicitly transmitted.

After CRC attachment follows channel coding with a tail-biting convolution codes, rate matching and QPSK modulation. Depending on the PDCCH message size (three sizes are supported, size A, B and C) and the channel coding rate (including rate matching), the size of the coded PDCCH corresponds to 1, 2, 4 or 8 *control-channel elements* (CCEs), where each CCE corresponds to 36 resource elements (for 5 MHz).

The coded and modulated PDCCHs are multiplexed such that all control-channel elements corresponding to the first PDCCH are followed by all the control-channel elements corresponding to the second PDCCH and so on. The multiplexed CCEs are then mapped to resource elements, which is described as a permutation of groups of four QPSK symbols followed by a cell-specific cyclic shift. Groups of four QPSK symbols are used for the same reasons as for the PCFICH, namely to support the different Tx diversity schemes, and the cyclic shift serves the purpose of randomizing the mapping between different cells. Resource elements not used for PCFICH, PHICH or reference signals in the control region are used for transmission of the PDCCH. Furthermore, to obtain an even power distribution between the OFDM symbols and to allow for flexible power control, the mapping is done such that each CCE spans all OFDM symbols in the control region[6].

Similarly to the PCFICH, the transmission power of each PDCCH is under the control of the eNB. Power adjustments can therefore be used as a complementary link adaptation mechanism in addition to adjusting the code rate. Relying on power adjustments alone might seem a tempting solution and, although possible in principle, it can result in relatively large power differences between PDCCHs, which has implications from an RF implementation perspective. Therefore, the two mechanisms for link adaptation, power adjustments and different code rates, complement each other.

In many cases, not all the PDCCH that are possible to transmit in the control region are used. Unused PDCCHs are part of the interleaving and mapping process in the same was as any other PDCCH. At the terminal, the CRC will not check for those “dummy” PDCCHs. Preferably, the power is set to zero for those unused PDCCHs; power that can be used by some other control channel instead.

[6] This is the design target, some CCEs may in some cases not span all the OFDM symbols.

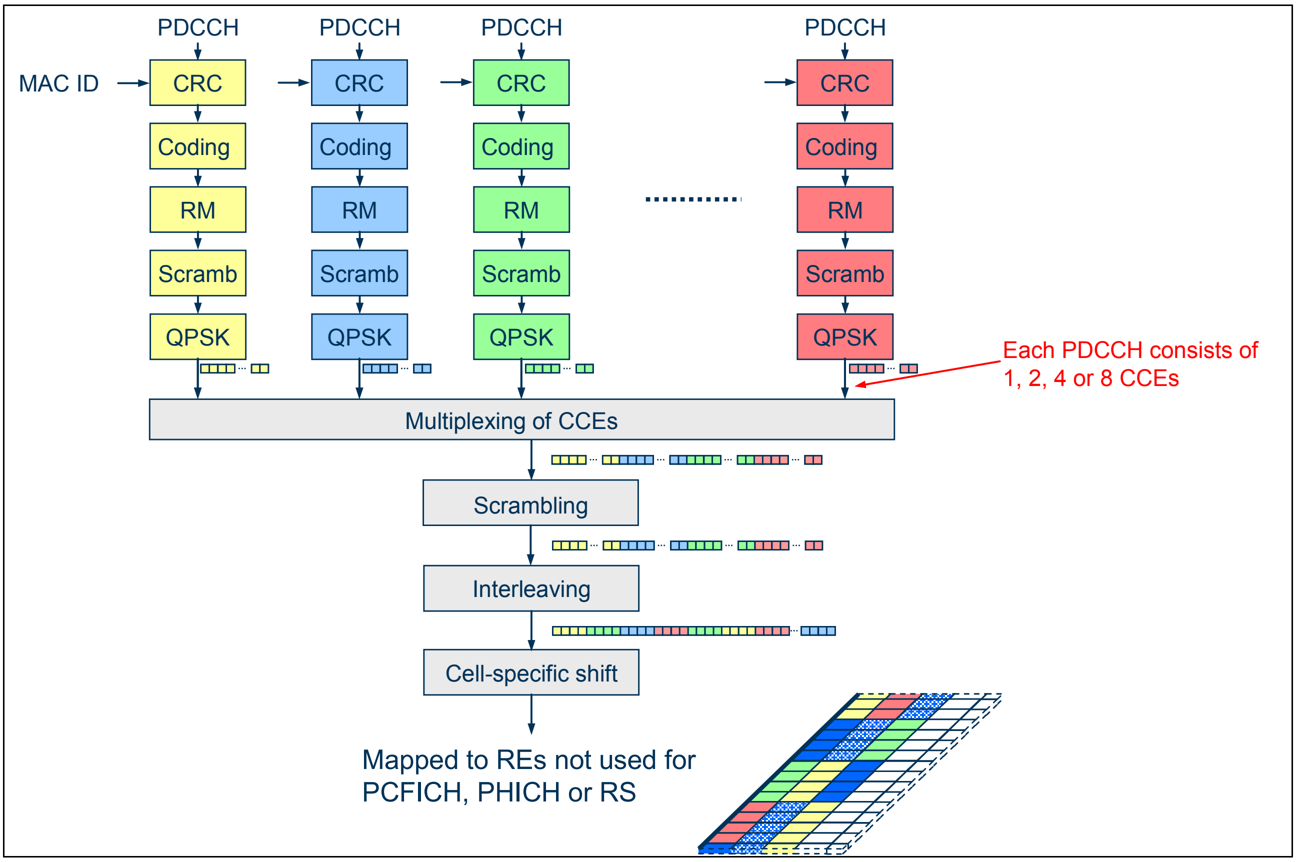


Figure 2-27 PDCCH processing.

As described above, each PDCCH supports multiple formats and the format used is a-priori unknown to the terminal. Therefore, the terminal needs to blindly detect the format of the PDCCHs. Clearly, with the requirement to monitor multiple PDCCHs, each with an unknown format, the number of blind decodings in the terminal may become unattractively high. Using a fixed CCE size and allowing aggregation of only 1, 2, 4 or 8 CCEs helps in reducing the number of blind decoding attempts. Additional restrictions in the CCE aggregation structure will most likely be imposed although at the time of writing this has not yet been decided upon in 3GPP.

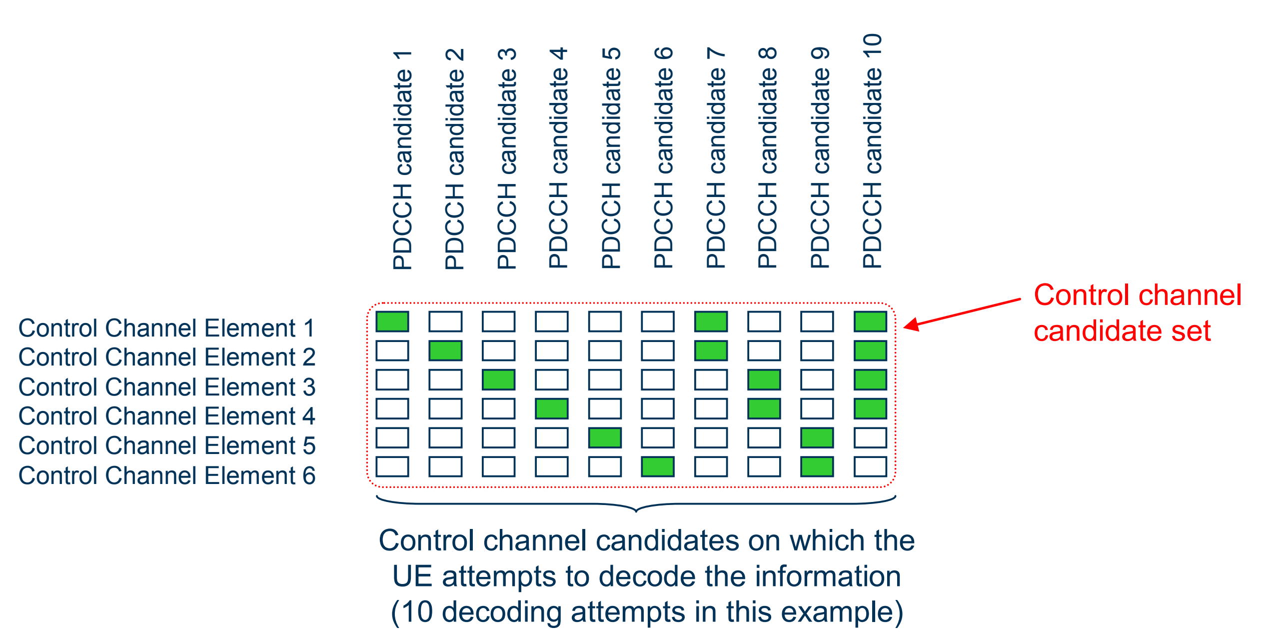


Figure 2-28. PDCCH blind decoding.

Downlink scheduling assignments

Downlink assignments can take three different payload sizes, where size A<B<C:

- Size A, supporting downlink scheduling with restrictions. Size A assignments have the same PDCCH payload size as uplink grants.
- Size B, supporting downlink assignments without spatial multiplexing.
- Size C, supporting downlink assignments with spatial multiplexing.

The downlink assignments consists of resource-block indication, modulation and transport-block size, hybrid-ARQ related information, PUCCH power control commands, and (if applicable) information related to spatial multiplexing.

Resource block indications can be of three different types: 0, 1, and 2. Type 0 and 1 are used for payload size B and C and use a bitmap to support non-contiguous allocations in the frequency domain. In type 0, each bit in the bitmap represents a group of *n* contiguous resource blocks, where *n* is given by the downlink system bandwidth. The reason for grouping resource blocks is to reduce the size of the bitmap; a bitmap with the resolution of one resource block in the frequency domain would result in a too large overhead for larger system bandwidths. However, also in large system bandwidths a frequency resolution of one resource block is sometimes useful. Therefore, type 0 is complemented by type 1, where the resource blocks are divided into subsets as shown in Figure 2-29. Within the subset used, a bitmap indicates upon which resource blocks the PDSCH is transmitted.

In order to save PDCCH overhead, there is a possibility to assign downlink resources using payload size A when there is no need for full flexibility. In this case, resource indication type 2 is used, supporting frequency-contiguous allocations only, using the same method as for the uplink grants (and results in the same PDCCH payload size as for uplink grants).

The final contents of the downlink assignments are not agreed in 3GPP at the time of writing.

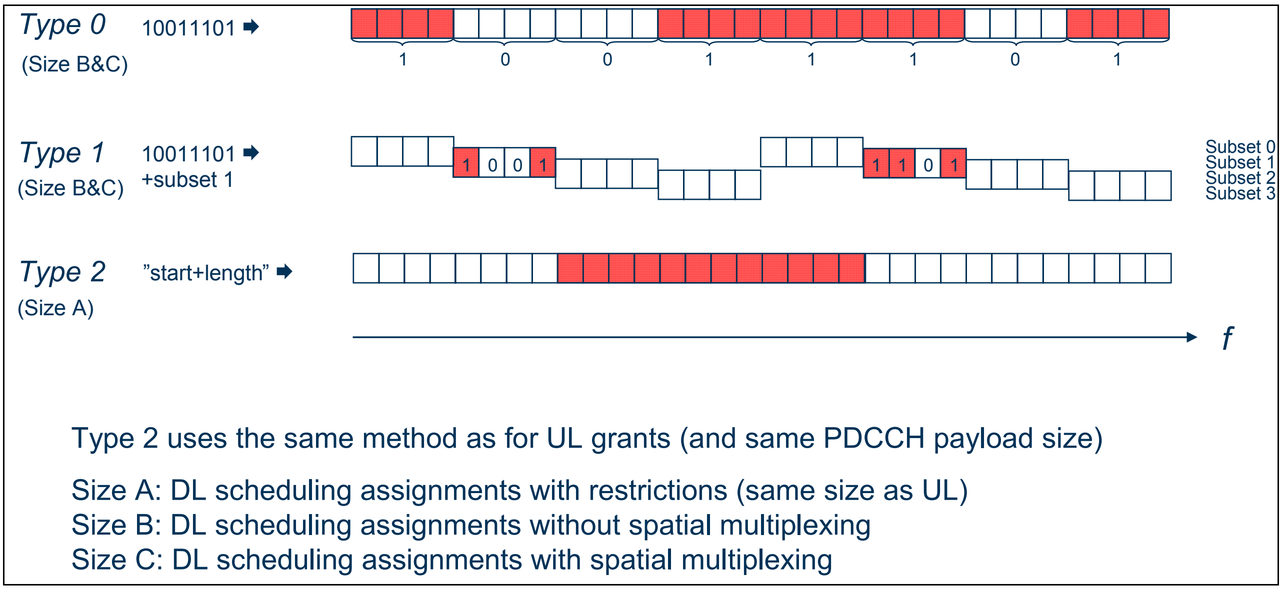


Figure 2-29. DL RB assignments.

The downlink scheduling assignments are sent to the user equipment on PDCCH. The Downlink Control Information (DCI) on the PDCCH has several supported formats, shown in Figure 2-30.

The formats supported are: DCI 0, 1A, 1, 2 and 2A. DCI 0 is for UL and uses an allocation type similar to type 2. DCI 1, 2 and 2A uses DL allocation type 0, which is a bitmap pointing out the allocated RBs. DCI 1A uses allocation type 2, which indicates start and length of the allocation of RBs. DCI 1 is used for tx-diversity while DCI 2 is used for closed loop spatial multiplexing and DCI 2A is used for open loop spatial multiplexing.

DCI format on PDCCH	**Resource Allocation Type**	**Use**
DCI 0	”Type 2”	Uplink
DCI 1	Type 0	Tx diversity
DCI 1A	Type 2	Independent of tx mode
DCI 2	Type 0	CL spatial multiplexing
DCI 2A	Type 0	OL spatial multiplexing

Figure 2-30. PDCCH signaling formats.

Below follows an example of the message contents for DCI Format 1A.

- DCI format 1A is used for the compact scheduling of one PDSCH codeword.
- The following information is transmitted by means of the DCI format 1A:
  - 1 bit for the format Flag for PDSCH allocation
    - Used to indicate N_{RB} assignment for RA-RNTI, P-RNTI, or SI-RNTI
  - 1 bit to indicate Localized/Distributed VRB (Virtual Resource Block) assignment
  - N bits for the Resource block assignment (depends on N^{DL}_{RB})
  - 5 bits for the Modulation and coding scheme
  - 3 bits (FDD) or 4 bits (TDD) HARQ process number
  - 1 bit for New data indicator (indicates gap size for overhead messages)
  - 2 bits for Redundancy version
  - 2 bits for TPC command for PUCCH
  - 2 bits for Downlink Assignment Index (TDD only)
- Zeros are used to pad out the message to fit the correct block size
- Some of these fields are reserved when the CRC is scrambled with a RA-RNTI, P-RNTI, or SI-RNTI

Figure 2-31. DCI Format 1A, message contents.

Uplink scheduling grants

Uplink scheduling grants all have payload size A and consist of resource-block indication, the modulation and transport block size the terminal shall use for the transmission, hybrid-ARQ related information and PUSCH power control commands. The resource block indication is encoded as the first resource block to transmit upon and the number of resource blocks. The final contents of the uplink scheduling grants are not agreed in 3GPP at the time of writing.

Power control commands

As a complement to the power control commands sent as part of the downlink scheduling assignments and the uplink scheduling grants, there is a possibility to transmit a power control command using payload size A. The power control message is directed to a group of terminals using a group identity. Each terminal in the group has two bits on reserved for power control commands, i.e., even thought he message is directed to a group of terminals the power control is individual per terminal.

PHICH – Physical Hybrid-ARQ Indicator Channel

The PHICH is used for transmission of hybrid-ARQ acknowledgements in response to UL-SCH transmission. There is one PHICH present for each terminal expecting an acknowledgement in the subframe.

Each PHICH carries one bit, which is repeated three times, modulated, spread with a spreading factor of four and mapped to three groups of four resource elements each. Multiple PHICHs form a PHICH group and the PHICHs within a PHICH group are code-multiplexed using different orthogonal spreading sequences and share the same set of resource elements. This is motivated by power control of the PHICH; with CDM the power difference between subcarriers is not as large as with pure FDM. If more PHICH capacity than possible with a single PHICH group (corresponding to 12 resource elements) additional PHICH groups can be configured. Within each PHICH group, CDM is used while FDM is used between the groups.

The power setting of the PHICH, and consequently the PHICH error rate, is not specified but considered an implementation issue. However, 3GPP typically assumes an ACK-to-NAK error rate of 10^{-2} and an NAK-to-ACK error rate in the range of 10^{-3} to 10^{-4} in the LTE design. The reason is that an NAK-to-ACK error would imply a loss of a transport block at the MAC level, a loss that has to be recovered by RLC retransmissions with the associated delays. As the PHICH target error rates are lower than the PCFICH error rate, the PHICH mapping is designed not to be dependent on the PCFICH value. Therefore, semi-static configuration is used to reserve resources for PHICH.

Typically, the PHICH is transmitted in the first OFDM symbol only. However, in some propagation environments, this would unnecessarily restrict the PHICH coverage. To alleviate this, it is possible to configure a PHICH duration of three OFDM symbols[7]. In this case the control region is three OFDM symbols long in all subframes.

The PHICH configuration is part of the system information (MIB on the BCH); one bit indicates whether the duration is one or three OFDM symbols and two bits indicate the amount of resources set aside for PHICHs.

There is no explicit indication in the scheduling grant upon which PHICH the terminal shall expect the acknowledgement. Instead, the PHICH number used for transmission of the acknowledgement is derived from the number of the first CCE of the PDCCH carrying the grant.

[7] In case of a mixed unicast/MBSFN subframe, the extended PHICH duration is two OFDM symbols.

PHYSICAL-LAYER PROCEDURE

This section describes different downlink physical layer procedures being part of the LTE concept

POWER CONTROL

Downlink power control, or power boosting, can be used on both the data channel (PDSCH) and control channels (PBCH, PDCCH, PCFICH, and PHICH).

As a default solution, the data channel power is distributed uniformly over the scheduled resource blocks (i.e. no power control is used). More sophisticated strategies include e.g. (i) allocating relatively high power, but few resource blocks to power limited users and vice-versa for bandwidth-limited users, and (ii) allocating more power to resource blocks with good channel quality.

Power control on the control channels may be used to improve coverage. For common control channels, which have to reach the cell border (e.g. PBCH and P/S-SCH), this can be done by borrowing power from user plane resource blocks transmitted simultaneously. In the extreme case the full eNB power is allocated to the PBCH and P/S-SCH. For control channels targeting individual UEs, e.g. the PDCCH, a simple approach is to use similar strategy. Alternatively, dynamic power control based on the addressed UEs channel quality can be used. This will enable more PDCCHs to be multiplexed, and hence the ability to schedule more users in parallel.

No special measurements exist for downlink power control. It relies on CQIs and handover measurements.

LINK ADAPTATION

For unicast traffic, link adaptation is used and is controlled by the eNB. A common modulation and channel code is used in the frequency domain per UE and codeword. The modulation and coding scheme (MCS) is selected based on CQI feedback and buffer content.

Rapid interference variations make it difficult to predict the link quality accurately, and select MCS based on such knowledge. Instead, preliminary, MCS selection is based on averaged link quality. Different operating points can then be used. To reach low delay (few retransmissions), a margin to the interference variations can be included. This however leads to limited throughput, as often an unnecessary robust MCS is used. To reach high throughput, a low margin (even negative) is used. This will instead lead to a larger number of retransmissions, and hence a larger delay. The risk of throughput loss or large delays in case of negative margins is reduced by the use of incremental redundancy for retransmissions.

PAGING – PHYSICAL-LAYER ASPECTS

Paging is used for network-initiated connection setup. An efficient paging procedure should allow the UE to sleep with no receiver processing most of the time and to briefly wake up at predefined time intervals to monitor paging information from the network.

In WCDMA, a separate physical-layer paging indicator channel, monitored at predefined time instants, is used to signal the UE to receive the paging information. As the paging indicator is significantly shorter than the duration of the paging information, this approach minimizes the time the UE is awake.

For LTE, paging relies on the PDCCH, monitored at predefined time instants according to a DRX cycle. This is illustrated in Figure 2-32. No separate physical-layer paging indicator channel is used as the potential power savings are very small due to the short duration of PDCCH transmission, at most three OFDM symbols. If the terminal detects its paging group identity on the PDCCH, it demodulates and decodes the PDSCH and forwards the decoded data on the paging transport channel (PCH) to the MAC layer. The PCH transport block contains the exact identity of the terminal being paged. A terminal not finding its identity on the detected PCH will discard the information and sleep according to the DRX cycle. Obviously, as the uplink is not necessarily time aligned when paging a terminal, no ACK/NAK signaling can take place and consequently hybrid ARQ with soft combining cannot be used for paging messages.

- The UE may use Discontinuous Reception (DRX) in idle mode in order to reduce power consumption and subsequently increase battery life.
- UE reads SIB2 to calculate when to wake to monitor the Paging channel.
- When DRX is used the UE needs only to monitor one P-RNTI per DRX cycle.

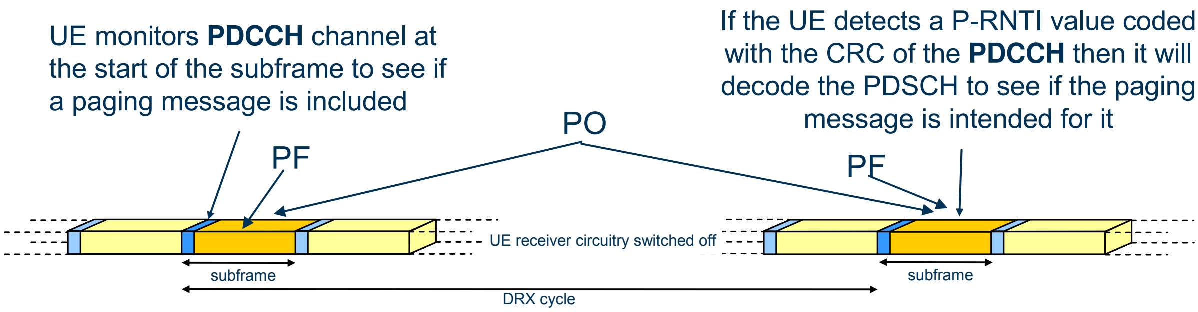


Figure 2-32 Idle mode DRX.

One Paging Occasion (PO) is a subframe where there may be P-RNTI transmitted on PDCCH addressing the paging message. One Paging Frame (PF) is one Radio Frame, which may contain one or multiple Paging Occasion(s). When DRX is used the UE needs only to monitor one PO per DRX cycle.

PF and PO is determined by following formulae using the DRX parameters provided in System Information:

PF is given by following equation:

SFN mod T= (T div N)*(UE_ID mod N)

Subframe Patterns for FDD:

Ns	PO when i_s=0	PO when i_s=1	PO when i_s=2	PO when i_s=3
1	9	N/A	N/A	N/A
2	4	9	N/A	N/A
4	0	4	5	9

Subframe patterns for TDD (all UL/DL patterns):

Ns	PO when i_s=0	PO when i_s=1	PO when i_s=2	PO when i_s=3
1	0	N/A	N/A	N/A
2	0	5	N/A	N/A
4	0	1	5	6

Index i_s pointing to PO from subframe pattern defined in the tables above (for FDD and TDD modes respectively) is derived from following calculation:

i_s = floor(UE_ID/N) mod Ns

System Information DRX parameters stored in the UE shall be updated locally in the UE whenever the DRX parameter values are changed in SI. If the UE has no IMSI, for instance when making an emergency call without USIM, the UE shall use as default identity UE_ID = 0 in the PF and i_s formulas above.

The following Parameters are used for the calculation of the PF and i_s:

T: DRX cycle of the UE. T is determined by the shortest of the UE specific DRX value, if allocated by upper layers, and a default DRX value broadcast in system information. If UE specific DRX is not configured by upper layers, the default value is applied.

- nB: 4T, 2T, T, T/2, T/4, T/8, T/16, T/32.
- N: min(T,nB)
- Ns: max(1,nB/T)
- UE_ID: IMSI mod 1024.

IMSI is given as sequence of digits of type Integer (0..9), IMSI shall in the formulae above be interpreted as a decimal integer number, where the first digit given in the sequence represents the highest order digit.

For example:

IMSI = 12 (digit1=1, digit2=2)

In the calculations, this shall be interpreted as the decimal integer "12", not "1x16+2 = 18".

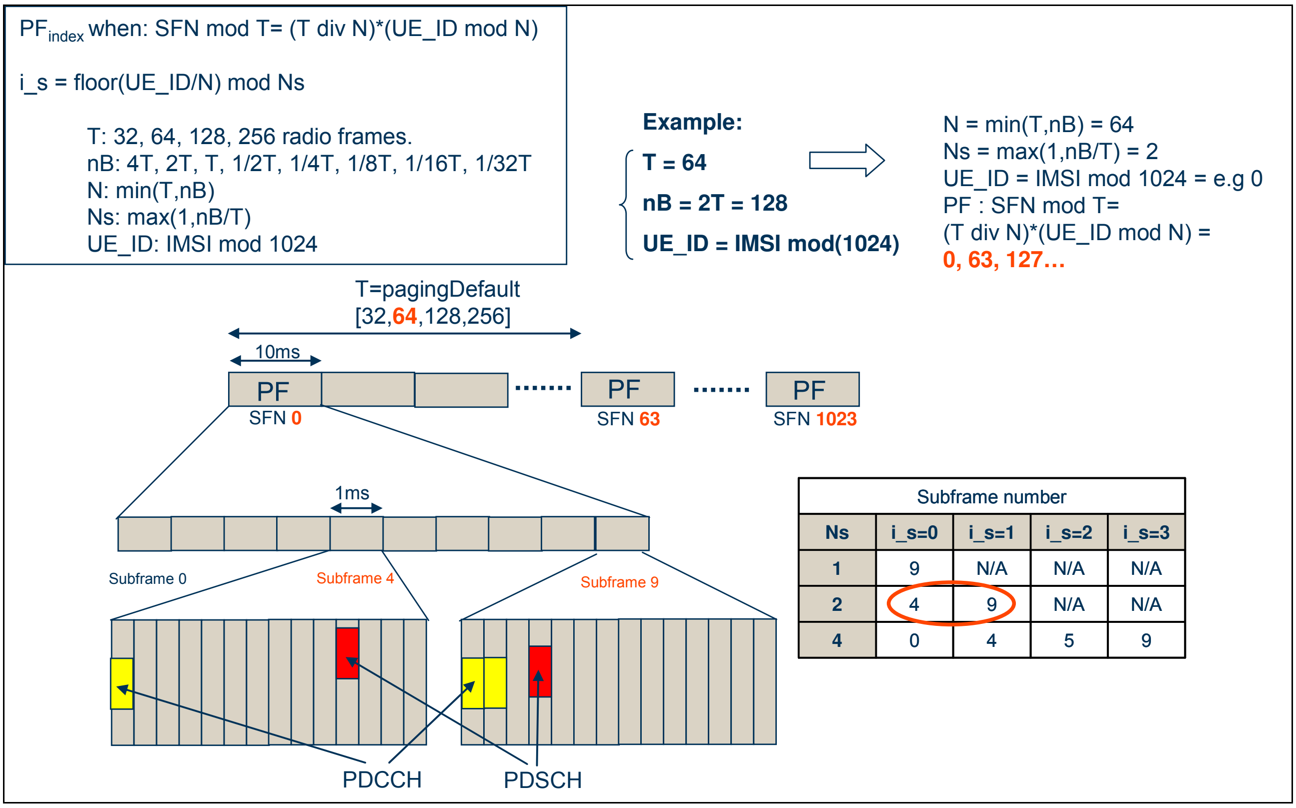


Figure 2-33. DRX Paging Frame.

CELL SEARCH

Cell search is the process of identifying and obtaining downlink synchronization to cells, so that the broadcast information from the cell can be detected. This procedure is used both at initial access and at handover.

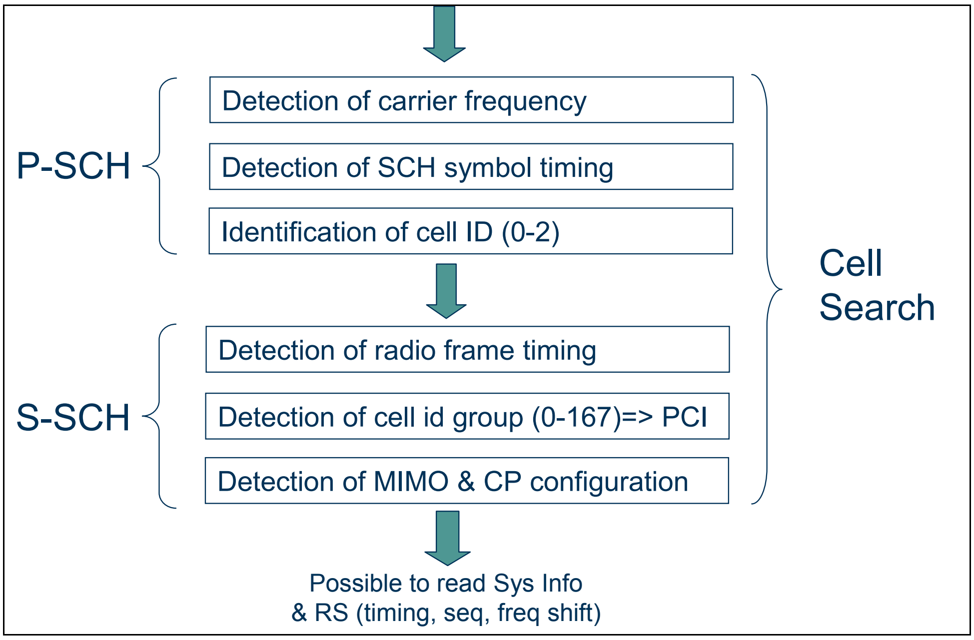


Figure 2-34. Cell search flow diagram.

In order to simplify initial cell search – where the UE has no a-priori information about the spectrum allocation of the cell – the Synchronization Channel (SCH) always occupies only 63 (62 + DC carrier which is not used) sub-carriers in the center of the available spectrum. The UE therefore always processes only these 63 sub-carriers, independent of the spectrum allocations.

The SCH is transmitted twice per frame, in sub frame #0 and #5.

One SCH signal is comprised of a primary SCH (P-SCH) and a secondary SCH (S-SCH). Figure 2-35 shows the positions for P-SCH and S-SCH in FDD. P-SCH and S-SCH span the duration of the OFDM symbol #6 and #5, respectively (assuming a short CP, in the long CP case, OFDM symbol #5 and #4). For TDD however, S-SCH is transmitted in the last OFDM symbol in sub frame #0 and #5 while P-SCH is transmitted in the first OFDM symbol in the DwPTS slot. Placing P-SCH and S-SCH close to each other enables coherent detection of S-SCH using the channel estimate obtained from P-SCH. A drawback of this placement is that the duration between P-SCH and S-SCH depends on the length of the CP and its length must therefore be blindly estimated.

- Primary and secondary synchronization signal (P-SCH & S-SCH)
  - Transmitted in subframe #0 and #5
    - Primary synchronization signal can be used as phase reference for secondary reference signal
  - Uses 62 center subcarriers (~6 resource blocks) ➡ cell search procedure independent of system bandwidth

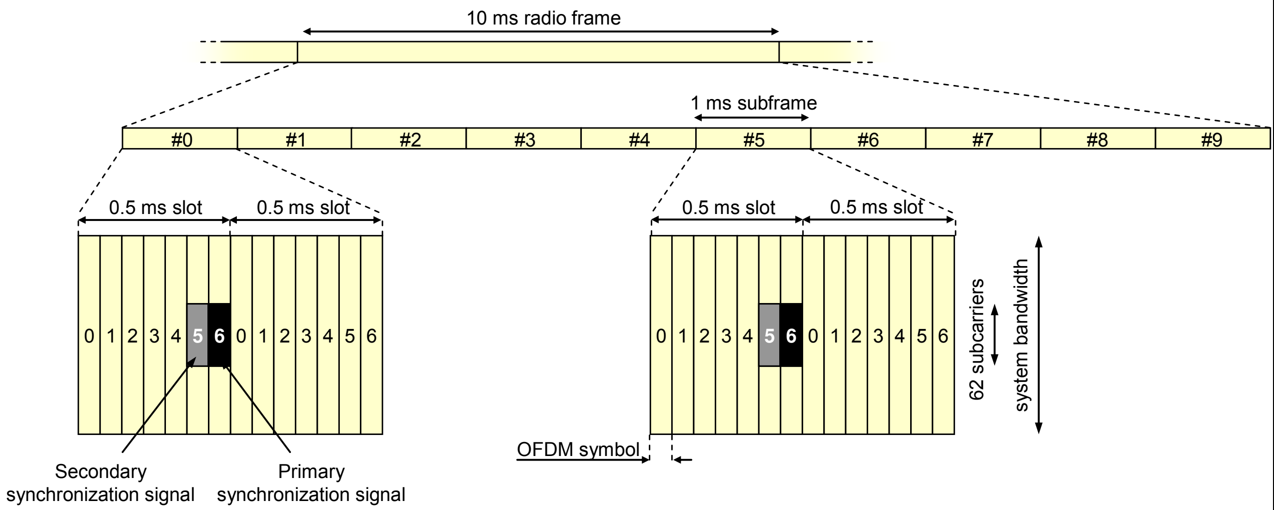
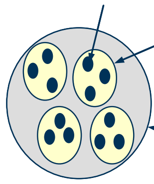


Figure 2-35. Cell Search (FDD).

P-SCH is used to find the timing of SCH as well as to correct possible frequency errors of the local UE oscillator. Three different P-SCHs are defined, each of them are mapped to a certain cell identity within a cell group. Furthermore, P-SCH are frequency domain defined Zadoff-Chu sequences of length 63, with the DC carrier punctured (indices 25, 29, 34 are used). Since P-SCH occurs twice per frame it does not uniquely determine the frame timing but has an ambiguity of 5 ms. Therefore the S-SCH signals transmitted in sub-frame #0 and #5 differ and are used to resolve this ambiguity. Furthermore, the S-SCH encodes the cell group – in total 168 cell groups - to which the cell belongs. Hence, after detection of P-SCH (giving the cell ID within a cell group) and S-SCH (giving the cell group) the 10 ms frame timing as well as the total cell ID (among the available 3*168=504) is detected.

- 168 cell identity groups with 3 identities each
  - 168×3=504 cell identities
  - identity within cell identity group
    ➡ orthogonal RS sequence



- Step 1 – primary synchronization signal
  - 3 different sequences possible
    - to 'break the SFN channel'
  - Used to determine (at least) 5 ms timing
  - Used to determine identity within cell identity group
- Step 2 – secondary synchronization signal
  - 168 different sequences possible
  - Used to determine frame timing
  - Used to determine cell identity group

Figure 2-36. Cell search.

When the terminal now has determined the cell ID, frame timing and CP length, it has to determine the number of transmit antennas used for PBCH. That has to be blindly detected by the terminal.

SYSTEM INFORMATION

The System Information (SI) that is broadcasted in the whole cell area, is carried by the logical channel BCCH, which in turn is carried by either of the transport channels BCH or DL-SCH.

A static part of SI is called MIB (Master Information Block) is transmitted on the BCH, which in turn is carried by the PBCH.

A dynamic part of SI, called SIBs (System Information Blocks) is mapped onto RRC System Information messages (SI-1,2,3…) on DL-SCH, which in turn is carried by PDSCH.

BCCH information split into two parts

- ***Static part*** consisting of ***Master Information Block*** (MIB)
  - Transmission period = 40 ms
  - Transmitted on BCH
- ***Dynamic part*** consisting of ***System Information Blocks*** (SIB 1-8) mapped onto different RRC ***SI messages*** (SIs)
  - Period SI-1*:* 80 ms, Period SI-2*:* 160 ms, Period SI-3*:* 320 ms,
  - Transmitted on DL-SCH

Figure 2-37. System Information.

- Master Information Block (MIB)
  - Fixed amount of information (~40-60bits)
  - Transmitted using BCH transport channel (PBCH physical channel)
  - Fixed transport format and scheduling
- System Information Blocks (SIBs)
  - Transmitted using DL-SCH transport channel
  - Flexible transport format and scheduling
  - Transmitted as any other information carried on DL-SCH

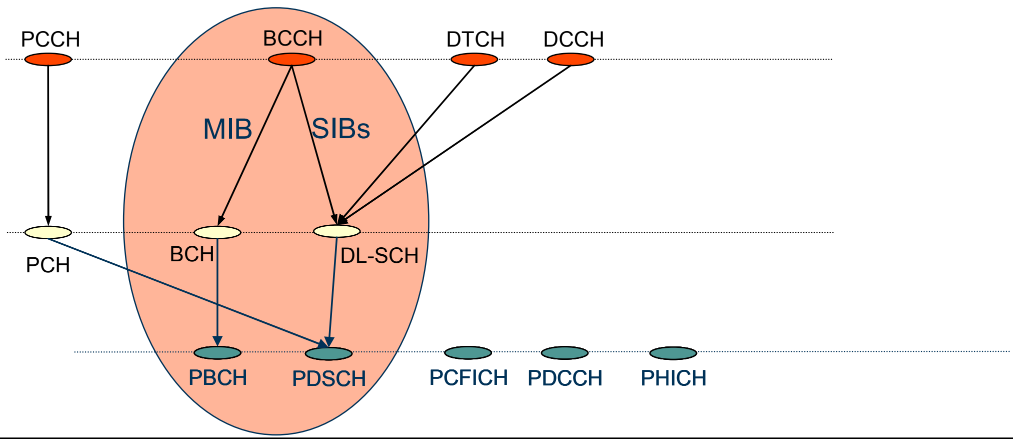


Figure 2-38. System Information channel mapping.

The MIB contains e.g. number of antennas, system bandwidth, PHICH configuration, transmitted power and scheduling information on how the SIBs are scheduled together with other data on DL-SCH.

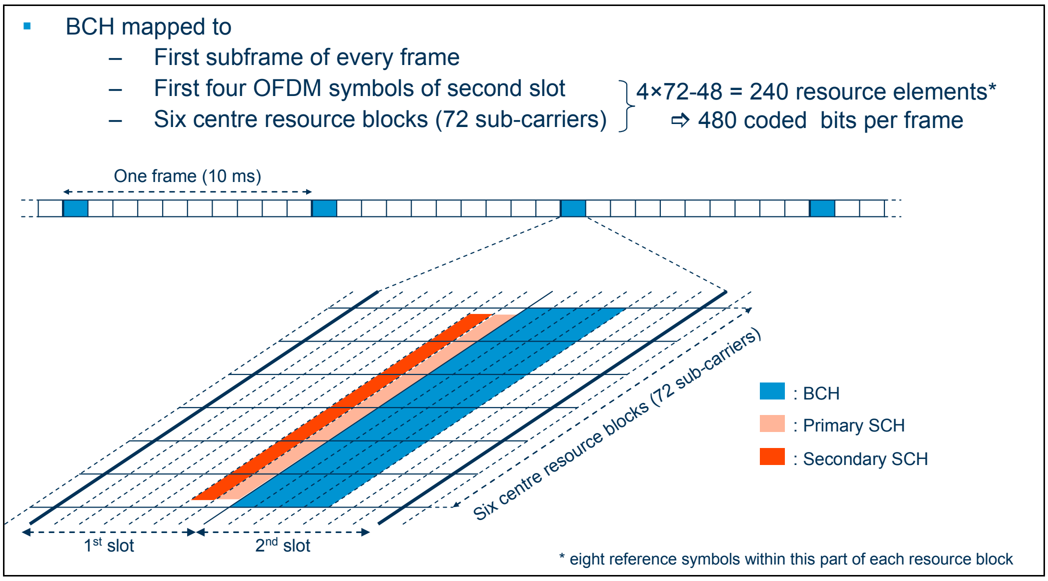


Figure 2-39. Physical Broadcast Channel - PBCH.

The PBCH is mapped onto the first four OFDM symbols of the second slot in the first subframe of every frame. In the frequency domain, PBCH uses the 72 centre sub-carriers, which corresponds to six resource blocks.

Over one radio frame, this corresponds to 4 (symbols) x 72 (subcarriers) = 288 resource elements. However, 48 resource elements (8 reference symbols per resource block and 6 resource blocks) are occupied by reference symbols and thus 240 resource elements are used for PBCH per frame. This corresponds to 480 coded bits per frame, since QPSK is used.

The BCH TTI is 40 ms, and thus a BCH transport block of 1920 bits are delivered to L1 every 40 ms.

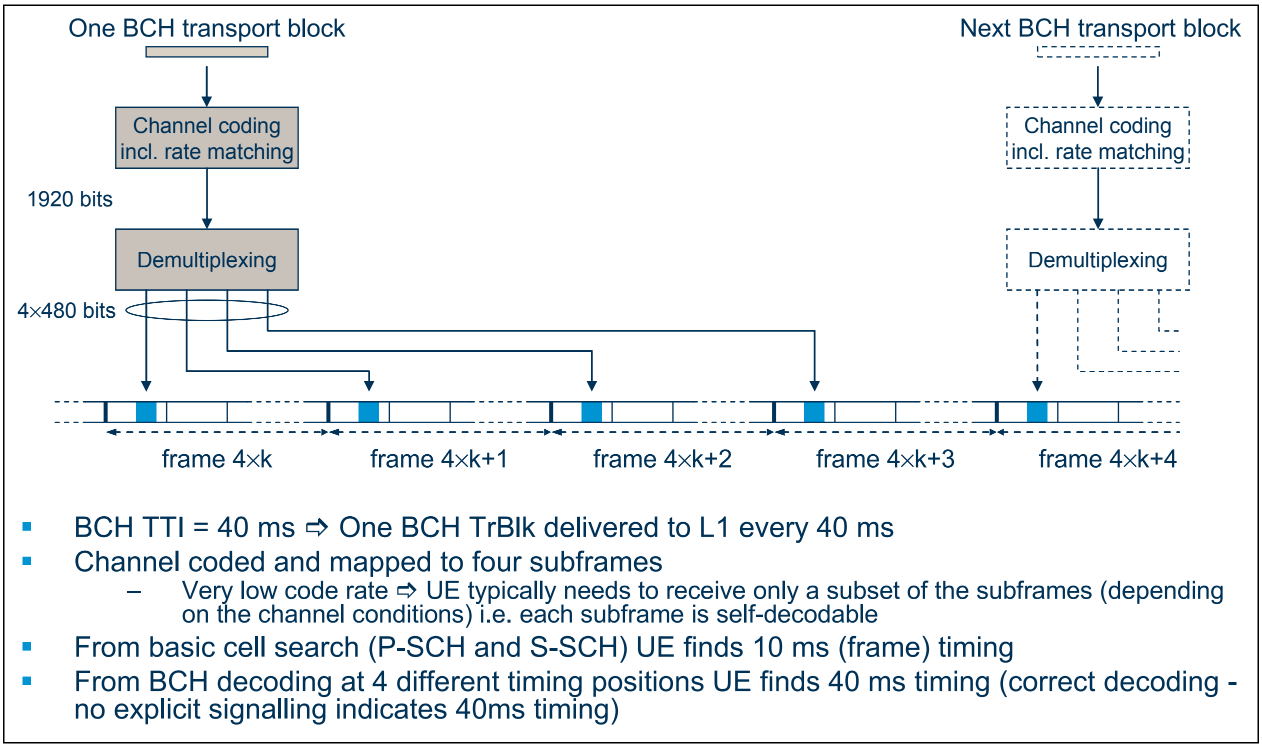


Figure 2-40. BCH coding and mapping.

480 bits are mapped onto one subframe per radio frame in four consecutive radio frames. These 480 bits are self-decodable, with a very low code rate (a lot of redundancy), so UEs with good radio conditions only need to receive a subset of the subframes. UEs with bad radio conditions, on the other hand, need to receive all subframes. This will have impact on the battery consumption and SIB acquisition time.

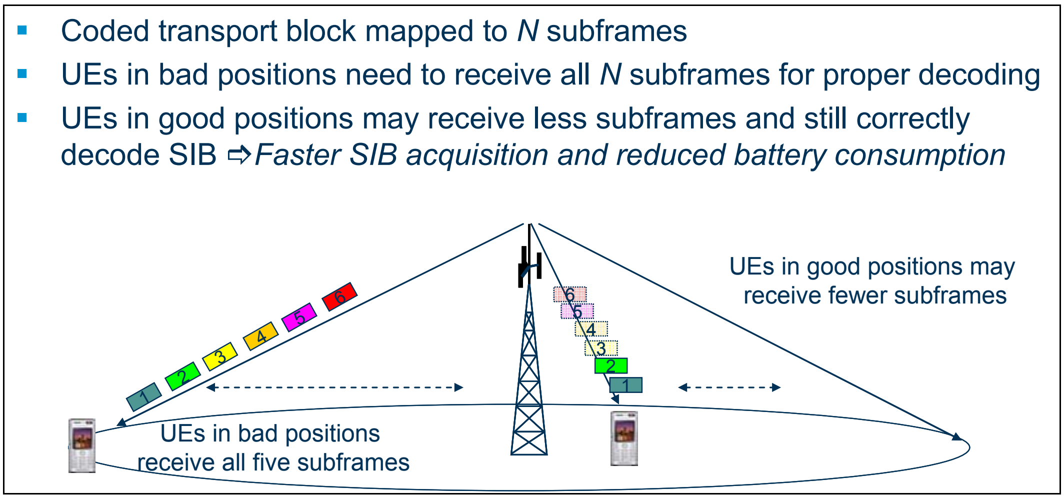


Figure 2-41. Decoding of SIB.

BCCH uses soft combining with incremental redundancy, which in this case means that UEs with good radio condition can decode the information from only subframe. UEs with bad radio conditions have to receive more subframes in order to successfully decode the information. There is no feedback information sent back to the RBS.

Figure 2-42 illustrates how the first BCCH transmission is sent without redundancy, which results in code rate one. Subsequent transmissions will decrease the code rate by adding redundancy. When three subframes are received, the code rate is 1/3. After that the received energy is added by further transmissions.

- No RRC segmentation (L1 does the segmentation)
- Use of Incremental Redundancy without specific feedback
- L1 starts from a high code rate and adds redundancy & power with subsequent transmissions
  - Less L2/L3 overhead – no segmentation.
  - A loss of one ”segment” does not destroy the reception of the SU

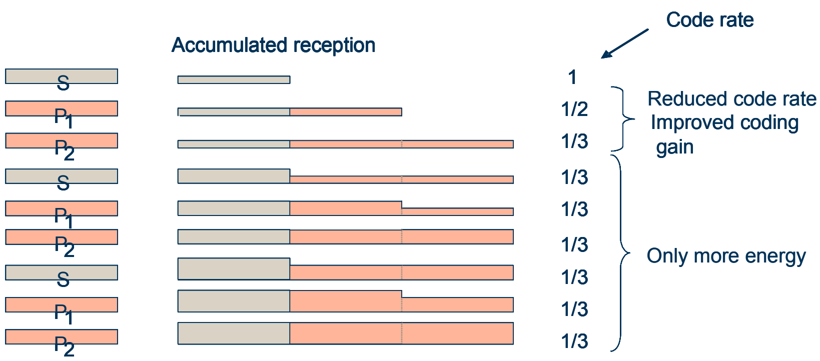


Figure 2-42. BCCH soft combining.

UPLINK RADIO ACCESS

THE UPLINK PHYSICAL RESOURCE

LTE uplink transmission is based on *DFT-spread OFDM* (Discreet Fourier Transform Spread OFDM, DFTS-OFDM). It is also often referred to as *Single-Carrier FDMA* (SC-FDMA).

Figure 2-43 shows the basic structure of DFTS-OFDM modulation with a size-M DFT being applied to the block of M modulation symbols. The output of the DFT is then mapped to selective inputs of a size-N IFFT. The DFT size M, i.e. the number of non-zero inputs to the IFFT, determines the instantaneous bandwidth of the transmitted signal while the frequency mapping determines the position of the transmitted signal within the overall available uplink spectrum. Finally, a cyclic prefix is inserted. In the figure we can also see how two different users are assigned different carrier frequencies and bandwidths. This makes the uplink orthogonal.

- OFDM with DFT-based pre-coding ⇨ Low PAPR
- Same basic ”OFDM” parameters as for downlink
  - Δf = 15 kHz, $T_{CP} \approx 4.7 / 5.2$ µs, $T_{CP\text{-}E} \approx 16.7$ µs
- Orthogonal uplink – no intra cell interference

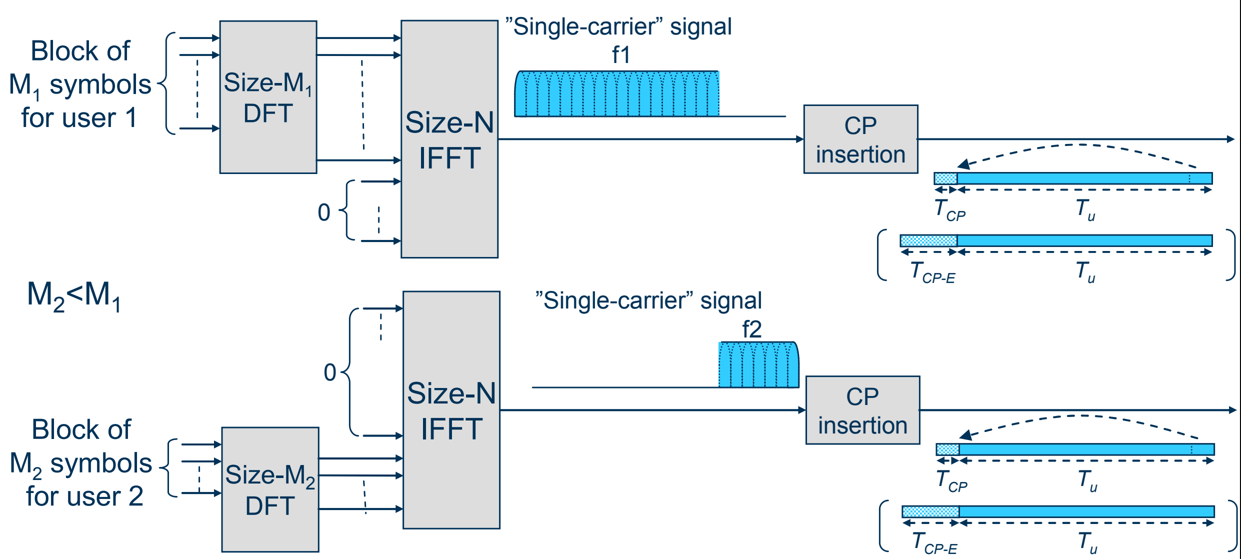


Figure 2-43 UL transmisson scheme – DFTS-OFDM.

DFTS-OFDM can also be seen as conventional OFDM transmission, combined with DFT-based pre-coding. Thus one can very well speak about a “subcarrier spacing” also in case of DFTS-OFDM. Furthermore, similar to OFDM, the DFTS-OFDM physical resource can be seen as a time-frequency grid with the additional constraint that a resource assigned to a mobile terminal must always consist of a set of consecutive subcarriers in order to keep the single-carrier property of the uplink transmission.

The uplink DFTS-OFDM subcarrier spacing equals $\Delta f = 15$ kHz and resource blocks, consisting of twelve subcarriers in the frequency domain, are defined also for the uplink. However, in contrast to the downlink, no unused DC subcarrier is defined for the uplink as this would destroy the “single-carrier” property of the uplink transmission (single-carrier characteristics require the transmission of *consecutive* subcarriers).

Similar to the downlink, also for the uplink the LTE physical-layer specification allows for a very high degree of flexibility in terms of the overall transmission bandwidth by allowing for, in essence, any number of uplink resource blocks. However, once again there will be restrictions in the sense that there will, at least initially, only be radio-frequency requirements defined for a limited set of uplink bandwidths.

Furthermore, in order to limit the complexity of the DFT operation, the uplink resource assignment should always be such that the DFT size can always be factorized into factors of 2, 3, and 5. As the resource-block size itself can be factorized into these factors, this means that also the number of assigned resource blocks can be factorized into factors of 2, 3, and 5. As an example, a UE can thus be dynamically assigned an instantaneous bandwidth corresponding to e.g. six, eight, or nine resource blocks, but cannot be assigned a bandwidth corresponding to seven resource blocks.

Also in terms of the more detailed time-domain structure, the LTE uplink is very similar to the downlink. Each 1 ms uplink subframe consists of two slots of length $T_{slot} = 0.5$ ms. Each slot then consists of a number of DFTS-OFDM blocks including the cyclic prefix. Also similar to the downlink, two cyclic-prefix lengths, a normal cyclic prefix and an extended cyclic prefix, are defined for the uplink.

In contrast to the downlink, uplink resource blocks assigned to a mobile terminal must always be consecutive in the frequency domain, as illustrated in Figure 2-44. This is necessary in order to keep the “single-carrier property of the uplink transmission. Note that, similar to the downlink, the uplink resource block is defined as twelve DFTS-OFDM sub-carriers during one 0.5 ms slot. At the same time, uplink scheduling is carried out on a sub-frame (1 ms) basis. Thus, similar to the downlink, the uplink resource assignment is carried out in terms of pairs of resource blocks, where each pair consists of two resource blocks in consecutive slots.

- Each subframe consists of two slots
- Each slot consists of
  - 6 blocks for data (each block is one DFTS-OFDM symbol)
  - 1 block for reference signals
- Transmission bandwidth and location in frequency controlled by eNodeB scheduler
  - DFT pre-coding size, IFFT inputs used

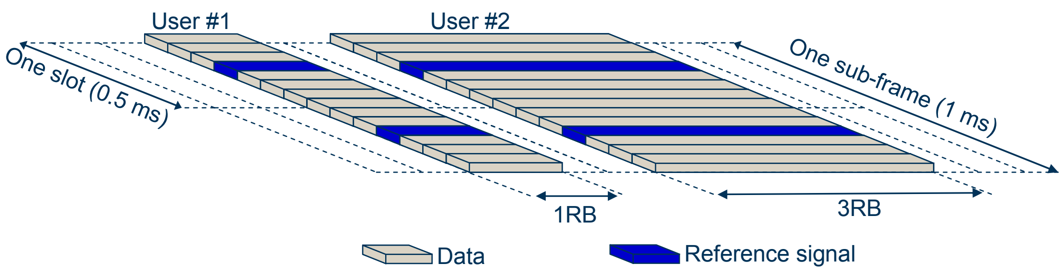


Figure 2-44 Uplink resource allocation

In the upper picture in Figure 2-45, the uplink resource is the same (the same set of DFTS-OFDM subcarriers) in the two slots of a subframe. As an alternative, frequency hopping may be applied for the LTE uplink. Uplink frequency hopping implies that the physical resource used for uplink transmission in the two slots of a subframe does not occupy the same frequency band as illustrated in Figure 2-45. Note that, as least as long as the mobile-terminal transmission bandwidth coincides with the overall available uplink spectrum, uplink frequency hopping is a pure baseband operation, simply changing the DFT-to-IFFT mapping of the DFTS-OFDM modulator.

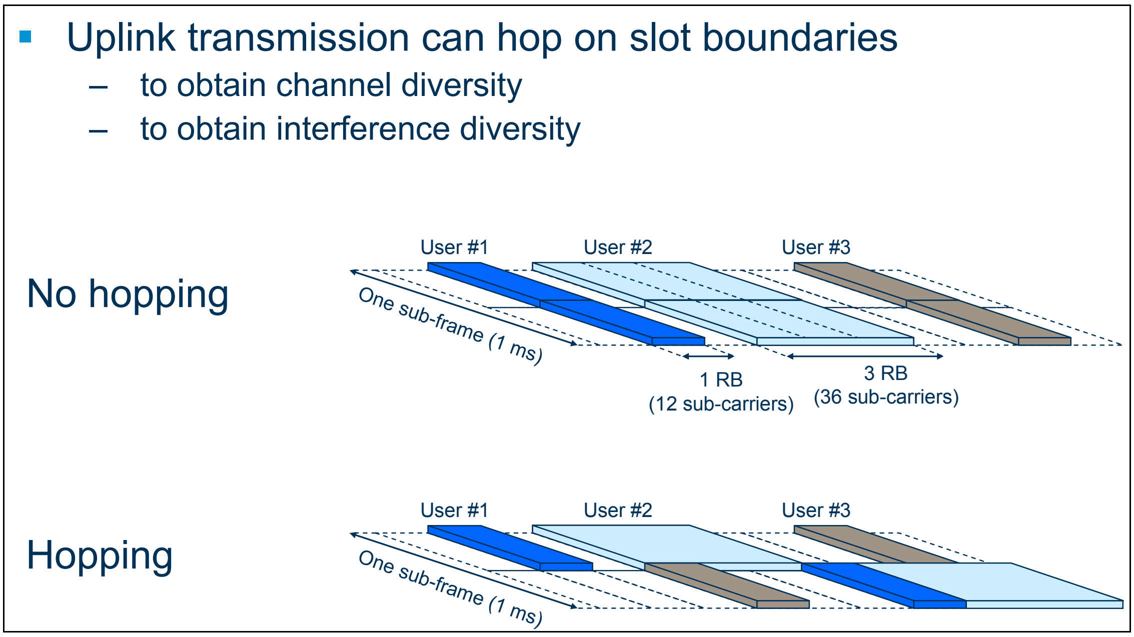


Figure 2-45 Uplink frequency hopping

Uplink reference signals

There are two types of uplink reference signals in LTE, reference signals for channel estimation to support coherent uplink transmission and so-called sounding reference signals.

Reference signals for channel estimation

As illustrated in Figure 2-44, the uplink reference signals used for channel estimation are transmitted within the fourth block of each uplink slot[8] and with an instantaneous bandwidth equal to the bandwidth of the data transmission. Note that, in the general case, uplink frequency hopping may be applied, implying that the two slots of Figure 2-44 are transmitted on different, perhaps substantially separated, frequencies. In this case, interpolation between the two reference-signal blocks of a subframe may not be possible as the channel, due to the frequency separation, may differ substantially between the two blocks.

[8] This assumes the normal cyclic prefix, i.e. seven blocks per slot

Reference signals for channel sounding

As mentioned above in addition to the above discussed reference signals, which are used for uplink channel estimation, so-called *sounding* reference signals (SRS) can also be transmitted on the LTE uplink. The intention with the sounding reference signals is for the network to be able to estimate the channel quality of the uplink channel for different UEs in order to be able to apply uplink channel-dependent scheduling. The sounding reference signals can also be used to estimate the timing of UE transmissions and to derive timing-control commands for uplink time alignment.

Sounding reference signals are transmitted independently of the transmission of any uplink data, i.e. a UE may transmit a sounding reference signal also in subframes where the UE does not have any data transmission. Furthermore, the sounding-reference-signal bandwidth can very well be, and typically is, different from that of any simultaneous data transmission from the same UE, see Figure 2-46.

It is yet to be determined if the sounding reference signals are to be transmitted within the first or the last[9] DFTS-OFDM block of a subframe (Figure 2-46 assumes the first symbol).

The basic principles for generating the channel-sounding reference signals are similar to those of the demodulation reference signals, with basically one difference: The frequency-domain reference-signal sequence (the same sequences as for the uplink demodulation reference signal sequences) is mapped to every second input of the IFFT.

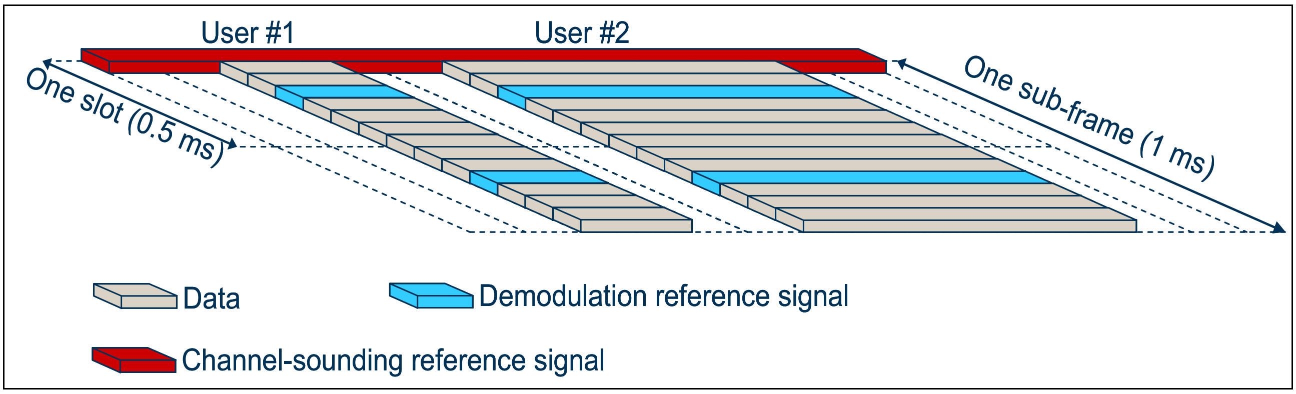


Figure 2-46 Uplink channel-sounding reference signal

[9] Yet to be determined if the sounding RS is in the first or the last DFTS-OFDM block.

Sounding-reference-signal transmissions are configured with

- a certain bandwidth, indicating how many resource blocks (in the frequency domain) the sounding reference signal will cover
- a certain period, indicating the distance, in time, between consecutive SRS transmissions (current assumption is 2, 5, 10 , 20 , 40, 80, and 160 subframes)
- a certain duration, indicating how many times the sounding reference signal will be transmitted

Uplink transport-channel processing

The LTE uplink transport-channel processing can be outlined according to Figure 2-47. Assuming no uplink spatial multiplexing, only a single transport block, of dynamic size, is transmitted for each TTI.

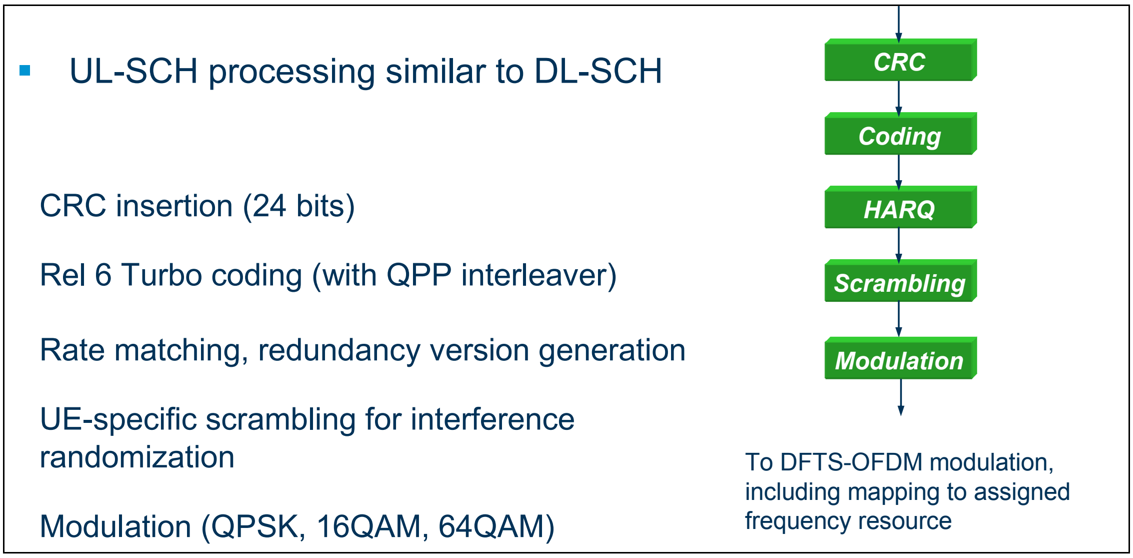


Figure 2-47 UL-SCH processing.

CRC insertion

Similar to the downlink, a CRC is calculated and appended to each uplink transport block.

Channel coding

Uplink channel coding relies on the same Turbo code, including the same QPP-based internal interleaver, as is used for the downlink.

Physical-layer hybrid-ARQ functionality

The uplink physical-layer aspects of the LTE uplink hybrid-ARQ are, in essence, identical to the corresponding downlink functionality, i.e. the hybrid-ARQ physical-layer functionality extracts, from the block of coded bits delivered by the channel coder, the exact set of bits to be transmitted at each transmission/retransmission instant.

Bit-level scrambling

Similar to the downlink, bit-level scrambling can also be applied to the coded bits on the LTE uplink.

Data modulation

Similar to the downlink, the uplink data modulation maps blocks of coded/scrambled bits to complex modulation symbols. The set of modulation schemes supported for the LTE uplink includes QPSK, 16QAM and 64-QAM, corresponding to two, four and six bits per modulation symbol respectively.

The block of modulation symbols are then applied to the DFTS-OFDM modulator which also maps the signal to the assigned frequency band.

UPLINK L1/L2 CONTROL SIGNALING

Uplink L1/L2 control signaling consists of one (or more) of the following pieces of information:

- Hybrid-ARQ acknowledgements related to reception of DL-SCH transport blocks,
- CQI (Channel-Quality Indicator) indicating the instantaneous downlink channel quality perceived by the terminal. Similar to HSPA, the CQI reports can be used by the network for downlink channel-dependent scheduling and rate control. However, in contrast to HSPA, the LTE CQI reports indicate the channel quality in both the time and frequency domain
- Scheduling requests, used by the terminal to request UL-SCH resources in case it does not have a valid scheduling grant.

Note that the uplink transport format is completely decided by the scheduler in the eNB. Consequently, and in contrast to HSPA, there is no need for signaling the transport format in the uplink control signaling.

Two different cases can be differentiated with respect to transmission of uplink control signaling:

- The terminal does *not* have a valid scheduling grant, i.e., no UL-SCH resources have been assigned in the current subframe. A separate physical channel, the *Physical Uplink Control Channel* (PUCCH) is used for transmission of uplink control signaling in this case.
- The terminal has a valid scheduling grant, i.e., UL-SCH resources have been assigned in the current subframe. In this case the uplink control signaling is transmitted on the PUSCH in order to preserve the single-carrier properties. Obviously, as the terminal has been assigned UL-SCH resources, there is no need to support transmission of the scheduling request in this case.

Control signaling on PUCCH

Control signaling on PUCCH is transmitted using one out of four formats: format 1A and 1B are used for transmission of ACK/NAK, format 2 is used for transmission of CQI and format 1 is used for scheduling request.

Spatial mux, 2 TB

- Uplink control signaling
  - ACK/NAK, triggered by DL data transmission (PUCCH format 1A,1B or PUSCH)
  - CQI, transmitted at regular time intervals (PUCCH format 2 or PUSCH)
  - Scheduling request (PUCCH format 1)
- If data and control are transmitted simultaneously -> PUSCH
  - control located in the same region as data (time multiplexed)
  - required to preserve single-carrier properties
- If only control is transmitted -> PUCCH
  - control located at reserved region at band edges
  - one RB is shared by multiple UEs through orthogonal spreading sequences

Figure 2-48. UL control signaling.

The PUCCH is transmitted on resources located at the edges of the uplink system bandwidth as illustrated in Figure 2-49. Each such resource consists of twelve “subcarriers” (one resource block) within each slot of an uplink subframe. In order to provide frequency diversity, these frequency resources are frequency hopping on the slot boundary, i.e. one resource consists of 12 subcarriers at the upper part of the spectrum within the first slot of a subframe and an equally sized resource at the lower part of the spectrum during the second slot of the subframe or vice verse. If more resources are needed for the PUCCH, e.g. in case of very large overall transmission bandwidth supporting a large number of users, additional resources blocks can be assigned next to the previously assigned resource blocks.

The bandwidth of one resource block during one subframe is too large for the control signaling needs of a single terminal. Therefore, to efficiently exploit the resources set aside for control signaling, multiple terminals can share the same resource block. This is done by CDMA between different terminals where different cyclic shifts of a cell-specific length-12 CAZAC sequence are assigned to the terminals. The resource used by a PUCCH is therefore not only specified in the time-frequency domain by the resource-block pair, but also by the cyclic shift (and, for format 1A and 1B, additionally by an orthogonal cover as described further below). Typically, up to six cyclic shifts can be used in a cell. The length-12 CAZAC sequence is generated in the same way as the sequences for uplink reference signals.

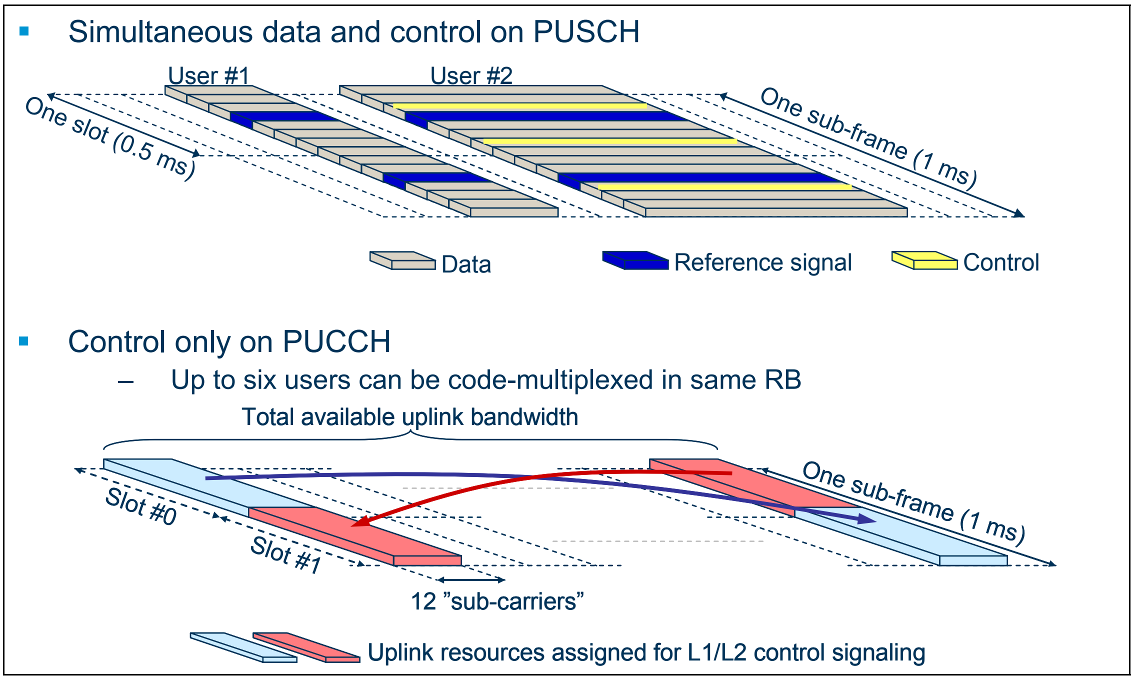


Figure 2-49 UL control signaling PUSCH/PUCCH

PUCCH format 1A and 1B – hybrid-ARQ acknowledgement

PUCCH format 1A and 1B are used for transmission of hybrid-ARQ acknowledgements with the difference between the two being the number of bits. Format 1A supports a single acknowledgement bit to be used in absence of downlink spatial multiplexing, while format 1B supports two acknowledgement bits for the case of DL-SCH spatial multiplexing with two transport blocks per TTI.

One (format 1A) or two (format 1B) acknowledgements bits are modulated using BPSK or QPSK, respectively, resulting in one modulation symbol. In addition to the PUCCH-specific cyclic shift of the length-12 CAZAC sequence as described above, the PUCCH resource for format 1A and 1B is further specified by an orthogonal cover sequence. Orthogonal cover sequences are applied to both the four information symbols in a slot as well as to the three reference signal symbols. Thus, with three[10] reference symbols per slot, up to three acknowledgements can be transmitted for each of the cyclic shifts. Typically, up to six cyclic shifts can be used, resulting in up to 18 terminals with PUCCH format 1A/1B sharing one resource block.

The same PUCCH structure is used in the two slots of a subframe. To further randomize the inter-cell interference between PUCCH resource blocks, cyclic shift hopping (per OFDM symbol) and orthogonal cover hopping (per slot) are used.

Hybrid-ARQ acknowledgements are transmitted a fixed time after the reception of a DL-SCH transport block. Furthermore, the PUCCH resource to use is derived from the index of the first control channel element in the PDCCH used for scheduling the downlink transmission (or from RRC signaling in case of persistent scheduling).

PUCCH format 1 – Scheduling Request

PUCCH format 1 is used for transmitting scheduling requests. The overall structure is similar to that used for hybrid-ARQ acknowledgements.

Each active terminal is assigned a dedicated resource for scheduling request through RRC signaling, providing the possibility to request an uplink grant every *x* subframe.

[10] This assumes normal cyclic prefix. The same structure is used for extended cyclic prefix but with only two reference signals per slot.

PUCCH format 2 – CQI reports

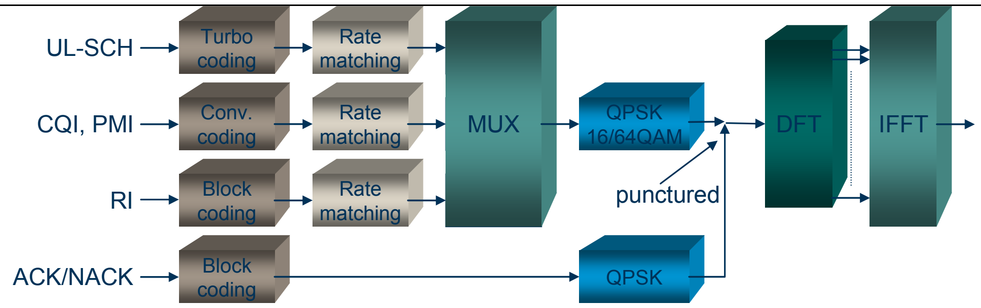
PUCCH format 2 is used for CQI reports. The CQI reports coded and modulated using QPSK. Each of the ten QPSK symbols (assuming normal cyclic prefix) is multiplied by a cyclically shifted length-12 CAZAC sequence and transmitted in one DFTS-OFDM symbol. As the same underlying principle of cyclically shifted CAZAC sequences is used for PUCCH format 2 as for format 1A/1B, hybrid-ARQ acknowledgements and CQI from different terminals can be transmitted on the same time-frequency resource by assigning different cyclic shifts. One cyclically shifted CAZAC sequence carries a single CQI report, i.e., consumes the same amount of resources as three hybrid ARQ acknowledgements (assuming normal cyclic prefix).

CONTROL SIGNALING ON PUSCH

When the terminal is transmitting data on PUSCH, i.e., has a valid scheduling grant in the subframe, control signaling cannot be simultaneously sent on PUCCH as this would violate the single-carrier properties. Instead, control signaling is time multiplexed with data on the PUSCH. Only hybrid-ARQ acknowledgements and CQI reports are transmitted on the PUSCH as there obviously is no need to request a scheduling grant when the terminal already is scheduled. Buffer status and other scheduling-related information are instead provided as “inband” MAC reports.

CQI and hybrid-ARQ acknowledgements are time-multiplexed with coded data bits prior to the DFT precoder as illustrated in Figure 2-50. The mapping of the control signaling is defined such that the control signaling is located next to the reference signals as illustrated in Figure 2-51. The reason to this is to improve the decoding performance of the critical control signaling as the channel estimates are of better quality close to the reference symbols. For data, this is not as critical as, unlike control signaling, hybrid-ARQ retransmissions can be used.

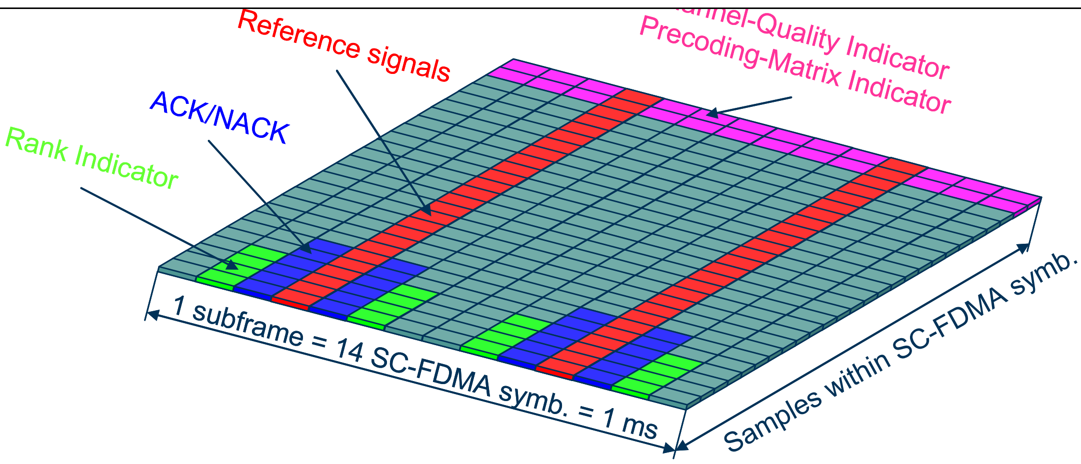
For CQI, it is known from RRC signaling in which subframes the CQI report will be transmitted and the presence or absence of CQI reports is taken into account in the DL-SCH rate matching. As the RRC signaling is robust, there is (in practice) no risk of CQI-related mismatch of rate matching parameters between the terminal and the eNB. The hybrid-ARQ acknowledgements, on the other hand, are triggered by scheduling assignments on the PDCCH. As the PDCCH is not as robust as RRC signaling (the error rate on the PDCCH is in the order of one percent), the presence or absence of acknowledgements are not accounted for in the DL-SCH rate matching. Instead, the acknowledgements are punctured in to the coded bit stream. Thus, the non-punctured bits are not affected by presence/absence of hybrid-ARQ acknowledgements and the problem of a mismatch between the rate matching in the terminal and the eNB is avoided.



- ACK/NACK
  - Always transmitted using QPSK
  - Is punctured into UL-SCH to avoid errors due to missed DL assignments and thus different interpretations of ACK/NACK symbols
- CQI, PMI, and RI
  - Use the same modulation scheme as UL-SCH but different code rate
  - Are multiplexed into UL-SCH since configured by reliable higher layer signaling

Figure 2-50 Time-multiplexing of control- and user-data onto PUSCH

The figure below shows where in time and frequency the different signaling is sent.



- ACK/NACK close to reference signals
- RI rather close to reference signals since needed for correct interpretation of CQI and PMI

Figure 2-51 Control signaling on PUSCH, normal CP

FEEDBACK REPORTS WITHOUT SPATIAL MULTIPLEXING

Feedback from the user equipment is used by Link Adaptation. The structure of the feedback depends on whether spatial multiplexing is used or not. Without spatial multiplexing (only one layer, with or without TX diversity), only the Channel Quality Indicator (CQI), the recommended transport format based on measurements on the reference signals, is sent from the user equipment to the RBS.

The feedback can be sent on either the PUCCH if no PUSCH resources are scheduled, or on PUSCH if PUSCH resources are scheduled. Periodic reporting with PUCCH format 2 is used when spatial multiplexing is used. Without spatial multiplexing, reporting mode 1-0 is used. On PUSCH, uplink grant polling from the RBS triggers the feedback reporting, also referred to as a-periodic reporting. On PUSCH, without spatial multiplexing, reporting mode 3-0 is used.

The CQI on PUCCH is a wideband average over the whole bandwidth, while the CQI on PUSCH is reported per subband. See Figure 2-52.

When the report is transmitted on PUSCH, it is multiplexed together with the HARQ-ACK after coding and before interleaving. The power and the modulation and coding scheme is the same for the feedback report and HARQ-ACK and follows the PUSCH power control.

When no CQI resources are configured on PUCCH for user equipment, or when there is downlink traffic, the link adaptation must schedule the feedback reports on PUSCH. The CQI reflects the recommended transport format of the modulation scheme and coding rate. The CQI is estimated by the user equipment from measurements on the downlink reference signal and Signal to Noise and Interference Ratio (SINR).

FEEDBACK REPORTS WITH SPATIAL MULTIPLEXING

With spatial multiplexing, a more extensive feedback report is needed. The structure depends on whether open or closed loop spatial multiplexing is used.

The feedback for closed loop consists of Channel Quality Indicator (CQI), Precoder Matrix Indicator (PMI), and Rank Indicator (RI). For the closed loop there are separate CQIs per layer. The CQI on PUCCH is a wideband report, while the CQI on PUSCH is reported per subband in case of open loop spatial multiplexing. Closed loop uses a wideband report on PUSCH.

The feedback for open loop uses only CQI and RI. The PUCCH report is periodically scheduled, with CQI and PMI on one rate and RI on another rate. For open loop, there is one CQI sent from the user equipment to the RBS.

The number of CQI resources per slot is configurable.

The periodicity of the reporting is common for all user equipment in the cell. On PUCCH the reporting mode for closed loop is 1-1 and for open loop 1-0. On PUSCH, the reporting mode is 1-2 for closed loop and 3-0 for open loop.

The PUSCH and PUCCH reporting modes and CQI and PMI feedback types are shown in Figure 2-52.

	PUSCH				PUCCH			
	Reporting Mode	**CQI**	**PMI**	**RI**	**Reporting Mode**	**CQI**	**PMI**	**RI**
No Spatial Mux /Tx Div	3-0	Sub-band	-	-	1-0	Wide-band	-	
Open Loop	3-0	Sub-band	-	YES	1-0	Wide-band	-	YES
Closed Loop	1-2	Wide-band	Sub-band	YES	1-1	Wide-band	Wide-band	YES

Figure 2-52. PUSCH and PUCCH Reporting Modes.

The sub-band size is configured by higher layers, according to 3GPP TS 36.213.

PHYSICAL-LAYER PROCEDURES

POWER CONTROL

Uplink power control is used both on the PUSCH and on the PUCCH. In both cases, a parameterized open loop combined with a closed loop mechanism is used. Roughly, the open loop part is used to set a point of operation, around which the closed loop component operates. Different parameters (targets and 'partial compensation factors') for user and control plane are used.

In more detail, for the PUSCH the UE sets the output power P_{PUSCH} according to the formula:

$$P_{PUSCH} = \min \{P_{max,}\ 10\log M + P_{0\_PUSCH} + \alpha \cdot PL + f(\Delta_i) + \Delta_{MCS}\}\ \ [dBm] \qquad (2)$$

where P_{max} is the maximum UE power, M is the number of scheduled resource blocks, PL is the estimated pathloss, P_{0_PUSCH} and α (enabling fractional pathloss compensation) are parameters controlling the target received power, Δ_i is a UE specific offset or 'closed loop correction' (the function f may can represent either absolute or accumulative offsets), and Δ_{MCS} is a Modulation and Coding Scheme (MCS) specific offset. The closed loop correction Δ_i is sent in UL grants on the PDCCH, or in special TPC_PUSCH messages on the PDCCH. For all other parameters, cell specific values are broadcast. For a subset of the parameters (e.g. P_0), it is possible to send UE specific values via RRC. For persistent scheduled resources, it is possible to use an offset to P_0. The sounding reference signal power follows the PUSCH power for a reference MCS with a Node B controlled offset.

- $P_{PUSCH} = 10 \cdot \log_{10}(M) + P_{0\_PUSCH} + \alpha \cdot PL + f(\Delta_i) + \Delta_{mcs}$
  - P_0 : UE-specific parameters
  - M : Number of assigned resource blocks
  - α : Cell-specific factor
  - Δ_{mcs} : MCS-depending compensation
  - f(.) : Accumulation function or transparent function (f(x) = x)
  - P_L : Estimated DL path loss
  - Δ_i : Power-control step ("PUSCH TPC command")
- Δ_i included in Uplink Scheduling Grant

Figure 2-53. Uplink Power Control - PUSCH.

For PUCCH, the UE sets the power according to the formula

$P_{PUCCH} = \min\{P_{max}, P_{0\_PUCCH} + PL + f(\Delta_j)\}$ [dBm] (3)

Note that for PUCCH, full pathloss compensation is always used, and the resource allocation is always one resource block. Further, the function f for the PUCCH always represents accumulation. The closed loop correction Δ_j is sent in DL assignments on the PDCCH, or in special TPC_PUCCH messages on the PDCCH. The latter may be configured to be the same as the TPC_PUSCH.

- $P_{PUCCH} = P_{0\_PUCCH} + P_L + f(\Delta_i)$
  - P_0 : UE-specific parameters
  - P_L : Estimated DL path loss
  - Δ_i : Power-control step ("PUCCH TPC command")
  - f(.) : Accumulation function
- Δ_i included in Downlink Scheduling Control (*when present*)
- Δ_i for multiple UEs jointly coded and transmitted on PDCCH
  - Used when no Downlink Scheduling Control

Figure 2-54. Uplink Power Control - PUCCH.

So called 'inter-cell power control' is assisted by the X2-based overload indicator. This may be used by the eNB as an input to power control and scheduling.

LINK ADAPTATION

Uplink link adaptation, i.e., selection of modulation and channel coding, is controlled by the network. The eNB measures the uplink channel quality and orders the UE to use a specific modulation and coding scheme (MCS) based on this. Other parameters may also be taken into account, such as UE power headroom, scheduled bandwidth, buffer content and acceptable delay.

Rapid interference variations make it difficult to predict the link quality accurately, and select MCS based on such knowledge. Instead, preliminary, MCS selection is based on averaged link quality. Different operating points can then be used. To reach low delay (few retransmissions), a margin to the interference variations can be included. This however leads to limited throughput, as often an unnecessary robust MCS is used. To reach high throughput, a low margin (even negative) is used. This will instead lead to a larger number of retransmissions, and hence a larger delay. The risk of throughput loss or large delays in case of negative margins is reduced by the use of incremental redundancy for retransmissions.

RANDOM ACCESS- PHYSICAL-LAYER ASPECTS

When UEs are not uplink synchronized and need access to the network, they carry out a random access procedure which takes into account the timing misalignment that may exist in the uplink.

General

During initial access, the UE seeks access to the core network in order to register and commence services. The random access (RA) serves as an uplink control procedure to enable the UE to access the network.

Although the UE can time synchronize to the downlink broadcast control channels (BCCH), due to the propagation (round-trip) delay, there will be a timing uncertainty in the uplink. Therefore, the RA shall reserve a sufficient time window to accommodate various arrival times.

Since the initial access attempt cannot be scheduled by the network, the RA procedure is by definition contention based. Collisions may occur and an appropriate contention-resolution scheme needs to be implemented. Including user data on the contention-based uplink is not spectrally efficient due to the need for guard periods and retransmissions. Therefore, it has been decided to separate the transmission of the random access preamble, whose purpose is to obtain uplink synchronization, from the transmission of user data.

In addition to the usage during initial access, the RA will also be used when the UE has lost the uplink synchronization, is in an idle or a low-power mode or handover.

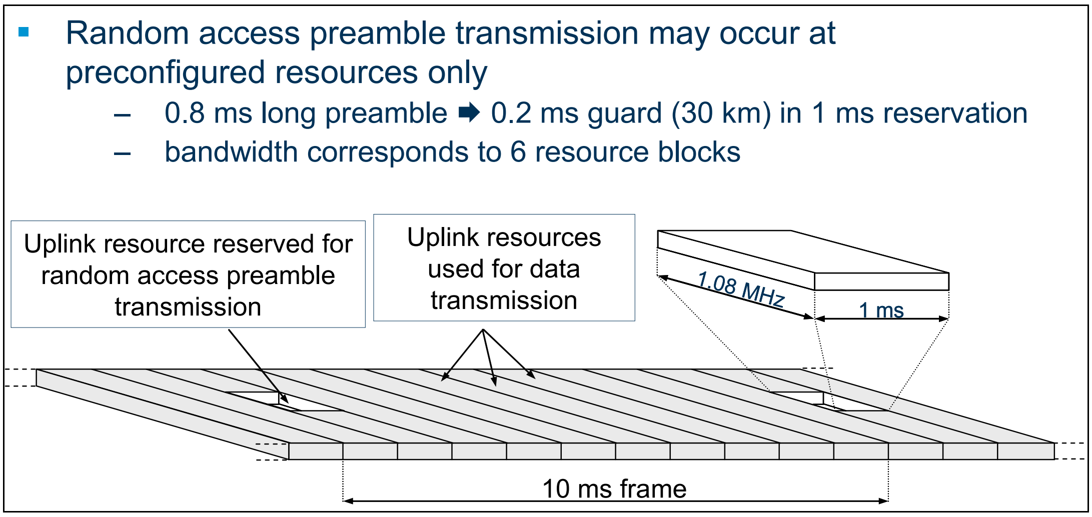


Figure 2-55. Random access.

Preamble and message transmission

The RA procedure is illustrated in Figure 2-56. In the first step, the uplink transmission is non-synchronized and only a preamble is sent. The resources used for the non-synchronized RA and the format of the preamble are further clarified in the following two sections. In the first steps (1, 2, 3, 4, 5), the UE obtains uplink synchronization and is assigned resources for uplink transmission. During the next steps (6, 7, 8), uplink transmission is synchronized. The UE transmits information on the scheduled resource, e.g., information necessary for further scheduling or setting up a connection (RRC connection request message).

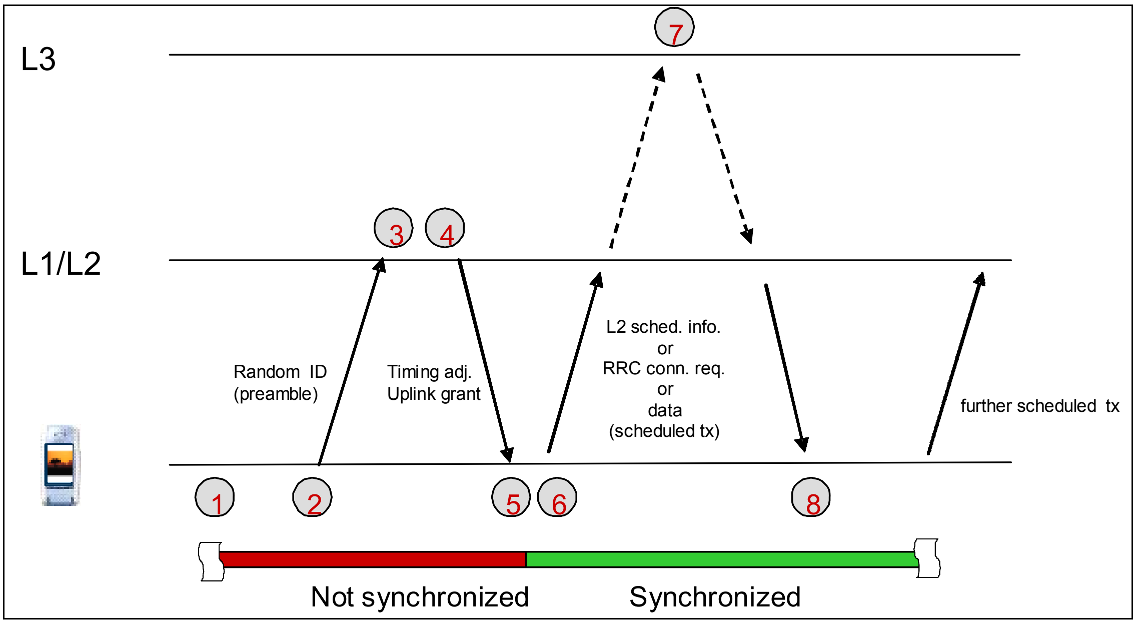


Figure 2-56 Non-synchronized Random Access.

RA physical resource

A single RA opportunity consists of a time slot and a fixed bandwidth. The RA time slot length T_{RA} shall accommodate the preamble sent by the UE and the required guard period (GP) to take into account the unknown uplink timing. The timing misalignment amounts to 6.7 µs/km. 3GPP has decided for a minimum T_{RA} of 1 ms. Here the preamble length is then 902.5 µs including a cyclic prefix of around 102.5 µs. A guard time of 97.5 µs suffices for cell radius up to 15 km. Larger guard periods and cyclic prefix are needed to accommodate timing uncertainties from cells larger than 15 km. Such large cells may also require longer preambles to increase the received energy. In order to support RA under various cell conditions RAN1 has defined additionally 3 RA preamble formats which require a T_{RA} of 2 ms or even 3 ms. These larger slots are created by the eNB by not scheduling traffic in the consecutive subframe(s). Those extended preambles contain repetitions and/or a longer cyclic prefix.

For TDD an additional “short” RA is defined. The short RA preamble only spans 133 µs. Because of this very short duration the preamble will most likely not contain a cyclic prefix but a technique called overlap-and-add will be used to enable frequency-domain processing. At the time of writing many details regarding applicability and performance of this short RA are still open.

According to 3GPP, the bandwidth of a RA opportunity is 1.08 MHz (6RB). The effective bandwidth utilized by the RA preamble is 1.05 MHz leaving small spectral guard bands on each side. This is necessary since RA and regular uplink data are separated in frequency-domain but are not completely orthogonal.

For FDD systems, RA opportunities do not occur simultaneously in different frequency bands but are separated in time. This spreads out processing load in the RA receiver. 3GPP defines RA configurations determining how often RA opportunities occur. In total 16 such configurations are defined, ranging from one RA opportunity every 20 ms (very low RA load) to one every 1 ms (very high RA load).

In TDD not all subframes are DL subframes reducing subframes that can be allocated to RA. To provide also in TDD configurations for high RA loads multiple RA opportunities can be scheduled in a single subframe.

The rather small bandwidth of 1.05 MHz of the RA preamble has been considered to provide good enough timing estimates. Furthermore fit all RA preambles into all defined spectrum allocations enabling the same preamble formats for all spectrum allocations.[11]

In order to compensate for the rather low frequency diversity obtained within 1.05 MHz the RA opportunity hops in frequency-domain. No final decision has been made on the frequency hopping period, currently 10 ms and 40 ms are considered. A period of 40 ms has the drawback that knowledge of frame-timing is not sufficient to find a RA opportunity but other means are required to obtain the correct 40 ms timing. For FDD RA opportunities are restricted to the outermost 6 RBs of the physical uplink shared channel at each band edge.

The TDMA/FDMA structure of the RA opportunities in FDD is visualized in Figure 2-57. Here only one 1.08 MHz band is allocated to RA at each time whereas several bands are possible in case of TDD. The RA opportunities always occur at the band edges of the physical uplink shared channel directly adjacent to the physical uplink control channel.

The transmit power of the RA preamble during initial access is set according to an open loop power control. The power is calculated with the same formula as the transmit power for PUCCH, with the only differences that the closed-loop correction Δj is always zero and P_{0_PUCCH} is replaced by P_{0_RACH}.

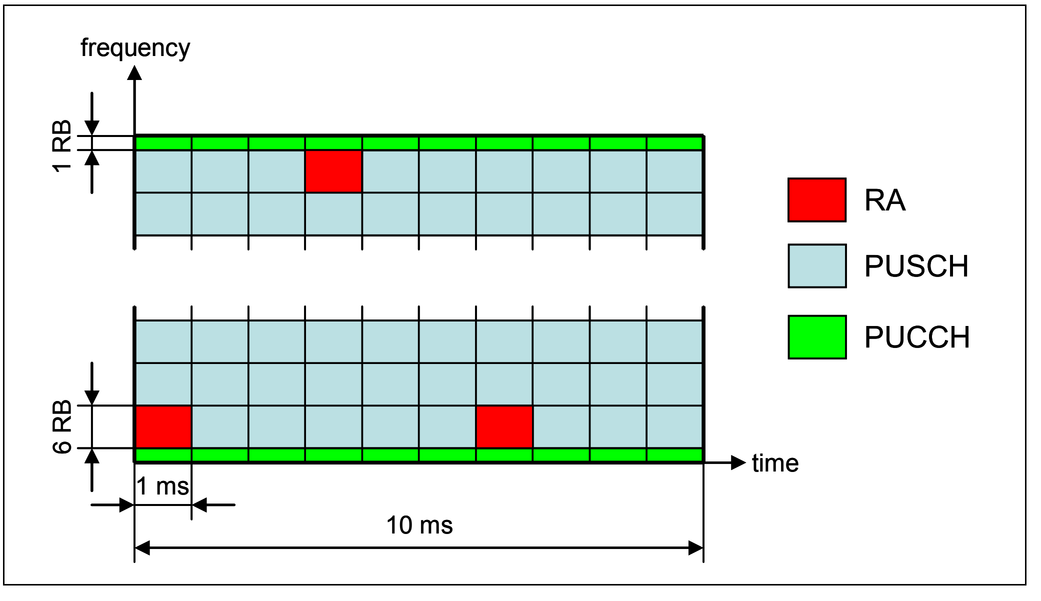


Figure 2-57. Time-frequency structure of non-synchronized RA for FDD.

[11] For the 1.4 MHz spectrum allocation (6 RB) RA and the physical uplink control channel (PUCCH) overlap. It is up to the base station implementation how to handle this overlap.

Preamble format

In the RA slot, the UE transmits a preamble which should provide sufficient guard time T_{GP} to cover the initial timing misalignment of the uplink transmission. The preamble implicitly includes a random ID which identifies the UE. LTE provides for each cell 64 such random IDs and thus 64 preambles.

The upper picture in Figure 2-58 shows the detailed timing of the basic random-access preamble. The preamble starts with a cyclic prefix (CP) to enable simple frequency-domain processing. Its length is in the order of $T_{GP} + T_{DS} = 97.5 + 5$ µs = 102.5 µs, where T_{DS} corresponds to the maximum delay spread and T_{GP} corresponds to the maximum round trip time. The CP ensures that the received signal is always circular (after removing the CP in the RA receiver) and thus can be processed by FFTs. Following the CP comes the RA sequence with duration 1000 µs - $2 \cdot T_{GP}$ - T_{DS} = 800 µs. The RA subcarrier spacing is 1/800 µs = 1250 Hz.

Figure 2-58 also shows the extended preamble formats. Format 1 has an extended CP and is suited for cell radius up to approximately 100 km. However, since no repetition occurs this format is only suited for environments with good propagation conditions. Format 2 contains a repeated sequence and a cyclic prefix of approximately 200 µs. With a RA opportunity length of 2 ms the remaining guard period is also approximately 200 µs. This format supports cell radii of up to approximately 30 km. Format 3 also contains a repeated sequence and an extended CP. Using a RA opportunity length of 3 ms this format supports cell radius of up to approximately 100 km. In opposite to format 1 format 3 contains a repeated sequence and is therefore better suited for environments with bad propagation conditions.

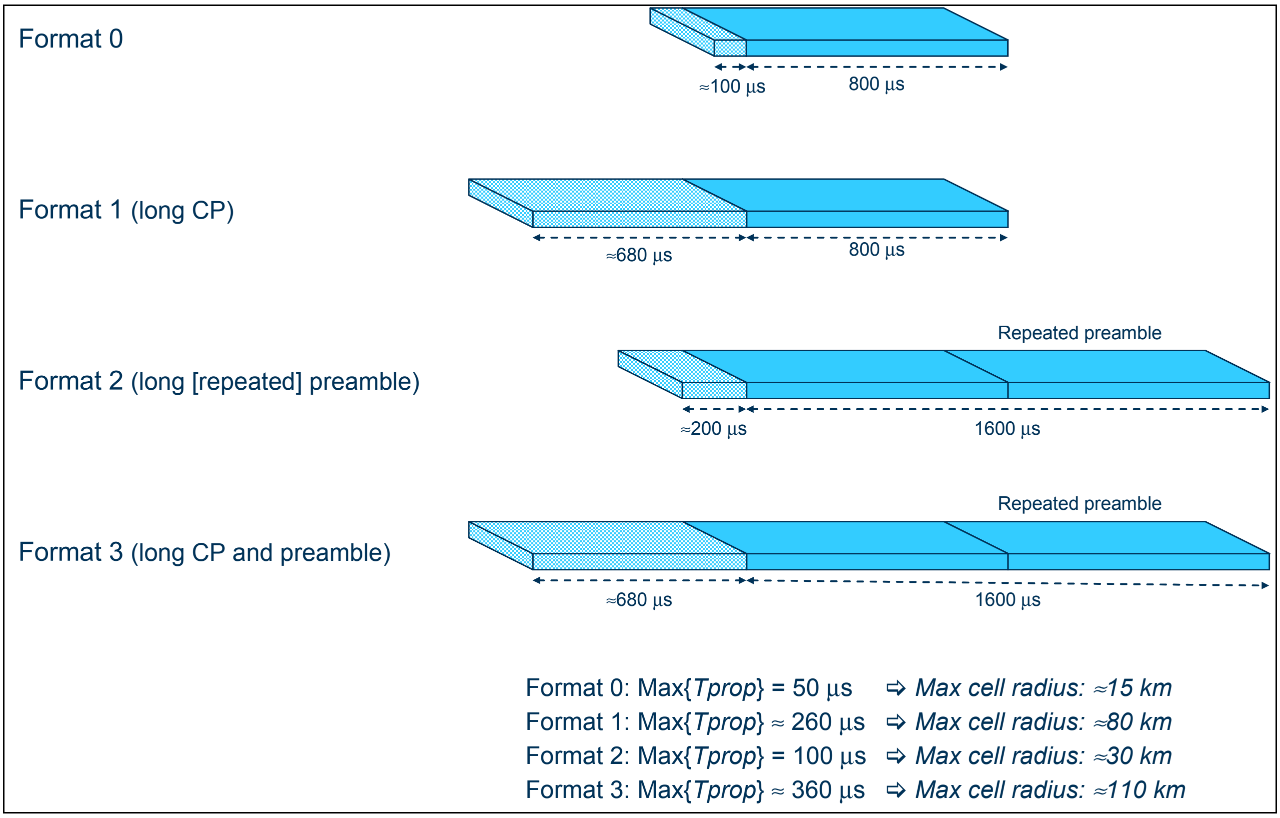


Figure 2-58. Random access preamble formats.

The requirements on the RA sequence comprising the preamble are two-fold: good auto-correlation function (ACF) properties and good cross-correlation function (CCF) properties. A sequence that has ideal (periodic) ACF and good CCF properties is the Zadoff-Chu sequence: the periodic ACF of Zadoff-Chu sequence is only non-zero at time-lag zero (and periodic extensions) and the magnitude of the CCF is equal to the square-root of the sequence length *N*. Due to special properties of Zadoff-Chu sequences the number of sequences is maximized if *N* is chosen prime. This together with the requirement that the effective RA bandwidth $N \cdot 1250$ Hz should fit into 1.05 MHz leads to $N = 839$.

Out of one Zadoff-Chu sequence – in the following also denoted root sequence – multiple preamble sequences can be derived by cyclic shifting: Due to the ideal ACF of Zadoff-Chu sequence multiple mutually orthogonal sequences can be derived from a single root sequence by cyclic shifting one root sequence multiple times the maximum allowed round trip time plus delay spread in time-domain. The correlation of such a cyclic shifted sequence and the underlying root sequence has its peak no longer at zero but at the cyclic shift. If the received signal has now a valid round trip delay – i.e. not larger than the maximum assumed round trip time – the correlation peak occurs at the cyclic shift plus the round trip delay which is still in the correct correlation zone. For small cells up to 1.5 km radius all 64 preambles can be derived from a single root sequence and are therefore orthogonal to each other. In larger cells not all sequences can be derived from a single root sequence and multiple root sequences must be allocated to a cell. Sequences derived from different root sequences are not orthogonal to each other.

One disadvantage of Zadoff-Chu sequences is their behavior at high frequency offsets: A frequency-offset creates an additional correlation peak in time-domain. A frequency offset has to be considered high if it becomes substantial relative to the RA subcarrier spacing of 1250 Hz, e.g. from 400 Hz upwards. The offset of the second correlation peak relative to the main peak depends on the root sequence. An offset smaller than T_{CS} may lead to wrong timing estimates whereas values larger than T_{CS} increase the false alarm rate. In order to cope with this problem LTE has a high-speed mode (or better high frequency offset mode) which disables certain cyclic shift values and root sequences so that transmitted preamble and round trip time can uniquely be identified. Additionally a special receiver combining both correlation peaks is required. For cells larger than approximately 35 km no set of 64 preambles exists that allows unique identification of transmitted preamble and estimation of propagation delay, i.e. cells larger than 35 km cannot be supported in high speed mode.

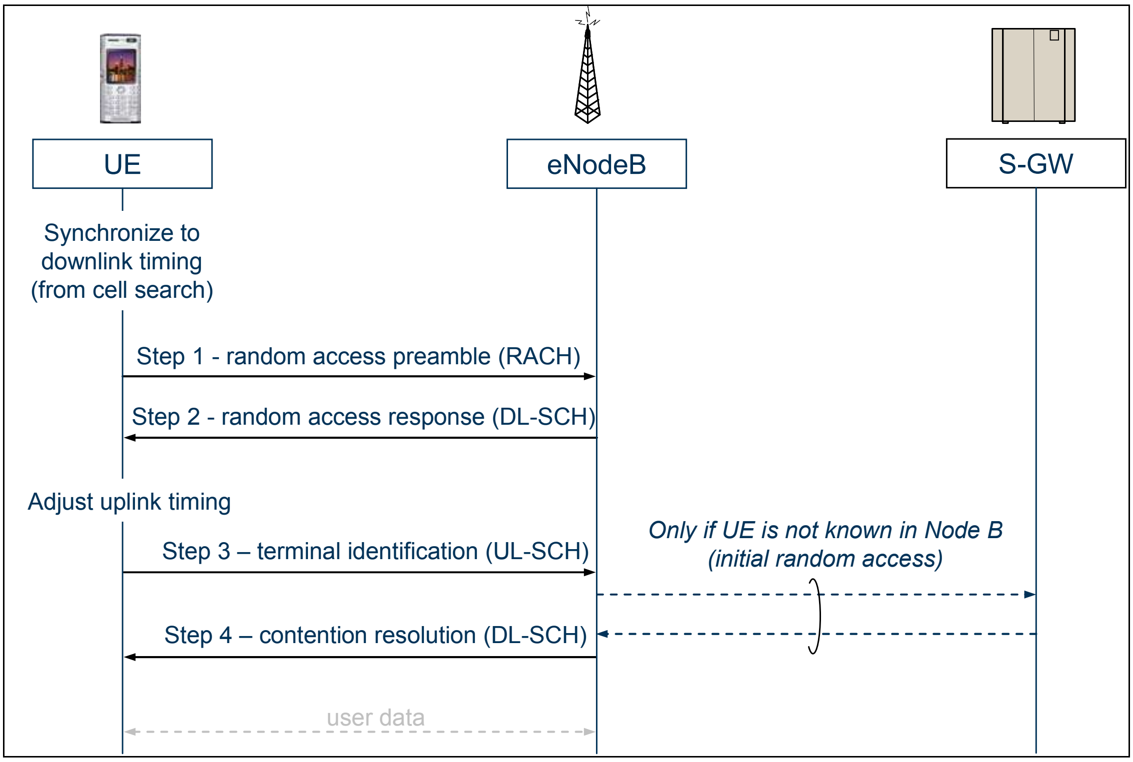


Figure 2-59. RA signaling flow.

UPLINK TRANSMIT-TIMING CONTROL

Different UEs within a cell will experience different propagation delay to/from the cell site, depending on their exact position within the cell coverage area. If UEs set their transmit timing based only on the timing of the received downlink timing, their corresponding uplink transmissions will thus arrive at the cell site with potentially very different timing. If these receive-timing differences are too large, the orthogonality between the uplink transmissions of different UEs will not be retained. Thus, an active uplink *transmit-timing control* is needed to ensure that uplink transmissions from different UEs are received with approximately the same timing at the cell site.

The transmit-timing control operates such that the network measures the received uplink timing of the different UEs. If the received timing of a specific UE is “lagging” behind, the UE is commanded to advance its transmit timing a certain amount. Similarly, a UE can be ordered to retard it transmit timing. The steps by which the UEs can advance/retard their timings are multiple of $16 \cdot T_s \approx 0.52$ µs. The timing-control commands are transmitted as higher-layer signaling (MAC) to the UEs.

As long as a UE carries out uplink data transmission, this can be used by the receiving cell site to estimate the uplink receive timing and can thus as a source for the timing-control commands. When there is no data available for uplink, the UE may still carry out transmission of sounding reference signals with a certain period, to continue to enable uplink receive-timing estimation and thus retain uplink time alignment. In this way, the UE can immediately restart uplink-orthogonal data transmission without the need for a timing re-alignment phase.

If the UE does not have uplink data to transmit for a longer period, no uplink transmission should be carried out. In that case, uplink time alignment may be lost and restart of data transmission must then be preceded by an explicit timing-re-alignment phase (random access) to restore the uplink time alignment.

MULTIPLE INPUT MULTIPLE OUTPUT (MIMO)

The LTE specifications support the use of multiple antennas at both transmitter (tx) and receiver (rx). MIMO (Multiple Input Multiple Output) uses this antenna configuration.

With multiple antennas at the transmitter and only single antenna at the receiver (referred to as MISO) it is possible to obtain so called Beamforming. With this method the transmission signal is steered in a beneficial direction (typically towards the UE). This is accomplished by adjusting the phase (and sometimes amplitude) of the different antenna elements by multiplying the signal with complex weights. This method increases the SNR (Signal to Noise Ratio) and thus the capacity.

With this configuration it is also possible to achieve Transmit Diversity. This is done by transmitting time-shifted copies of the signal and thus achieving diversity in the time-domain. This method also increases the SNR.

With multiple antennas at the receiver (SIMO or MIMO), it is possible to use receive diversity. A combining method (typically MRC – Maximum Ratio Combining) is applied to increase the SNR of the received signal.

With multiple antennas at both transmitter and receiver, it is possible to use all of the above mentioned methods.

However, with multiple antennas at both transmitter and receiver, it is also possible to achieve spatial multiplexing, also referred to as MIMO. This method creates several layers, or “data pipes” in the radio interface. The maximum number of layers that can be created depends on the radio channel characteristics and the number of tx and rx antennas. The maximum number of layers that the radio channel can support is equal to the *channel rank*. The maximum number of layers that effectively can be used is equal or less than the minimum number of antenna elements at the tx or rx side or the channel rank. The number of layers that actually is used for transmission is referred to as the *transmission rank.*

The data rate can at optimal circumstances be multiplied by the number of layers.

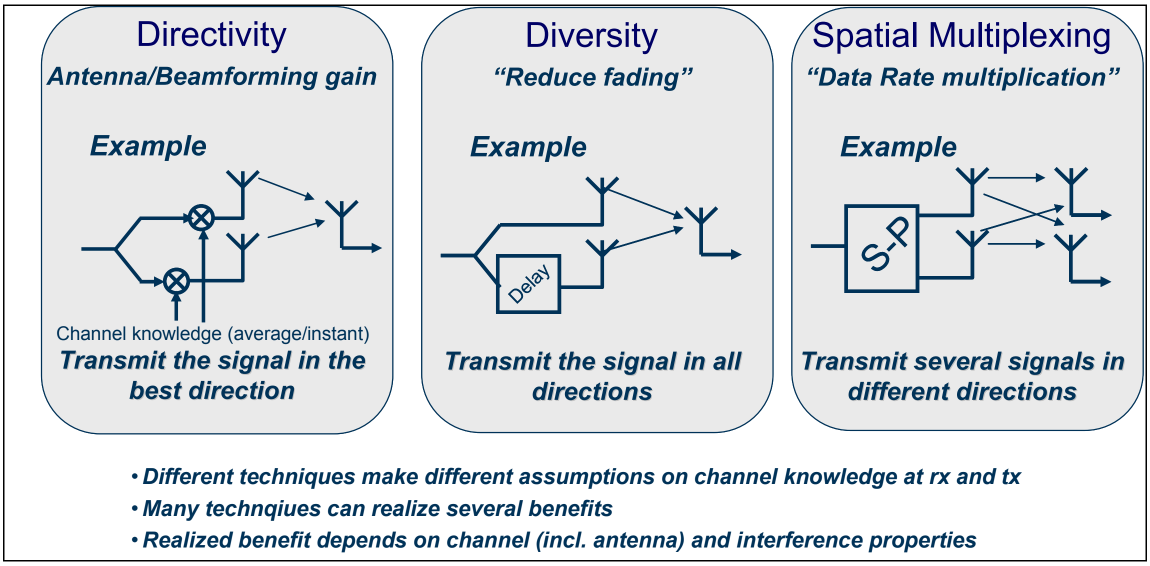


Figure 2-60. Multi-antenna possibilities.

The LTE specifications support up to four antennas at the tx side and up to four antennas at the rx side (here referred to as 4x4 MIMO configuration).

In the first release of LTE it is likely that the UE only has one tx antenna, even if it uses two rx antennas. This leads to that so called Single User MIMO (SU-MIMO) will be supported only in DL (and maximum 2x2 configuration).

- Single user MIMO (SU-MIMO)
  - Precoded spatial multiplexing with rank adaption
- Multi user MIMO (MU-MIMO)
  - Tailored for multiple UEs per RB
  - Max one layer per UE
- Transmit diversity
  - Block code based

Figure 2-61. DL MIMO schemes.

SU-MIMO increases the data rate for a single user by creating several layers for that user. In UL multi user MIMO can be applied. This means that the base-station uses MU-MIMO to separate different UE transmissions spatially. This leads to that several UEs can be scheduled in the same resource block simultaneously (same frequency, same time). This increases the capacity in the cell.

- High SINRs needed
  - Service area close to cell center
    - Less likely that cell edge UEs use multiple layers
      - go for beamforming or diversity instead
- Service area grows if surrounding cells have low load
  - Multiple layers on or near the cell edge not uncommon

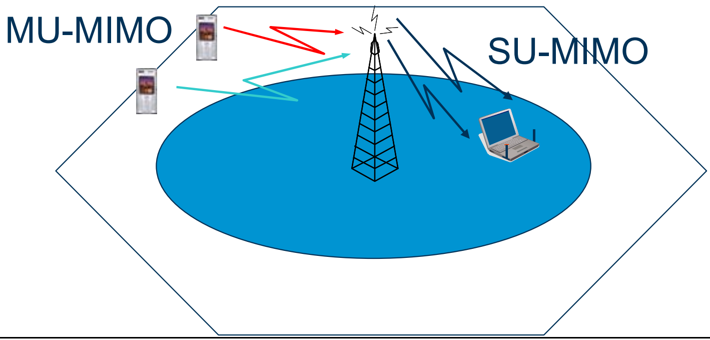


Figure 2-62. Spatial multiplexing operation.

Multiple layers means that the time- and frequency resources (Resource Blocks) can be reused in the different layers up to a number of times corresponding to the channel rank. This means that the same resource allocation is made on all transmitted layers.

- OFDM works particularly well with MIMO
  - MIMO becomes difficult when there is time dispersion
  - OFDM sub-carriers are flat fading (no time dispersion)
- 3GPP supports one, two, or four transmit ***Antenna Ports***
- Multiple antenna ports ⇨ Multiple time-frequency grids
- Each antenna port defined by an associated ***Reference Signal***

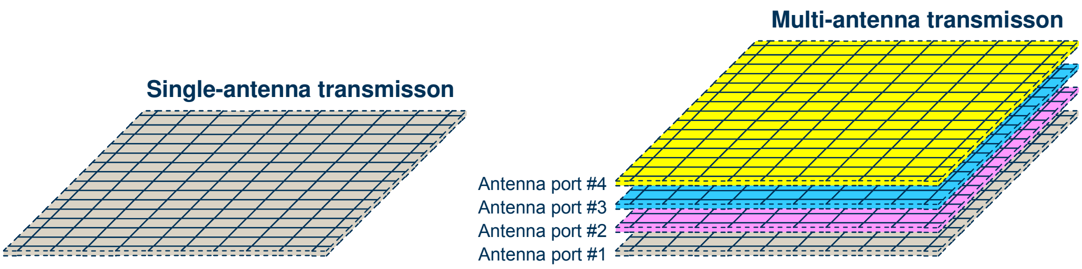


Figure 2-63. Multi-antenna transmission.

In MU-MIMO, the different UEs that are spatially multiplexed are allocated the same resource blocks, but spatially separated by the antenna arrangement and associated processing. This means that each UE does not experience a data rate multiplication as with SU-MIMO. Instead the cell benefits from the reuse of the resources.

- High load at least in cell of interest in order to find UEs for co-scheduling
  - Grouping UEs need careful scheduler design and sounding
- High SINRs needed
  - MU-MIMO service area close to cell center
    - Less likely that cell edge UEs use MU-MIMO
- Similar to single user MIMO (SU-MIMO) except the transmissions now come from different UEs
  - Uplink SU-MIMO not yet supported in LTE

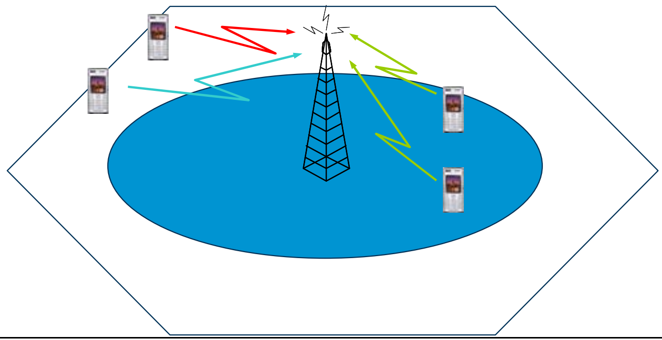


Figure 2-64. MU-MIMO operation.

The data rate only increases logarithmically as a function of the SNR (or SINR – Signal to Interference and Noise Ratio), at a high SNR. This is according to the Shannon theorem

$r_{data} = BW \times \log_2(SNR+1)$

(max data rate r_{data} is equal to the bandwith, BW, multiplied by the base-2 logarithm of the SNR plus 1).

On the other hand, at a low SNR, the max data rate increases almost linearly. Therefore, it is not efficient aiming only to obtain a high SNR. It is more efficient to try to create several “data pipes” with lower SNR (sharing SNR), which will lead to a multiplication of the maximum achievable data rate with up to the channel rank r_{max}.

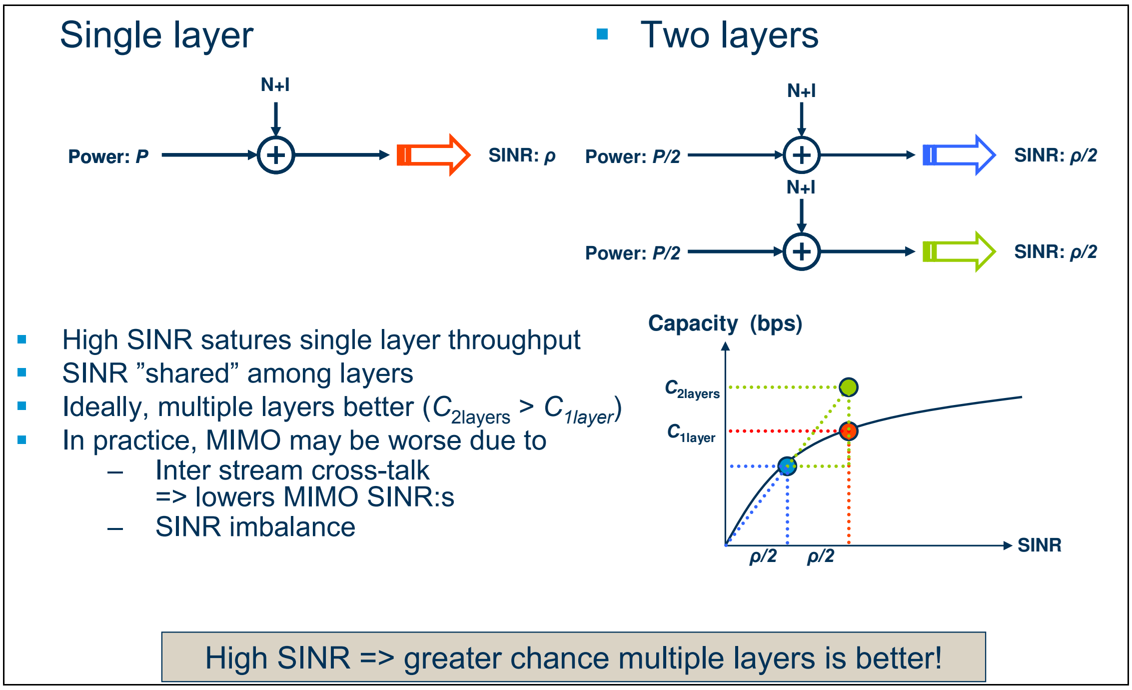


Figure 2-65. Single layer vs. Multiple layers.

LTE uses precoder based MIMO operation. A precoder, which is a complex matrix of size equal to the number of layers times the number of transmit antennas, is used to form the "beams" for the different layers separately.

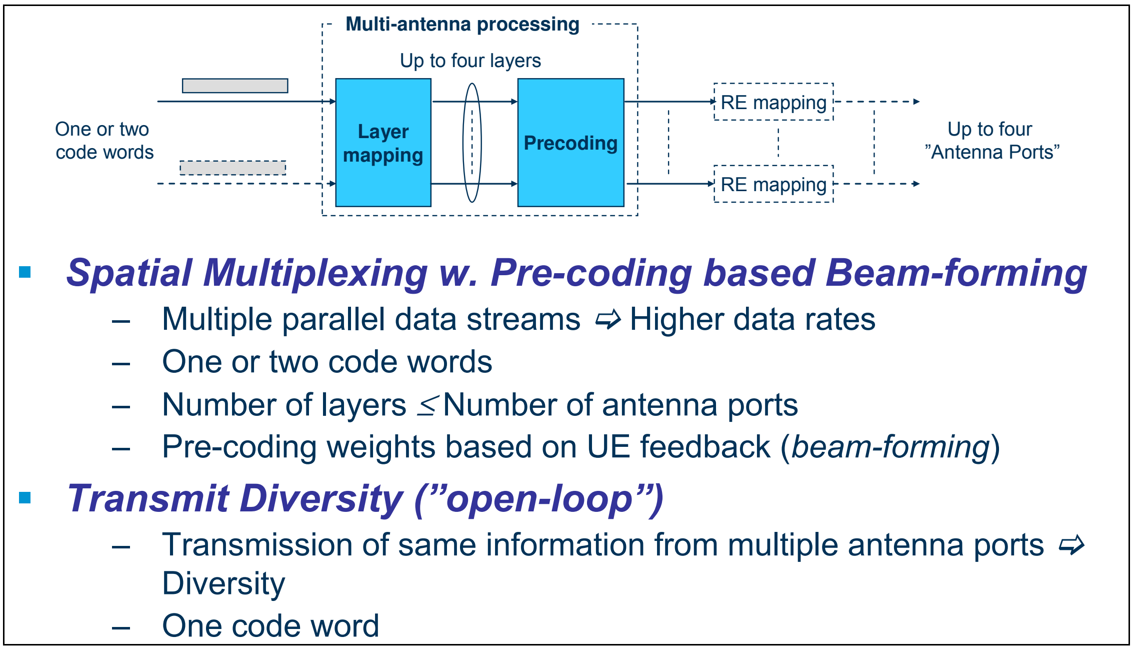


Figure 2-66. LTE Multi-antenna transmission.

When spatial multiplexing is used, maximum two codewords (transport blocks) per TTI will be used. When no spatial multiplexing is used, only one codeword per TTI will be used.

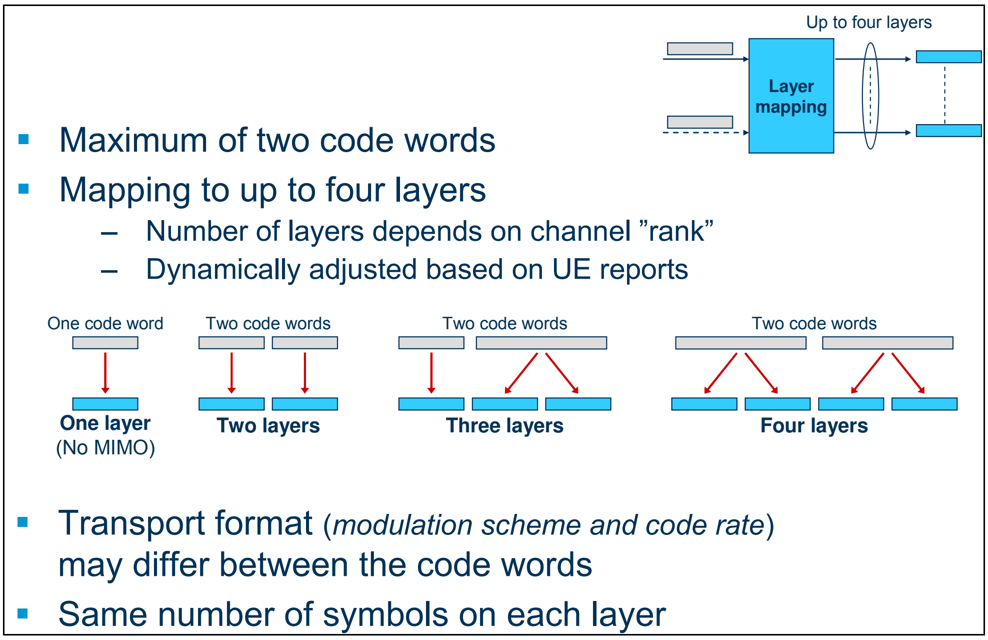


Figure 2-67. DL spatial multiplexing - layer mapping.

Given the minimum number of transmit or receive antennas, the transmission rank can at maximum be equal to that minimum number. For example, if four transmit antennas and two receive antennas are used, then the transmission rank can one or two. If the transmission rank is lower than the channel rank (i.e. there are more antennas than layers), then the remaining antenna ports can be used for beamforming at the same time as the spatial multiplexing.

- Better data rate coverage and capacity
  - Directivity and diversity improves link budget
- Potential for higher data rates
  - Spatial domain provides extra dimension
    - Extra dimension offers increased data rates
    - Ideally: r_{max} times higher data rate than single Tx (r_{max} = min{#tx antennas, #rx antennas})
- Transmit $r \le r_{max}$ parallel symbol streams (layers)
- Max r_{max} parallel ”data pipes”
- Number of layers *r* depends on channel properties
  - Channel rank *r:* #effective data pipes channel can support (data pipes with sufficiently strong SINR)
- Rank adaption dynamically adjusts #layers

Higher spectral efficiency!

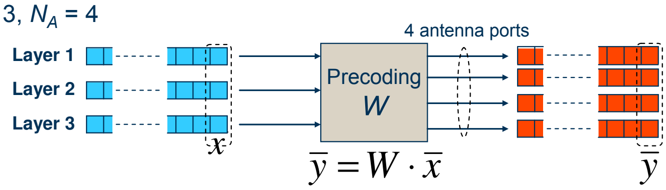
Up to r_{max} times higher throughput!

Figure 2-68. Possible multi-antenna benefits.

The number of useful layers is here denoted r, and the maximum number of layers r_{max}.

- One symbol from each of N_L layers linearly mapped to N_A antenna ports

Example: N_L = 3, N_A = 4

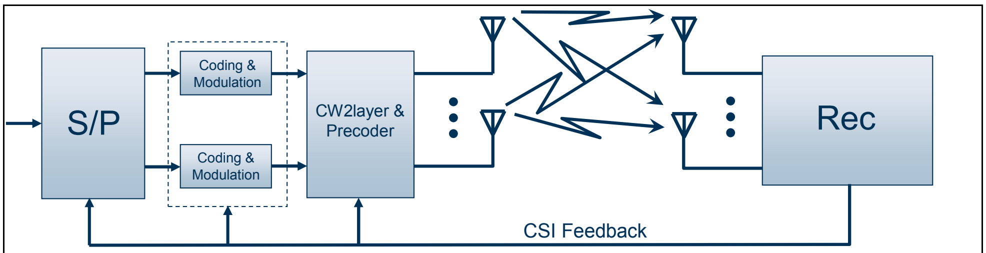


- UE reports *recommended* precoder matrix *W (including channel rank)*
  - Set of available precoder matrices = The precoder ”code book”
- Used precoder matrix signaled by network
  - Network does not need to follow UE recommendation
- One layer ⇨ ”Closed-loop” TX diversity = ”Beam forming”

Figure 2-69. DL spatial multiplexing.

In the DL, the UE estimates the spatial properties of the radio channel by measuring the DL reference symbols from the different antenna ports. This estimation is used to give feedback to the eNodeB so that the eNodeB can allocate an appropriate amount of resources make an optimal antenna mapping.

The feedback is the CQI (Channel Quality Index), the PMI (Precoder Matrix Indicator) and the RI (Rank Indicator). The CQI reflects the channel quality and is used whether or not spatial multiplexing is used. The RI indicates the number of useful layers, as estimated by the UE and the PMI indicates the precoder matrix that the UE considers as the best (gives the highest estimated SINR).

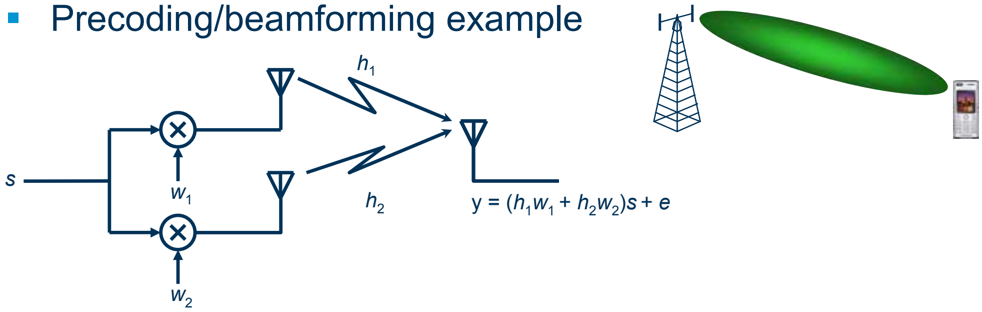


- UE feeds back channel state information (CSI) to assist link adaptation and scheduling
  - RI: Rank Indicator
    - Recommended transmission rank
  - CQI(s): Channel Quality Indicator(s)
    - Recommended transport format giving 10% BLER
    - Frequency-selective reporting possible
  - For closed-loop spatial multiplexing
    - PMI(s): Precoder Matrix Indicator(s)
    - Frequency-selective reporting possible
  - *CSI sensitive to feedback delay*

Figure 2-70. UE feedback of CSI.

In a simple beamforming example, the complex weights are adjusted in order to align the carrier phase in such a way that the individual antenna elements' signals are added constructively at the receiver side. With two antenna elements we need two complex weights, here denoted w_1 and w_2. These weights are adjusted with the support of some kind of feedback from the receiver (in this case the UE), in order to maximize the reception. With multiple antennas (here called antenna ports) at both tx and rx side and multiple layers, the complex weights will form a matrix. In case of 4x4 MIMO and four layers, a 4x4 matrix will be needed. This means that each layer will have its own complex weight vector of length equal to the number of antenna elements.

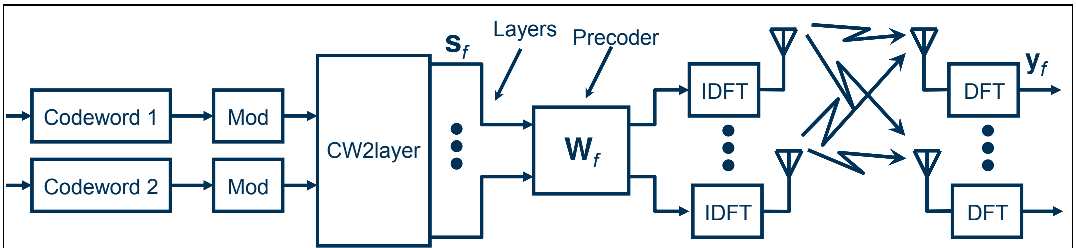
- Adapt spatial properties of transmission to match current channel conditions
- Precoding/beamforming example



- Coherent addition of signals at receive side increases SNR
- Similar to closed-loop TxD in WCDMA
- Precoding with multi layers
  - Multiply each layer with corresponding precoding vector => matrix weighting!

Figure 2-71. Precoding for exploiting channel info at tx side.

The use of a matrix of complex weights is referred to as *precoding*. The signal is "pre-coded" with the weight matrix before it is transmitted.



- Codeword to layer mapping (CW2layer)
  - 2 Tx at NodeB: max 2 layers
  - 4 Tx at NodeB: max 4 layers
- Note: Always max two codewords (transport blocks)
- Precoder $\mathbf{W}_f$ selected from finite codebook (except possibly in type II)
  - UE recommends precoder to be used at NodeB side
  - Finest frequency granularity: one precoder per 5 RB
  - Single Tx rank *r* reported per subframe
- May be combined with cyclic delay diversity (CDD)

Figure 2-72. Precoding with spatial multiplexing.

The UE will measure the different reference signals, which are transmitted separately on the different antenna ports in DL, and estimate the optimal precoder weights. The UE will choose a precoder matrix from a finite codebook, that consists of a number of precoder matrixes. Only the index of the chosen precoder matrix (Precoder Matrix Index – PMI) and Rank Indicator (RI) will be signaled to the eNB, together with the CQI.

The eNB does not have to follow the UE "recommendation" of precoder matrix, since the eNB might consider another matrix more appropriate when taking other UEs in the cell into account.

Figure 2-73 shows an example of different precoder matrixes up to channel rank two (max two layers).

Codebook index	Number of layers $N_L = 1$	$N_L = 2$
1	$\begin{bmatrix}1\\0\end{bmatrix}$	$\frac{1}{\sqrt{2}}\begin{bmatrix}1 & 0\\0 & 1\end{bmatrix}$
2	$\begin{bmatrix}0\\1\end{bmatrix}$	$\frac{1}{\sqrt{2}}\begin{bmatrix}1 & 1\\1 & -1\end{bmatrix}$
3	$\frac{1}{\sqrt{2}}\begin{bmatrix}1\\1\end{bmatrix}$	$\frac{1}{\sqrt{2}}\begin{bmatrix}1 & 1\\j & -j\end{bmatrix}$
4	$\frac{1}{\sqrt{2}}\begin{bmatrix}1\\-1\end{bmatrix}$	—
5	$\frac{1}{\sqrt{2}}\begin{bmatrix}1\\j\end{bmatrix}$	—
6	$\frac{1}{\sqrt{2}}\begin{bmatrix}1\\-j\end{bmatrix}$	—

Codebook subset and rank restriction:

eNB can restrict precoder and rank selection to arbitrary subset of possible combinations

Figure 2-73. Precoder codebook for SU-MIMO.

Spatial multiplexing is divided into closed-loop and open-loop spatial multiplexing.

Closed-loop spatial multiplexing is typically used when the UE feedback delay is sufficiently low for giving an up-to-date estimate of the current radio channel conditions. That is typically at low speeds (low mobility scenarios).

Open loop can be used when the feedback is too old (typically at high speeds). Then an averaged channel estimation is used over a longer term basis.

- Closed-loop spatial multiplexing mode:
  - Precoder $\mathbf{W}_f$ focuses transmission in ”strong directions” towards the UE
    - $\mathbf{W}_f$ selected from finite codebook
    - Track the channel in time as well as in frequency
  - Targeting scenarios with accurate CSI at eNodeB
    - Typically low mobility (unless highly spatially correlated channel)

Track instantanous channel to achieve array gain!

- Open-loop spatial multiplexing mode:
  - Transmit in ”all directions” by cycling through a sequence of four different precoders $\mathbf{W}_f$ during the transmission of a single subframe
    - Transmission rank one utilizes transmit diversity
  - Targeting scenarios with inaccurate CSI at eNodeB
    - Typically high mobility

Go for diversity to achieve robustness!

Figure 2-74. Closed and open loop spatial multiplexing.

The feedback from the UE to the eNodeB is called Channel State Information (CSI) and includes the CQI, PMI and RI. The CSI reporting can be made either periodically or a-periodically.

- Periodic CSI on PUCCH
  - Similar to HSDPA
  - Narrow bit pipe → small payload size → rough report
  - Wideband CSI appropriate
- Aperiodic dynamically requested CSI on PUSCH
  - Request CSI when needed!
  - Wide flexible bit pipe → large paylod size → detailed report
  - Frequency-selective CSI appropriate
    - Supports frequency domain scheduling
    - Array gain in frequency-selective uncorrelated channels
- Periodic CSI as baseline for more detailed aperiodic reports

Figure 2-75. Periodic and Aperiodic CSI.

The CQI and the PMI can be either a wide-band average over the whole system bandwidth or as frequency-selective (sub-band) reports.

The CSI is reported on either PUCCH or PUSCH. There are many different formats that can be used for this reporting. Figure 2-76 illustrates the possible usage of the reporting modes for the different types of CQIs and PMIs.

- Nine different CSI modes
  - 4 on PUCCH
  - 5 on PUSCH
  - Only a subset of modes possible for a certain transmission mode
- RI: UE recommends single wideband rank

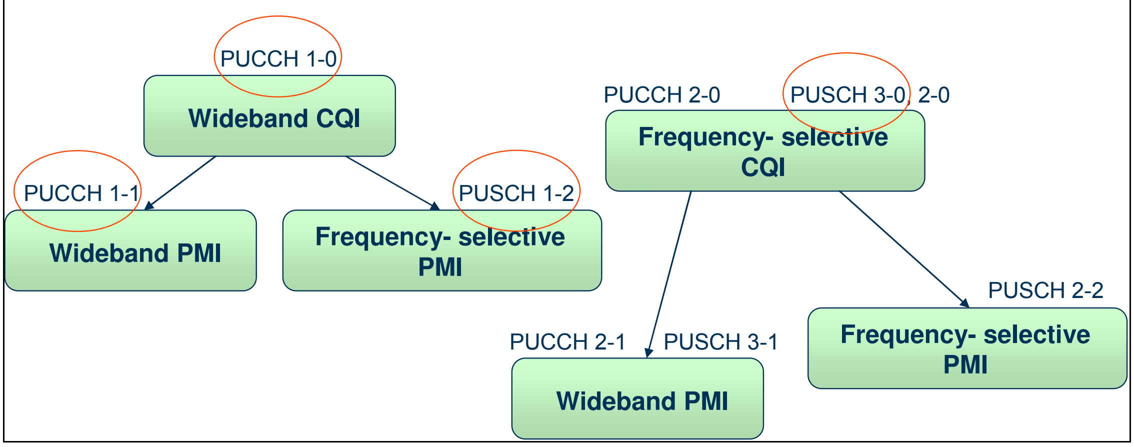


Figure 2-76. Reporting modes.

The UE estimates the CSI according to an algorithm summarized as an example in Figure 2-77.

- Brute force search for best combination of RI and PMI
- Ideal algorithm:
  - for each RI do
    - for each PMI do
      - compute SINR per layer
      - SINRs → predicted throughput
  - Select RI and PMI that gives highest predicted throughput over relevant reference period and bandwidth
  - Given selected RI and PMI(s)
    - Based on SINR(s) for transport block find highest transport format with BLER ≤ 10% → CQI

Figure 2-77. UE calculation of CSI.

How can we practically implement a four antenna-port configuration? Well, a suitable way of achieving uncorrelated antenna elements is to use polarization diversity with cross-polarization. But we only have two orthogonal polarizations, so we have to have two pairs of cross-polarized antenna pairs in order to get four antenna ports.

- Many different possible antenna configurations
  - Only two different ones considered here
- Exploit orthogonal polarizations
  - Reduces inter-layer interference
  - Dual-layer transmission possible also in line-of-sight
  - Line-of-sight not uncommon in urban environments
- Two cross-polarized antennas

- Two pairs of cross-polarized antennas
  - Dual stream spatial multiplexing
  - Array gain by means of beamforming on pairs of co-polarized antennas
  - Limited radome size

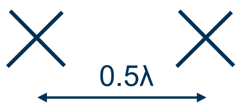


Figure 2-78. Antenna setup at eNodeB.

Different radio channel scenarios require different MIMO modes. Sometimes beamforming is most suitable, typically at bad SINRs close to cell edges, and sometimes spatial multiplexing is beneficial, typically closer to the basestation. Of course there are exceptions to this assumptions. Figure 2-79 summarizes the most likely usage of the different modes.

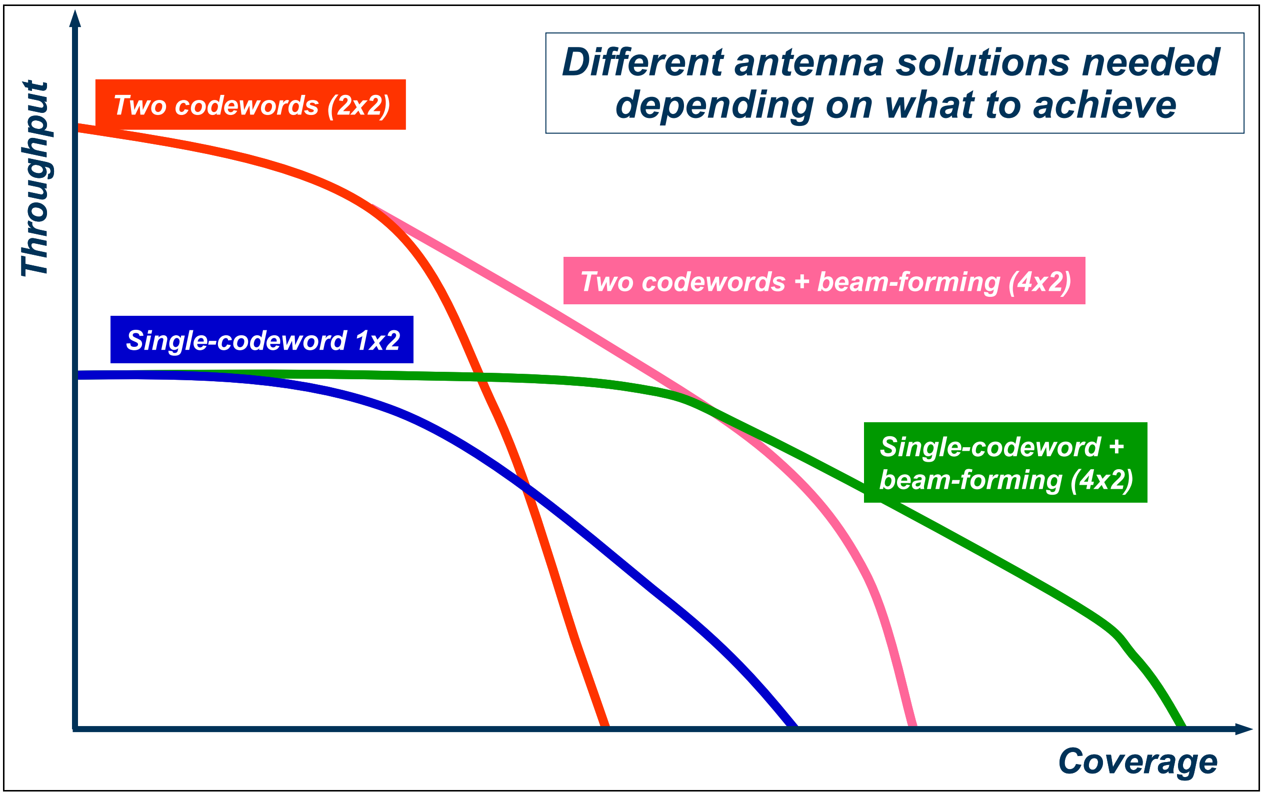


Figure 2-79. 3GPP - LTE advanced antenna solutions.

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3 Scheduling

OBJECTIVES:

On completion of this chapter the students will be able to:

- **Describe the Dynamic Resource Allocation (Scheduling)**
  - –Describe UL and DL Scheduling principles and signaling
  - –Explain the scheduler interactions with other functions
  - –Explain the concepts of dynamic and semi-persistent scheduling

Figure 3-1. Objectives.

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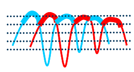
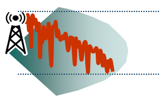
SCHEDULING

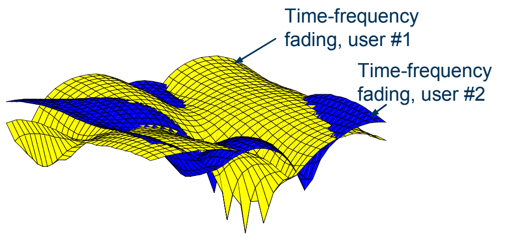
To provide efficient resource usage the LTE concept supports fast scheduling where resources on the shared channels PDSCH and PUSCH are assigned to users and radio bearers on sub-frame basis according to the users momentary traffic demand, QoS requirements and estimated channel quality. This task is done by the uplink (UL) and downlink (DL) schedulers, both situated in the eNB. Scheduling is also referred to as Dynamic Resource Allocation (DRA) and is part of the Radio Resource Management (RRM). There are important interactions with other RRM functions such as power control, link adaptation and Inter-cell Interference Control (ICIC).

- Shared channel transmission
- Select user and data rate based on instantaneous channel quality
- Scheduler located in eNB
- Same allocation for all layers in case of MIMO





- Scheduling in time ***and*** frequency domain on SB level (two RBs)
  - Link adaptation in time domain only



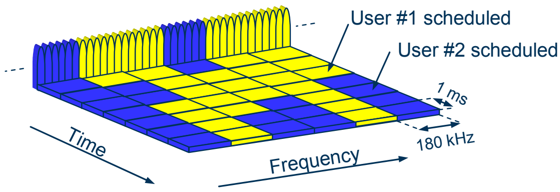


Figure 3-2. Channel Dependent Scheduling.

The smallest time/frequency entity that the scheduler may assign consists of twelve sub-carriers (180 kHz) in the frequency domain and a sub-frame (1ms) in time. This corresponds to two 180kHz × 0.5ms physical resource blocks that are consecutive in time and is referred to as a *Scheduling Block* (SB) in this chapter. In case of MIMO the resource allocation is the same for all streams. Channel variations can be exploited for multi-user diversity (i.e. scheduling users in constructive fading) both in time and frequency domain.

In the downlink, the scheduler may assign a set of resource blocks to a user according to the agreed PDCCH scheme while in the uplink resource blocks assigned to a specific user must be contiguous in the frequency to preserve the SC-FDMA structure. Also only a limited set of DFT sizes will be allowed, i.e. multiples of powers of 2, 3 and 5. This further limits the number of RB that can be assigned to a user.

In addition to providing an efficient utilization of the radio resource the scheduler is responsible for ensuring the QoS requirements for the individual logical channels to as large extent as possible. When this is not possible due to resource limitations the scheduler performs prioritization between users and logical channels according to the QoS requirements.

In the downlink, where the eNB has immediate access to the transmit buffers of the radio bearers, the scheduler performs the prioritization both between users and different radio bearers of a user.

In the UL on the other hand the scheduler only prioritizes between different users based on buffer status reports. The prioritization between different logical channels within one UE will be done in the UE with assistance from the network.

Although fast dynamic scheduling is the base line for LTE scheduling several methods for limiting the control signaling demands for services such as speech (VoIP) where small packets are generated regularly have been discussed in 3GPP. A concept where resources are assigned semi-statically called “semi-persistent” scheduling has been agreed.

Scheduling is part of the basic LTE functions. The Scheduler distributes radio interface and RBS resources between various user and control data flows requesting transmission in the cell. For every upcoming 1 ms transmission time interval, the Scheduler determines the users that are assigned resources.

Link Adaptation, which includes transport format selection, is closely related to scheduling and the two functions interact by exchanging information prior to each scheduling decision.

The operator controls part of the scheduling behavior via the QoS framework.

In the downlink, the resources handled by the Scheduler are:

- DL
  - Physical Resource Blocks (PRBs)
  - Downlink power
  - PDCCH resources
  - TX rank (layers)
  - Baseband processing capability
- UL
  - Physical resource blocks
  - Baseband processing capability
  - PDCCH resources
- The Scheduler considers possible user equipment limitations.
- Control signaling and retransmissions are given higher priority than user data.
- Downlink scheduling resides entirely in the RBS.
- In uplink scheduling, the user equipment is also involved in the scheduling procedure.

Figure 3-3. Resources handled by Scheduler.

Scheduling is also referred to as dynamic resource allocation (DRA). Link Adaptation resides entirely in the RBS.

The Scheduler handles the distribution of control and user data on the physical resource blocks in the time and frequency domains across the radio interface. It enables users to be multiplexed and scheduled simultaneously, and facilitates efficient use of spectral and hardware resources for optimization of user throughput and cell capacity. The LTE Scheduler supports fair distribution of resources between users, as well as priority for robust system control signaling.

The Scheduler is part of the basic LTE functions and part of radio resource management, designed to provide optimal performance and capacity at all times by automatically adapting to variations in traffic load and distribution. The automated behavior reduces the need for configuration and optimization to adapt to the concepts of the Self Organizing Network and Smart Simplicity.

The Scheduler controls in principle all radio resources and the allocation of these resources is done dynamically for every transmission time interval of 1ms.

Scheduling details

For every cell in every transmission time interval (1ms), the Scheduler determines the user equipment that is assigned resources. Each radio bearer is given a certain priority, based on algorithms which take the QCI (QoS Class Indicator) related parameters as input.

A higher scheduling priority gives the radio bearer a higher probability to obtain resources and enables the user equipment to perform transmission or reception. The allocation of resources is made per user equipment. The user equipment priority is defined as the highest scheduling priority of the radio bearers belonging to the user equipment, including retransmissions. The user equipment with the highest priority is selected first for transmission.

In the uplink, some radio bearers with lower priorities may get a "free ride" if a radio bearer with a high priority belongs to the same user equipment. In the uplink, when the user equipment has many radio bearers, they are grouped into Logical Channel Groups (LCGs, also sometimes referred to as radio bearer groups). The buffer status report is then expanded so it reports the buffer status per radio bearer group. Each radio bearer group is given a certain priority.

The Scheduler controls all radio interface resources, except the following physical signal and channel transmissions, as shown in Figure 3-4:

- Reference Signal (RS)
- Sounding Reference Signal (SRS)
- Synchronization Channel (SCH)
- Physical Broadcast Channel (PBCH)
- Physical HARQ Indicator Channel (PHICH)
- Physical Uplink Control Channel (PUCCH)
- Physical Random Access Channel (PRACH)
- Physical Control Format Indicator Channel (PCFICH)

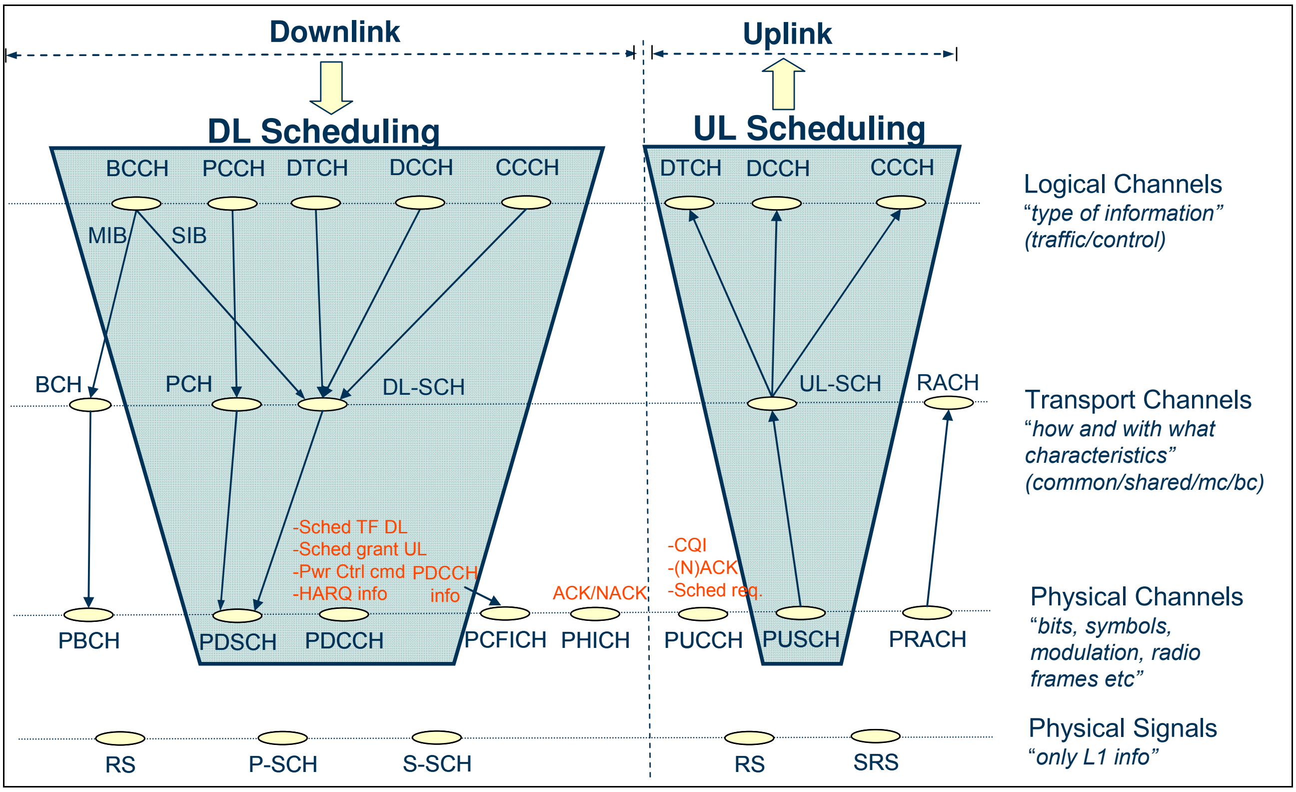


Figure 3-4. Scheduler control.

The different transmissions are prioritized in the following order:

- DL
  - Common channels
  - HARQ retransmissions
  - Initial transmissions of DCCH
  - Initial transmissions of DTCH
- UL
  - Transmissions of random access msg 3
  - HARQ retransmissions
  - Initial transmissions of DCCH
  - Initial transmissions of DTCH

Figure 3-5. Scheduling internal priorities.

No scheduling grants need to be transmitted for the synchronous retransmissions in the uplink.

At the beginning of each transmission time interval, the Scheduler receives information on available resource blocks, and available downlink power in the cell. It may also get an indication of the uplink buffer status from the UE in a Buffer Status Report (BSR). The Scheduler, together with Link Adaptation and power control then assigns an appropriate amount of resources to the UE. The scheduling block is the smallest unit that the Scheduler can assign to a user in the user plane. See Figure 3-6 .

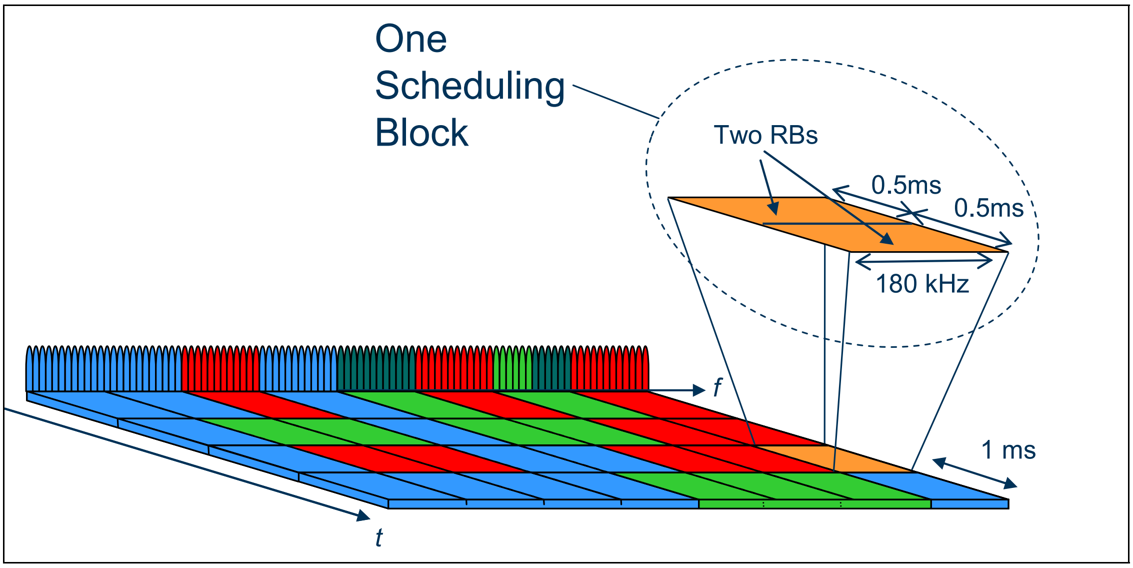


Figure 3-6. Scheduling Block.

The scheduler can assign resource elements to DTCH that are "left over" after L1/L2 control signaling has been allocated. Thus, a scheduling block can consist of both user data and control data.

The scheduling algorithms for DTCH and DCCH in both the uplink and downlink are based on either a Proportional Fair or Round Robin (Resource Fair) strategy. With Round Robin, the scheduling decisions are mainly delay-based (not to be confused with Delay Scheduling). The user equipment priority increases with the time elapsed since the last assignment/grant.

With Proportional Fair, the scheduling decisions are channel dependent in time, which to some extent will lead to prioritization of users with good radio conditions. The scheduling strategy is configurable per RBS.

The operator can configure the number of PUCCH resources for the scheduling request and the Channel Quality Indicator (CQI) to control the trade-off between the number of supported users and the uplink peak throughput. Users that are not assigned CQI resources on PUCCH will be assigned CQI resources on PUSCH instead.

An overview of the inputs and outputs of the Scheduler in uplink and downlink is shown in Figure 3-7. Unless otherwise stated, both uplink and downlink scheduling is considered.

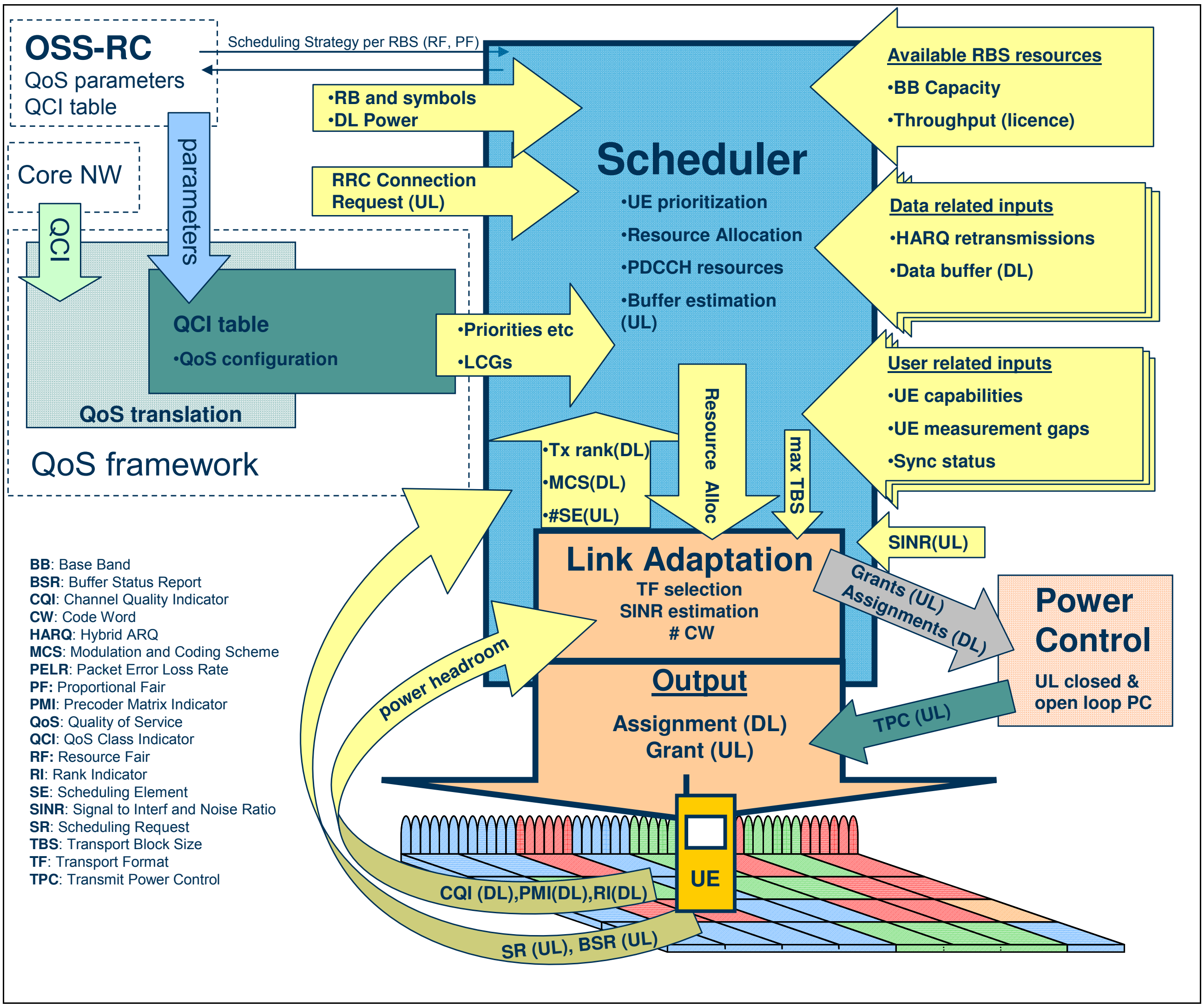


Figure 3-7. Scheduler interactions.

DOWNLINK SCHEDULING FRAMEWORK

The overall scheduling concept for the downlink is illustrated in Figure 3-8. To support fast channel dependent link adaptation and channel dependent time and frequency domain scheduling the UE may be configured to report the Channel Quality Indicator (CQI) reports. Typically, the UE bases the CQI reports on measurements on DL reference signals. For TDD the channel reciprocity could be utilized for channel dependent scheduling to some extent, although one must keep in mind that even if the fading characteristics are reciprocal in TDD the UL and DL will experience different interference and there might be an unbalance in pathgain between uplink and downlink. Based on the CQI reports and QoS requirements of the different logical channels the scheduler assigns time and frequency resources, i.e. scheduling blocks. The resource assignment is signaled on the Physical Downlink Control Channel (PDCCH). The UE monitors the control channels to determine if it is scheduled on the shared channel (PDSCH) and if so, what physical layer resources to find the data scheduled.

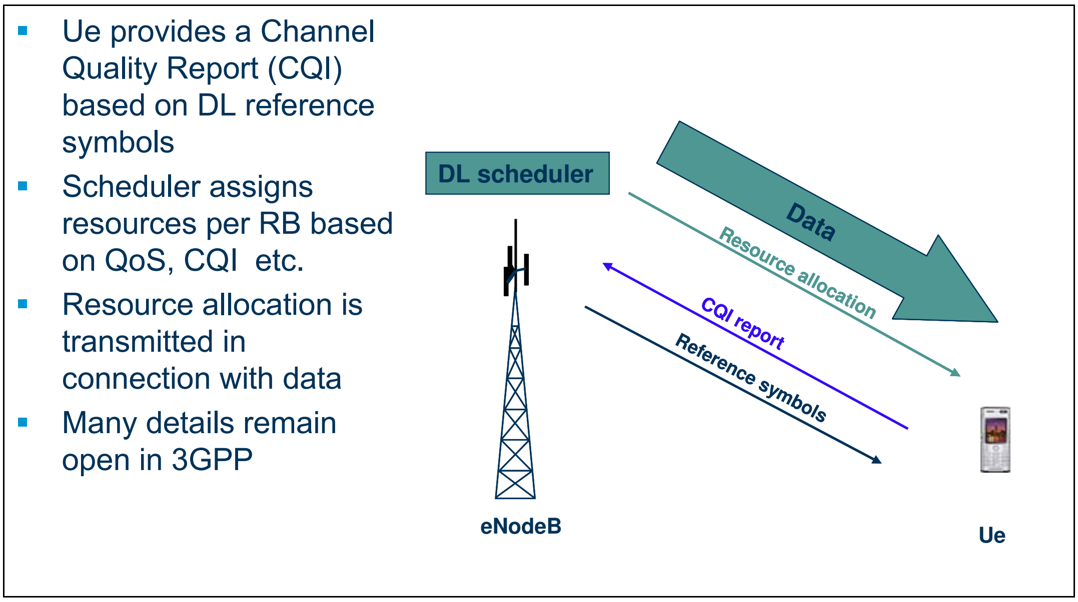


Figure 3-8. DL scheduling mechanism.

The Scheduler assigns physical resource blocks in the frequency domain, on a subframe/transmission time interval basis as a scheduling element. In the downlink, the physical resource blocks are assigned from lower frequencies to higher, that is from left to right as shown in Figure 3-9. The starting point in frequency is configurable per cell. This enables some basic frequency planning, for example in problem areas. To increase frequency diversity and at the same time keep intercell interference at low levels, the Random Frequency Allocation can be activated to automatically and randomly select the starting point.

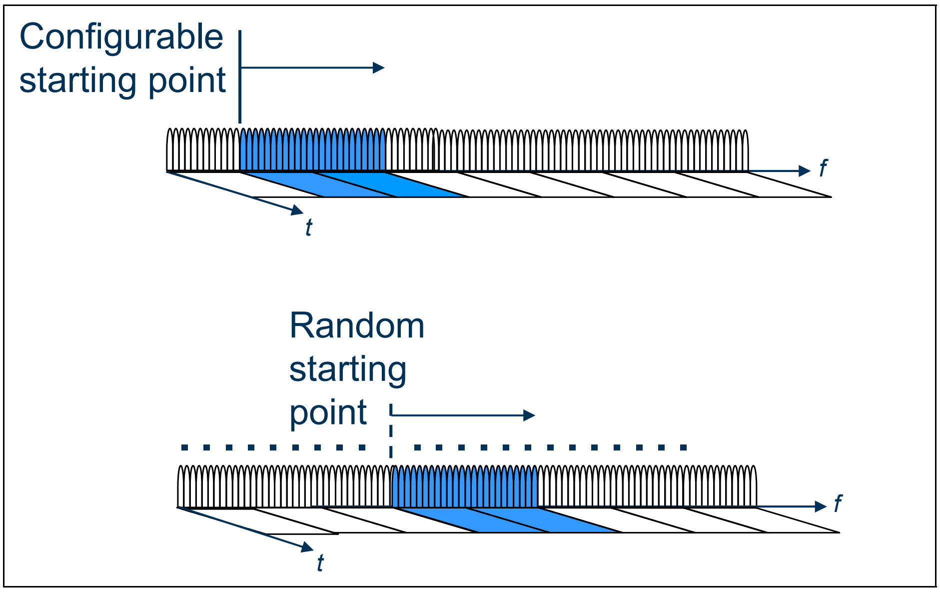


Figure 3-9. Downlink scheduling allocation.

Downlink Scheduling and Link Adaptation use the CQI as channel quality feedback from the user equipment. The CQI is sent in uplink on PUCCH or PUSCH. The number of CQI users per cell on PUCCH is configurable.

CQI reporting

The CQI reporting scheme must be designed with care to avoid excessive signaling in the uplink. For example, with a 20 MHz bandwidth there are roughly 100 resource blocks. If the UE reports one CQI value á five bits for all resource blocks we would get a 500-bit CQI report. In 3GPP it is agreed to allow for several types of CQI reports ranging form a single wide-band report to a report containing frequency granular information (multi-band) and MIMO information.

The CQI reports will be transmitted on the Physical Uplink Control Channel (PUCCH) if there is no Physical Uplink Shared Channel (PUSCH) resource available. The PUCCH resources for CQI reporting will be configured through RRC (possible MAC optimizations are FFS). The resources are autonomously revoked when the UE looses UL synchronization but can also be revoked through RRC. When the UE has simultaneous UL data and has an allocation on the PUSCH these resources cannot be used due to the single carrier structure. In this case the CQI reports are transmitted on the PUSCH time multiplexed (before DFT precoding) with the data transport block on PUSCH. It is agreed that the eNB should not need to blindly detect if there is a CQI report included. This means that the CQI transmissions must be known to the eNB and the UE cannot transmit CQI reports autonomously.

The size of a PUCCH CQI is very limited, in the order of 10 bits. This means that several consecutive sub-frames are needed to provide a multi-band report, i.e. sub-frame concatenation. The PUSCH report on the other hand could allow for more bits and it is agreed in 3GPP that different CQI formats can be used on the PUCCH and on the PUSCH as illustrated in Figure 3-10.

The eNB can configure (through RRC) the UE to transmit CQI report periodically. As illustrated in Figure 3-10, when a periodic CQI reporting instance coincides with an UL transmission on the PUSCH the CQI report will be transmitted on the PUSCH and the PUCCH resources are unused. In addition to the periodic reporting, a-periodic reporting has been agreed in 3GPP. It is also agreed that a CQI report could be requested from the eNB either using a poll bit in the grant or to use a specific TF for indicating “only” CQI.

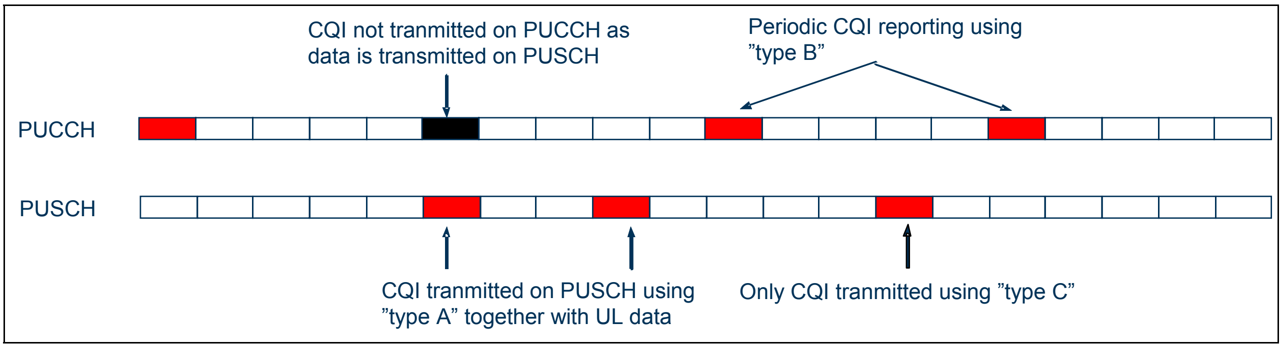


Figure 3-10. CQI transmission.

Periodic CQI will be transmitted on PUCCH unless the UE has a scheduled resource on the PUSCH. In this case the report will be transmitted on the PUSCH. Different CQI formats can be used on the PUCCH and PUSCH. In addition a-periodic CQI reports can be transmitted, either trigger with UL data or requested by the eNB.

With a “wide-band average” we refer to a mutual information based average where the SINR is averaged in the mutual information domain over a set of sub-bands. The set of sub-bands, S, is semi-statically configured through higher layer signaling (RRC). The actual averaging will not be specified but with appropriate requirements on the UE it is believed that a linear average or linear in dB will not be sufficient. A wide-band average CQI report could consist of a five bit index to a 32-entry CQI table (four bits with 16-entries is also discussed) with approximately equal step size in equivalent SINR. A step size of 1dB is considered with a 32dB dynamic range. The CQI is defined in terms of channel coding rate and modulation order (QPSK, 16QAM, 64QAM). The detailed CQI table is still under consideration in 3GPP.

In addition to a wide-band average two different schemes for PUSCH transmission have been identified for multi-band reports, a “UE-Selected sub-bands Feedback” and a “eNB Configured sub-bands”. In both cases a wide-band average is computed and used as a reference. In addition, M sub-bands (M could be fixed or configured) are selected and encoded differentially using three bits relative to the wide-band average. In the case “UE selected sub-bands” the UE selects M sub-bands to report. The UE internal procedure to select sub-bands will not be specified but the selected sub-bands should correspond to the highest CQI values. The sub-band selection is signaled using,

$$\left\lceil \log_2 \binom{N}{M} \right\rceil \qquad (4)$$

bits where N is the number of sub-bands needed to cover the system bandwidth. The supported sub-band sizes and M values will be a function of system bandwidths. However, the possibility of other M values and specifying multiple M values for each range of the system bandwidth not precluded. The “eNB selected sub-bands” scheme is similar with the exception that the eNB configures what sub-bands the UE should report.

Figure 3-11 shows the sub-band sizes and the number of sub-bands as a function of the allocated bandwidth. The number of sub-bands (M) is the M best sub-bands, selected by the UE.

BW [RBs]	k sub-band size [RBs]	M # of sub-bands
6-7	WB only	WB only
8-10	2	1
11-26	2	3
27-63	3	5
64-110	4	6

Figure 3-11. CQI periodic sub-band reporting on PUSCH.

The CQI measurement methodology is also being discussed in 3GPP. One issue is how to measure the interference and if filtering should be applied. The interference is preferably estimated measured on RE (Resource Element) not corresponding to RS (Reference Symbol) for surrounding cells to capture the actual cell load. If the interference is measured on RS the interference will be overestimated as the RS are always transmitted and do not reflect the load on the data channel. If the interference is instead measured on RE not corresponding to RS the interference will be dependent on if there is data transmission or not and reflect the actual load. In this case the interference might be bursty at low to medium loads. Even with full load the interference will vary rapidly with instantaneous pre-coding. The rapidly varying interference has proven to be a serious problem in simulations both for fast link adaptation and scheduling and results in very high HARQ BLER with loss of peak rates and efficiency. Interference filtering has proven to be an efficient tool for handling rapid interference variations. In 3GPP we are suggesting that the network may configure the UE to do filtering of the interference before compiling the CQI report. There is however no agreement currently.

UPLINK SCHEDULING FRAMEWORK

The basic UL scheduling concept is illustrated in Figure 3-12 and Figure 3-13. The UE informs the scheduler when data arrives in the transmit buffer with a Scheduling Request (SR). The scheduler selects the time/frequency resources the UE shall use. With support from the link adaptation function also the transport block size, modulation, coding and antenna scheme is selected, i.e. the link adaptation is performed in the eNB.

The selected transport format is signaled together with information on the user ID to the UE. This means that the UE is mandated to use a certain transport format and that the eNB is already aware of the transmission parameters when detecting the UL data transmission. As a consequence there is no need for an UL control channel to inform the eNB (E-TFCI in WCDMA). This reduces the amount of control signaling required in the uplink, which is important from a coverage perspective, especially with the short 1 ms TTI.

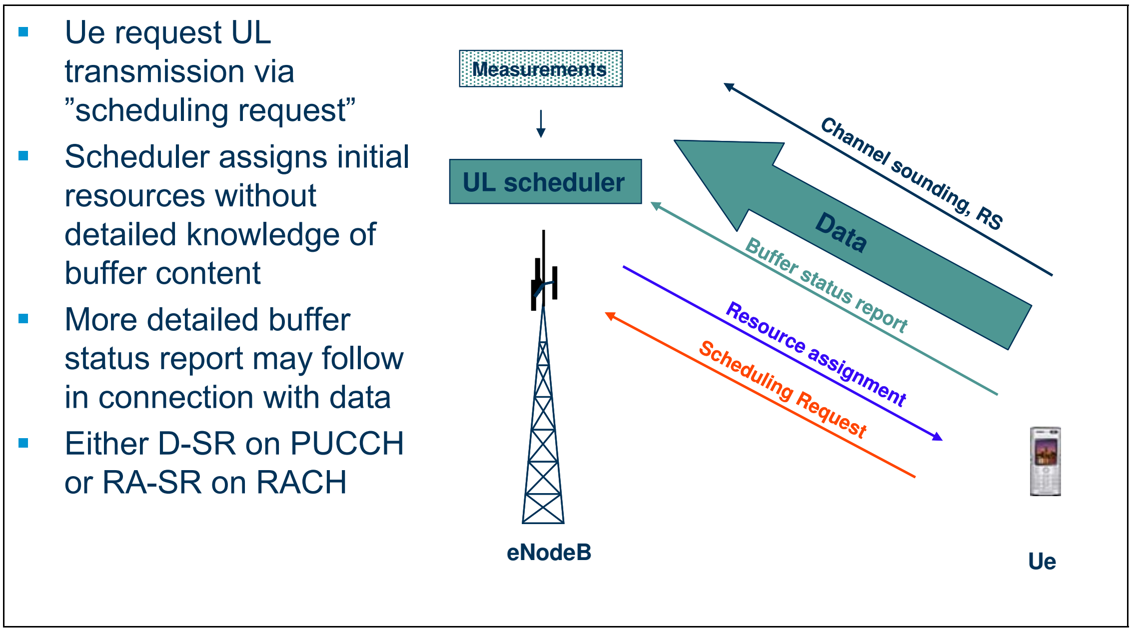


Figure 3-12. UL Scheduling mechanism.

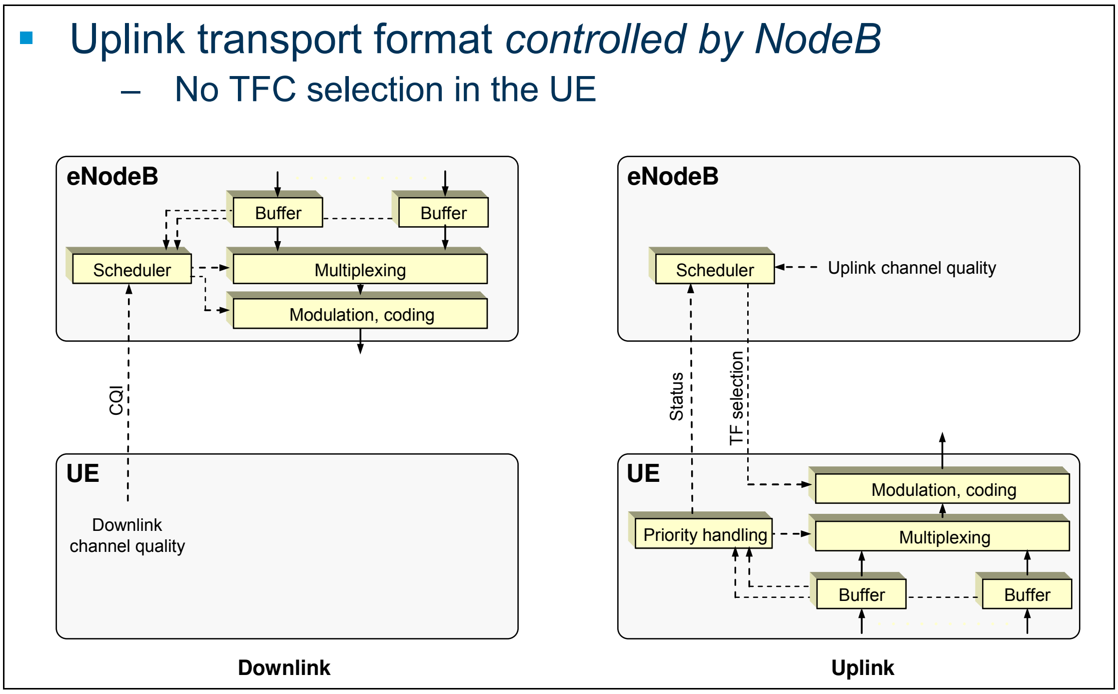


Figure 3-13. UL Scheduling.

The assigned resources and transmission parameters is revealed to the UE via the PDCCH. Additional Scheduling Information (SI) such as Buffer Status Report (BSR) or power headroom report may be transmitted together with data as MAC control elements. The eNB may configure the UE to transmit a wide-band sounding reference signal that can be used for estimating the UL channel quality. Additional channel quality estimates can be obtained from other UL transmissions such as, data transmission or control signaling (CQI reports and HARQ ACK/NACK signals).

Scheduling resources among users in the uplink is complicated by the fact that the scheduler is situated in the eNB and is not automatically aware of the users resource demand, i.e., what users and what radio bearers have data to transmit and how much data there is in the transmit buffers. The concept for uplink scheduling suggested is based on a resource reservation principle.

When data arrives to the transmit buffers of a UE and the UE has no grant for transmission on the PUSCH, the UE needs to request permission to transmit. According to current agreements a Buffer Status Report (BSR) is trigger. If the UE has no PUSCH resource a Scheduling Request (SR) is triggered as well. The SR will either be transmitted on the RACH channel (RA-SR) or on dedicated resources on the PUCCH (Dedicated SR, D-SR) if such resources are available. The PUCCH resources for dedicated SR are assigned and revoked by the eNB through RRC. In addition, the resources are autonomously revoked when the UE looses UL synchronization. The UL scheduler monitors the users' requests and distributes the available resources among the various users.

A Dedicated Scheduling Request (D-SR) is typically used when the UE uplink is time synchronized. The purpose is to enable UE to rapidly request resources for uplink data transmission. In 3GPP, a dedicated solution for the scheduling request has been agreed. For the dedicated approach, each active user is assigned a dedicated channel for performing the scheduling request. The benefit with this method is that no UE ID has to be transmitted explicitly, since the UE is identified by the channel used. Furthermore, no intra-cell collisions will occur in contrast to the contention based approach.

The D-SR is repeatedly transmitted on consecutive SR opportunities on PUCCH until the UE receives an UL grant on PDCCH. The transmission is stopped at least when PUCCH resources are released and/or UL synch is lost even if the UE has not received any UL grant on PDCCH. After stopping transmission on the D-SR, the UE transmits on the RA-SR (i.e. accesses the system via RACH).

The Random Access Scheduling Request (RA-SR) is used when the UE has lost UL synchronization or if it has no D-SR resources.

From a scheduling request the scheduler has limited knowledge of what type of data and of what priority the UE has. For further information a grant is issued by the scheduler. The grant addresses a UE and not a specific logical channel. In its simplest form the scheduling grant is valid only for the next UL TTI. However, to reduce the amount of control signaling required several proposals with alternative durations similar as for the downlink are being discussed.

Following the initial scheduling request, a more detained Buffer Status Report (BSR) can be provided by the UE to the eNB as a MAC control element. Additional information such as UE power headroom has also been discussed in 3GPP.

A BSR is triggered when at least one of the following criteria is fulfilled:

- UL data arrives in the UE transmission buffer and the data belongs to a radio bearer (logical channel) group with higher priority than those for which data already existed in the UE transmission buffer.
- BSR is triggered when UL-SCH resources are allocated and number of padding bits is larger than the BSR size
- when the UE arrives to a new cell

A triggered BSR is cancelled in case the uplink grant is large enough to accommodate all pending data, but not both data and BSR.

A SR is triggered and transmitted in addition if the BSR is not transmitted before the first available SR opportunity.

Uplink scheduling takes place in the RBS, and resources are assigned per user equipment. When user equipment has several radio bearers, the user equipment performs the prioritization between the radio bearers and is referred to as the user equipment rate control function.

The resources not used by the physical signals PUCCH and PRACH are used as scheduling elements for uplink scheduling, so PUCCH and PRACH have absolute priority over other control and user data channels in the uplink.

The random access response message on PDSCH contains the grant for random access message 3 (RRC connection request).

The user equipment sends a scheduling request on PUCCH to the scheduler to indicate that it has data in the buffer and asks uplink scheduling to start assigning uplink resource blocks to the user equipment in upcoming subframes.

When user equipment is scheduled in a subframe, the uplink scheduler transmits a scheduling grant to the user equipment, indicating the resource blocks and transport format to use for uplink transmission.

Uplink grants are produced by the Scheduler and sent to the user equipment on PDCCH.

Together with the uplink data, the user equipment transmits buffer status information to the RBS such that the uplink scheduler knows roughly the amount of data in the user equipment buffer. In cooperation with the link adaptation and power control functionality the uplink scheduler use this information together with the channel quality information to assign an appropriate number of resource blocks to user equipment in the uplink.

The scheduling request uses PUCCH format 1 and the number of scheduling request users per cell is configurable with a parameter that sets the number of users that are allocated scheduling request resources. The periodicity of the scheduling request is 10 ms, and equal for all user equipment in the cell. If no scheduling request resources are allocated on PUCCH for the user equipment, the user equipment uses the random access process to request resources.

To increase capacity and coverage, Time Spread Allocation Scheduling is used in uplink. This enables multiple user equipment to be scheduled in one subframe by distributing one user equipment transmission over several subframes, but at a lower bandwidth. This leads to an improved link budget and improved capacity and coverage. See Figure 3-14.

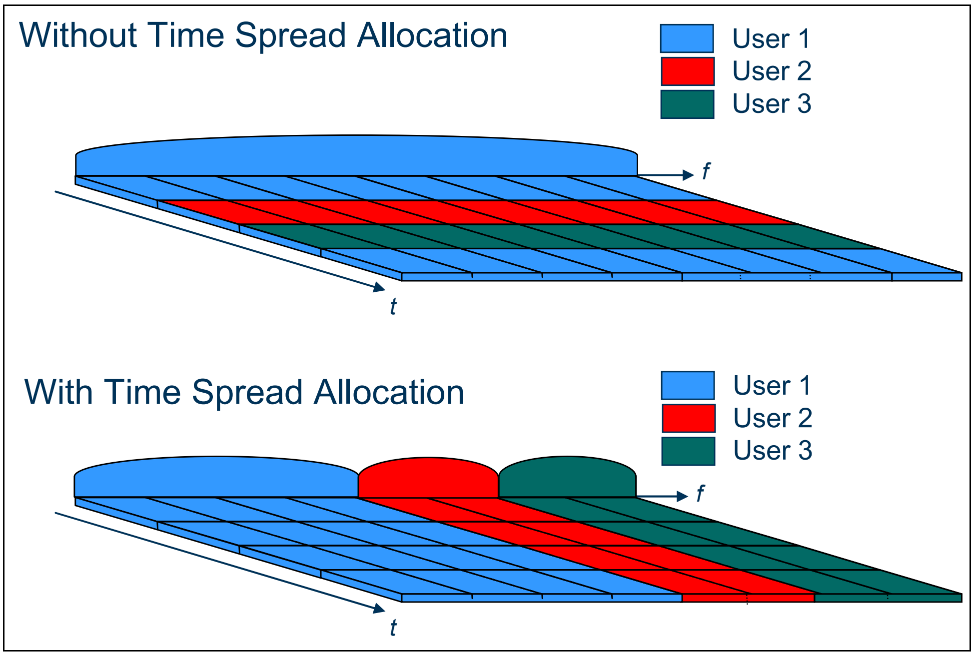


Figure 3-14. UL scheduling allocation..

Link Adaptation

Link Adaptation performs transport format selection to enforce the quality requirement while using the available resources in an efficient way. Transport format selection includes selecting the modulation and coding scheme and transport block size. In the downlink, the selection is channel dependent because Link Adaptation uses CQI reports from the user equipment to adapt the transmissions to current radio conditions.

For the uplink, Link Adaptation takes SINR into account. The SINR is based on measurements on the uplink demodulation reference signal. The transport format selection influences the scheduling decision, so the scheduling decision is implicitly influenced by channel quality estimations (CQI for downlink and SINR for uplink). Link Adaptation is not used in the uplink for random access message 3 (RRC connection request) or retransmissions.

Link Adaptation for downlink common channels uses a default SINR for these transmissions to reach the cell edge. The Scheduler provides link adaptation with RLC and MAC header sizes to consider when selecting a transport format.

The Scheduler retrieves information about the number of scheduling elements to use in uplink, number of layers and modulation and coding scheme to use in downlink from Link Adaptation.

Antenna mapping, part of Link Adaptation, controls multi-antenna transmission by deciding the antenna mapping mode (TX diversity, spatial multiplexing or beamforming, as well as submodes within each mode), spatial multiplexing rank and spatial multiplexing precoding matrix. Channel prediction, also part of Link Adaptation, provides information needed for decisions in the other Link Adaptation functions and Power Control. It includes collecting channel measurements, made in the downlink by the user equipment and sent to the RBS in channel feedback reports containing CQI, precoding matrix indicator (PMI), and rank indicator (RI). In UL the SINR is considered.

Semi-persistent scheduling

Fully dynamic scheduling allows for flexibility but it also leads to high signaling overhead as a grant needs to be signaled in each scheduling instance, for example for each VoIP packet in case of VoIP. To limit the signaling load for sources with regular arrival rate a concept referred to as semi-persistent scheduling has been agreed in 3GPP. The idea is to assign resources on a long-term basis, for example using RRC (how to assign resources is not agreed in 3GPP). The eNB assigns semi-persistently time and frequency resources for the initial transmission attempts. All HARQ retransmissions are scheduled dynamically. This concept is illustrated in Figure 3-15.

In the downlink semi-persistent scheduling with blind decoding has been agreed. This means that a few different ”formats” (combinations of coding, modulation, physical resource) are pre-configured. Any of the pre-configured formats can be used in the configured subframes, i.e. the UE needs to perform blind decoding to detect which one of the configured formats is used. In the uplink on the other hand it is agreed that there will only be a single format and blind decoding is not needed.

Figure 3-15 shows an illustration of the semi-persistent scheduling concept and that resources for the initial transmissions are allocated on a long-term basis and retransmissions are dynamically scheduled.

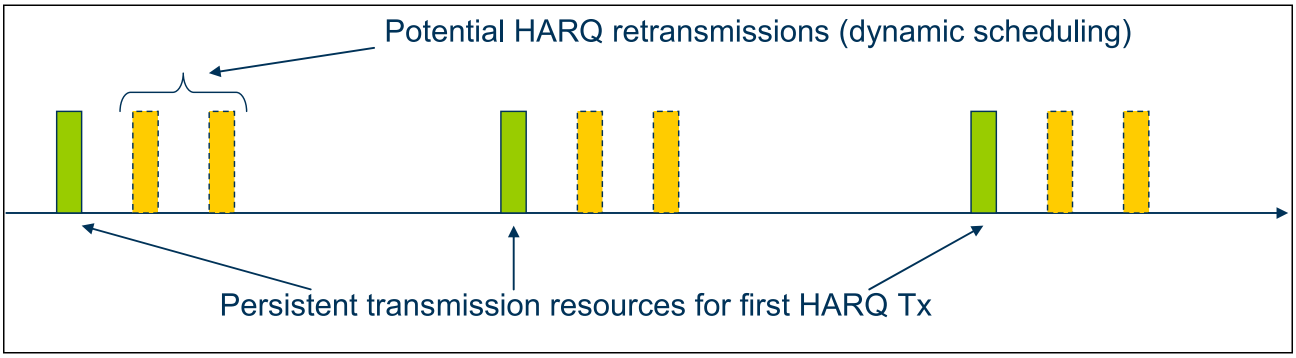


Figure 3-15. Semi-persistent Scheduling.

CONNECTION SETUP

The connection setup traffic case is shown in Figure 3-16. Note that after a shared channel transmission, HARQ retransmissions may occur due to negative HARQ acknowledgements.

All transmissions in the figure, including the possible asynchronous HARQ retransmissions in DL, are controlled by the Scheduler, except the RACH preambles. Another exception is the possible HARQ retransmissions in UL, which are synchronous and do not require a scheduling grant.

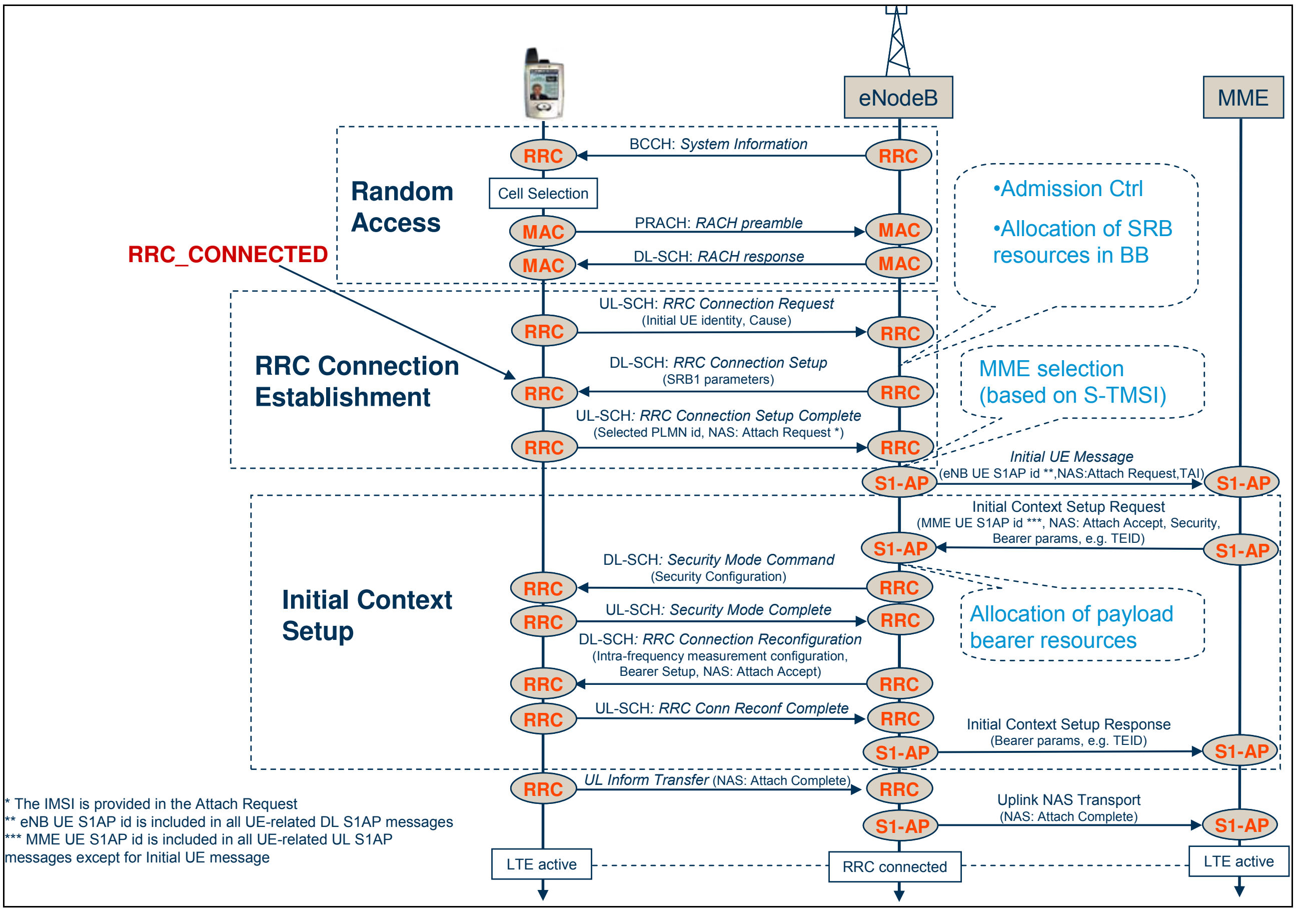


Figure 3-16. Connection Setup.

Inter-Cell Interference Coordination (ICIC)

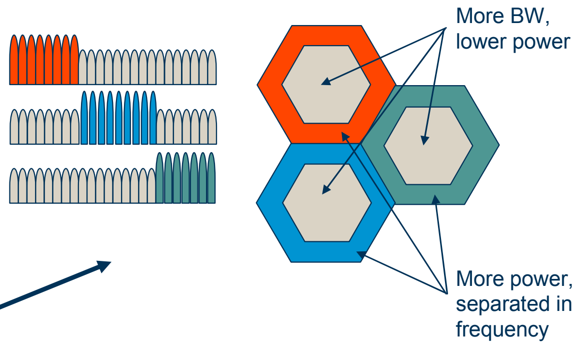
Inter-cell Interference Coordination, located in eNB, has the task to manage radio resources (notably the radio resource blocks) such that inter-cell interference is kept under control. The specific ICIC techniques that will be used in E-UTRA are for further study.

ICIC is inherently a multi-cell RRM function that needs to take into account the resource usage status and traffic load situation of multiple cells.

According to a fairly broad consensus in 3GPP RAN1, the Release 8 LTE standard will not support ICIC in the downlink.

Uplink inter-cell interference coordination consists of two inter-related mechanisms, the details of which are currently discussed within the 3GPP. The first part is a *pro-active* ICIC mechanism. The basic idea of this scheme is that a potentially disturbing eNB pro-actively sends a resource block specific indication to its potentially disturbed neighbor. This message indicates which resource blocks will be scheduled (with a high probability) with high power (i.e. by cell edge UEs). Thus this message allows the receiving eNB(s) to try to avoid to schedule the same resource blocks for its cell edge UEs. This way the pro-active scheme allows neighbor eNBs to reduce the probabilities of “exterior-exterior” (i.e. cell edge) UEs to simultaneously take into use the same resource blocks.

In addition, the 3GPP also discusses the use of the *overload indicator* (OI) that was originally proposed for inter-cell power control purposes. It is currently agreed in 3GPP that the OI also carries information at the resource block granularity. As opposed to the pro-active scheme, the overload indication is a *reactive* scheme that indicates a high detected interference level on a specific resource block to neighbor eNB(s). The details of OI based ICIC and its joint operation with the pro-active scheme is FFS at 3GPP.



- Pro-active:
  - eNBs coordinate the scheduling of RB at cell edges (high power)
- Re-active:
  - Overload Indicator indicates high interference on specific RB

Figure 3-17. Inter Cell Interference Coordination - ICIC.

Load Balancing (LB)

Load balancing, located in eNB, has the task to handle uneven distribution of the traffic load over multiple cells. The purpose of LB is thus to influence the load distribution in such a manner that radio resources remain highly utilized and the QoS of in-progress sessions is maintained to the largest extent possible while call dropping probabilities are kept sufficiently small. LB algorithms may result in handover and cell reselection decisions with the purpose of redistributing traffic from highly loaded cells to underutilized cells.

Load balancing in idle mode (called *camp load balancing*) as well as in connected mode (called *traffic load balancing*) have been identified as mobility drivers. Both camp and traffic load balancing are applicable in inter-frequency and inter-RAT cases only. (For intra-frequency the best radio condition is the main driver.)

X2AP Support for ICIC and Load Balancing

Load balancing for idle and connected mode has been recently discussed in RAN3. While load balancing is not identified as a mobility driver for intra-LTE intra-frequency scenarios, it is recognized as a mobility driver for inter-frequency and inter-RAT cases. In fact, for inter-RAT, load balancing (sharing) is explicitly identified as one of the RRM requirements.

For the intra-frequency intra-LTE case, X2AP is used for ICIC and load balancing purposes.

An eNB initiates the procedure by sending LOAD INFORMATION message to intra-frequency neighboring eNBs. The LOAD INFORMATION message can carry interference overload indication. The Load indication procedure shall be used to send interference overload indication when the eNB experiences too high interference level on some resource blocks.

Whether an eNB receiving a LOAD INFORMATION message should respond with a LOAD INFORMATION message is FFS.

RRM RELATED MEASUREMENTS IN LTE

Measurements are the key to ensure appropriate execution of RRM functions. Measurements are needed for single cell as well as for multi-cell RRM functions. Measurements are to be done both at the UE and at the eNB(s). Since E-UTRAN will support several RRM functions, different measurements serve different purposes. In general, the measurements should provide a good estimate of the used and available radio resources, cell coverage, short and long term channel quality, cell load, service quality, time alignment during handovers, load on the transport network etc. In addition, measurements should provide good mobility support not only within E-UTRAN but also between E-UTRAN and other access networks including UTRAN and GERAN. We note that another set of measurements is needed to support positioning services, but the description of these is out of the scope of this report.

For eNB and UE measurements, the downlink and uplink reference symbols play a key role.

eNB Measurements

In E-UTRAN, certain types of measurements shall be performed internally in the eNB and will not be exchanged between the eNBs. These measurements do not need to be specified in the standard, rather they will be implementation dependent. On the other hand, measurements, which are to be exchanged between the eNBs over the X2 interface need to be standardized.

The eNB measurements are described below. The positioning related measurements are not listed since they depend upon the exact positioning method used in E-UTRAN. Also, the current description does not explicitly take into account the impacts of multiple transmit and receive antennas on the measured quantities and measurement procedures (this issue is FFS). At the time of writing, all of the eNB measurements are implementation specific and need not be specified in the standard.

DL total Tx power: Transmitted carrier power measured over the entire cell transmission bandwidth.

DL resource block Tx power: Transmitted carrier power measured over a resource block.

DL total Tx power per antenna branch: Transmitted carrier power measured over the entire bandwidth per antenna branch.

DL resource block Tx power per antenna branch: Transmitted carrier power measured over a resource block.

DL total resource block usage: Ratio of downlink resource blocks used to total available downlink resource blocks (or simply the number of downlink resource blocks used).

UL total resource block usage: Ratio of uplink resource blocks used to total available uplink resource blocks (or simply the number of uplink resource blocks used).

DL resource block activity: Ratio of scheduled time of downlink resource block to the measurement period.

UL resource block activity: Ratio of scheduled time of uplink resource block to the measurement period.

DL transport network loss rate: Packet loss rate of GTP-U (or frame) packets sent by the access gateway on S1 user plane. The measurement shall be done per traffic flow. The eNB shall use the sequence numbers of GTP-U (or frame) packets to measure the downlink packet loss rate.

UL transport network loss rate: Packet loss rate of GTP-U (or frame) packets sent by the eNB on S1 user plane. The measurement shall be done per traffic flow. The access gateway shall use the sequence numbers of GTP-U (or frame) packets to measure the downlink packet loss rate.

UL RTWP: Received total wideband power including noise measured over the entire cell transmission bandwidth at the eNB.

UL received resource block power: Total received power including noise measured over one resource block at the eNB.

UL SIR (per UE): Ratio of the received power of the reference signal transmitted by the UE to the total interference received by the eNB over the UE occupied bandwidth.

UL HARQ BLER: The block error ratio based on CRC check of each HARQ level transport block.

Propagation delay: Estimated one way propagation delay measured during random access transmission.

UE Tx time difference: Time difference between the reception of the UE transmitted signal and the reference symbol transmission time instant.

DL RS TX power: Downlink reference signal transmit power is determined for a considered cell as the linear average over the power contributions (in [W]) of the resource elements that carry cell-specific reference signals which are transmitted by the eNB within its operating system bandwidth.

For inter-cell interference coordination purposes, it may be useful to measure the user plane load (for instance in terms of number of sent user plane packets/bits per second). The definition of such measurements and associated procedures are for further study.

UE Measurements

The UE measurement quantities are described below.

RSRP (Reference Symbol Received Power): It is determined for a considered cell as the linear average over the power contributions (in [W]) of the resource elements that carry cell-specific reference signals within the considered measurement frequency bandwidth.

RSRQ (Reference Symbol Received Quality): Reference Signal Received Quality (RSRQ) is defined as the ratio N×RSRP/(E-UTRA carrier RSSI), where N is the number of RB's of the E-UTRA carrier RSSI measurement bandwidth. The measurements in the numerator and denominator shall be made over the same set of resource blocks.

4 Mobility

OBJECTIVES:

On completion of this chapter the students will be able to:

- **Describe the Intra LTE mobility**
  - –Describe intra-LTE mobility in connected and idle mode
  - –Explain the concept of event triggered periodical reporting
  - –Describe the mobility measurements
- **Explain inter-working with 2G/3G**

Figure 4-1. Objectives.

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MOBILITY

The LTE mobility can be divided into “Intra-LTE mobility” and “Inter-LTE mobility” (inter-working with 2G/3G and CDMA 2000). It can be further divided into RRC_CONNECTED and RRC_IDLE mode mobility. IRAT-HO (Inter Radio Access Technology Handover) is one type of “Inter-LTE mobility” in RRC_CONNECTED mode while cell reselection is referred to as RRC_IDLE mode mobility.

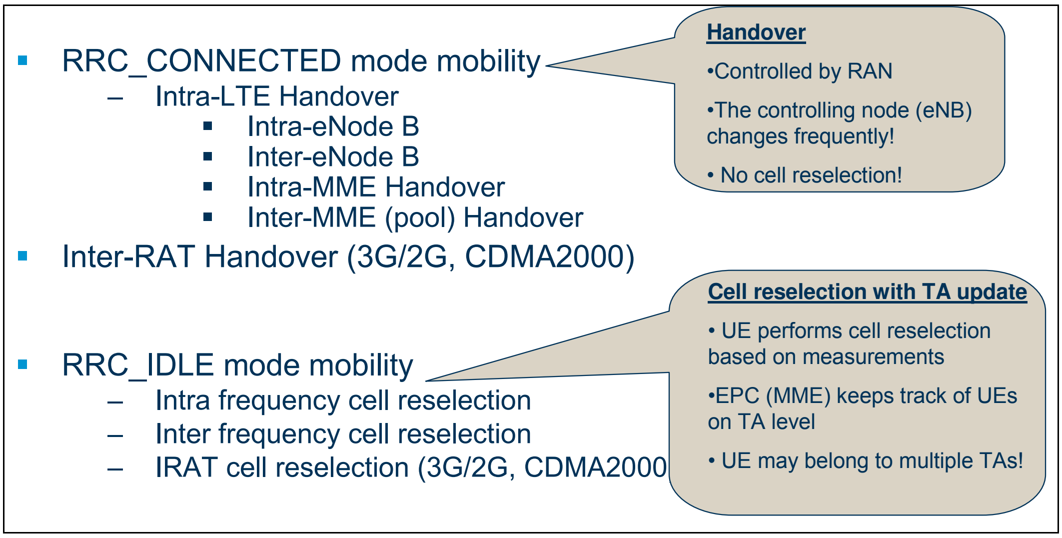


Figure 4-2. LTE mobility.

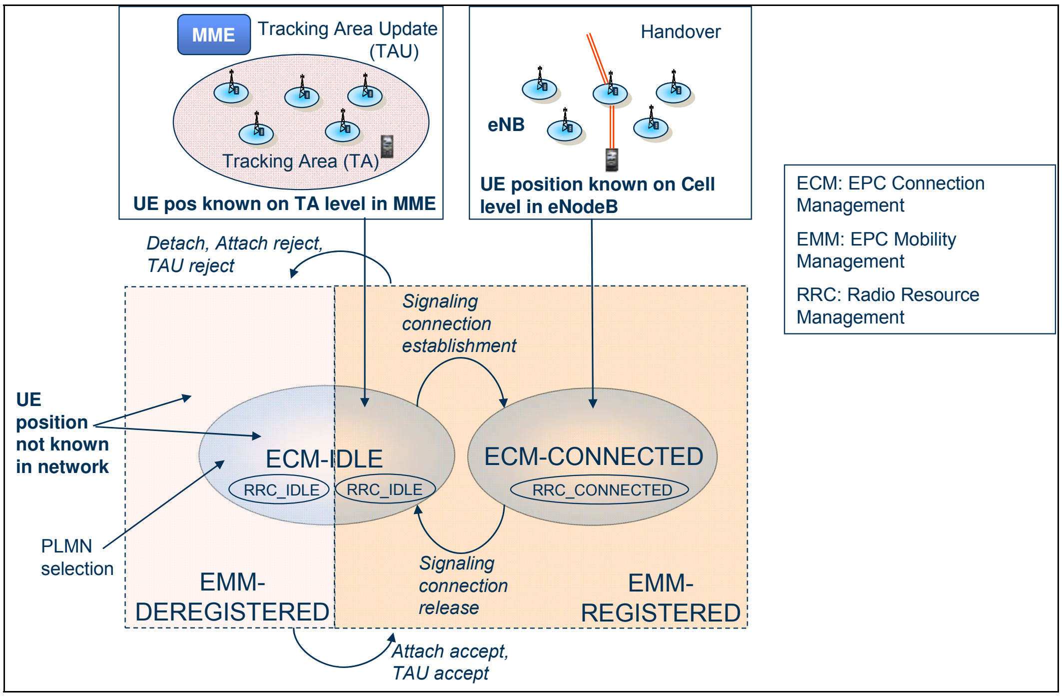


Figure 4-3. Protocol states and mobility.

- **RRC Idle mode mobility**
  - PLMN selection
  - RAT and frequency selection (frequency priority)
  - Cell selection (Cell barred, blacklisted cell, cell offset)
  - Intra frequency cell reselection control
  - IRAT cell reselection control (WCDMA, GSM, CDMA 2000, frequency priority)
  - Tracking Area support
  - Speed dependent scaling
- **RRC Connected mode mobility**
  - Evaluation
    - Best cell selection
    - Bad coverage
    - UE capability dependent redirection target choice
  - Execution
    - S1 HO
    - X2 HO
    - Intra eNB HO
    - Release with Redirect (IRAT: UTRAN, GERAN, CDMA2000)

Figure 4-4. RRC Mobility.

INTRA-LTE MOBILITY

In this section we describe intra-LTE mobility procedures both for RRC_CONNECTED and RRC_IDLE modes.

RRC_CONNECTED mode mobility

In LTE, network controlled UE assisted handovers with context transfer between eNB’s are used to support UE mobility. An intra-LTE handover can be executed either via the X2 or via the S1 interface. As long as the UE moves between eNB’s that belong to the same pooling area where the UE is currently registered, the handovers are always executed via the X2 interface. (Recall that the X2 interface is assumed to always exist between two neighbor eNB’s belonging to the same pooling area.)

In cases when the UE moves between eNB’s that belong to different pooling areas the handover procedure necessarily has to be executed via the S1 interface. In such cases at least the MME function, holding the UE context has to be relocated from one MME node in the first pool to another MME node in the second pool. There is possibility to relocate also the S-GW node during the S1 handover procedure, if it is needed (e.g., if no IP connectivity exists between the target eNB and the current S-GW). However, it is assumed that in the typical case the S-GW will not have to be relocated during an S1 handover, since IP connectivity will be configured in the network such that all S-GW’s will have connectivity to all eNB’s.

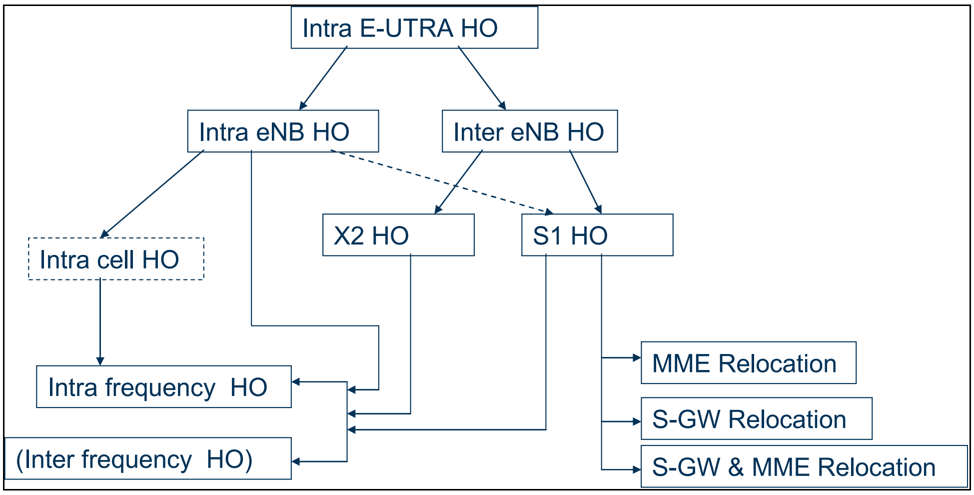


Figure 4-5. Intra LTE Handover procedures.

From a procedural and message sequence point of view the S1 handover procedure will be identical both for intra-LTE and for inter-3GPP access mobility. Note, however, that there might be need for some extra signaling messages in the intra-LTE S1 handover case for transferring the PDCP SN status, which is not used in the IRAT S1 handover case.

A simplified chart of the message sequence at intra-LTE handover is shown in Figure 4-6.

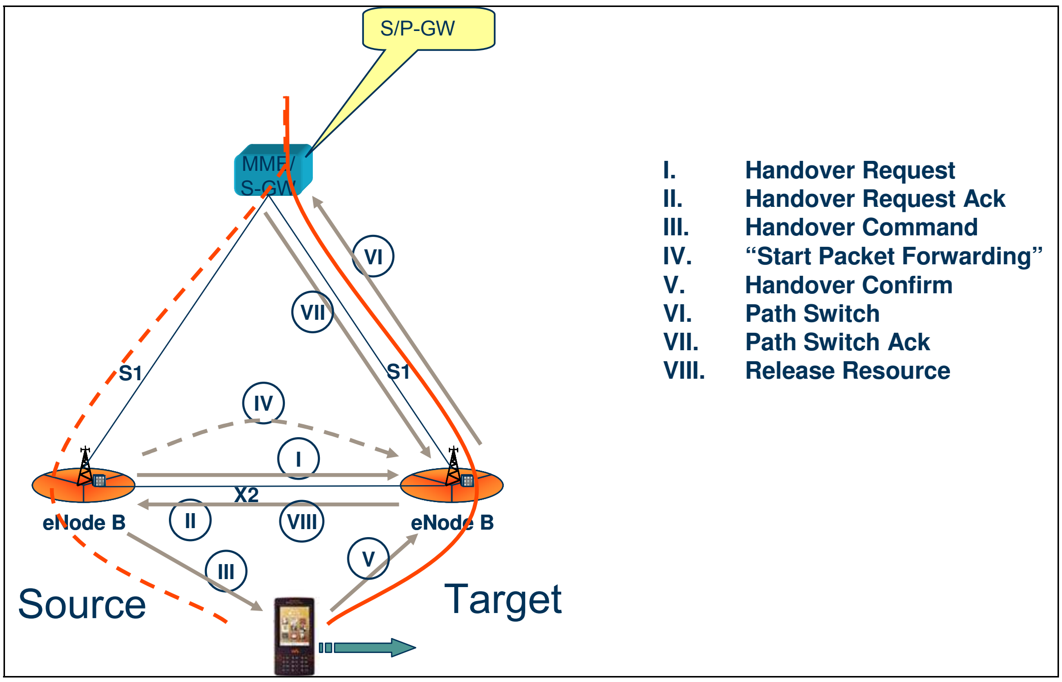


Figure 4-6. Intra-LTE HO (within one MME pool).

Figure 4-7 shows the procedure flow for intra frequency handover. It consists of Measurement configuration, handover evaluation, preparation, execution and completion. These procedures are also indicated in Figure 4-8.

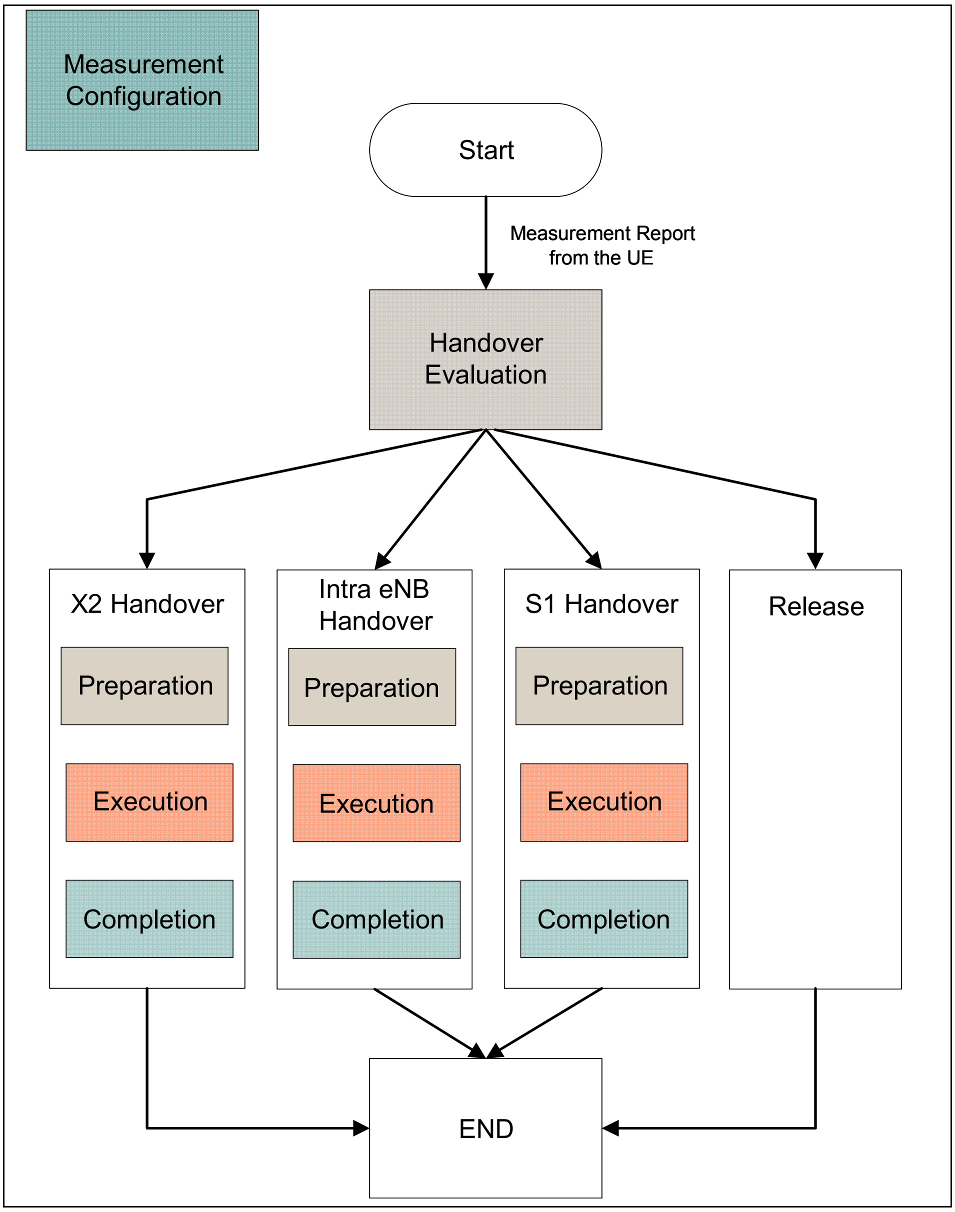


Figure 4-7. Intra frequency Handover.

Figure 4-8 shows the message sequence chart of the handover procedure for the basic case with no MME/S-GW relocation and assuming the error-free, successful case. The figure shows both the CP messages and the UP data.

The most important aspects of the UP and CP handling in case of intra-LTE mobility have been already agreed in 3GPP. According to the agreed principles, the EPC is not involved in the handover preparation signaling (unless it is an inter-pool mobility with S1 handover); instead the CP signaling is done between the eNBs directly on the X2 interface. The UP is handled by packet forwarding from source eNB to target eNB.

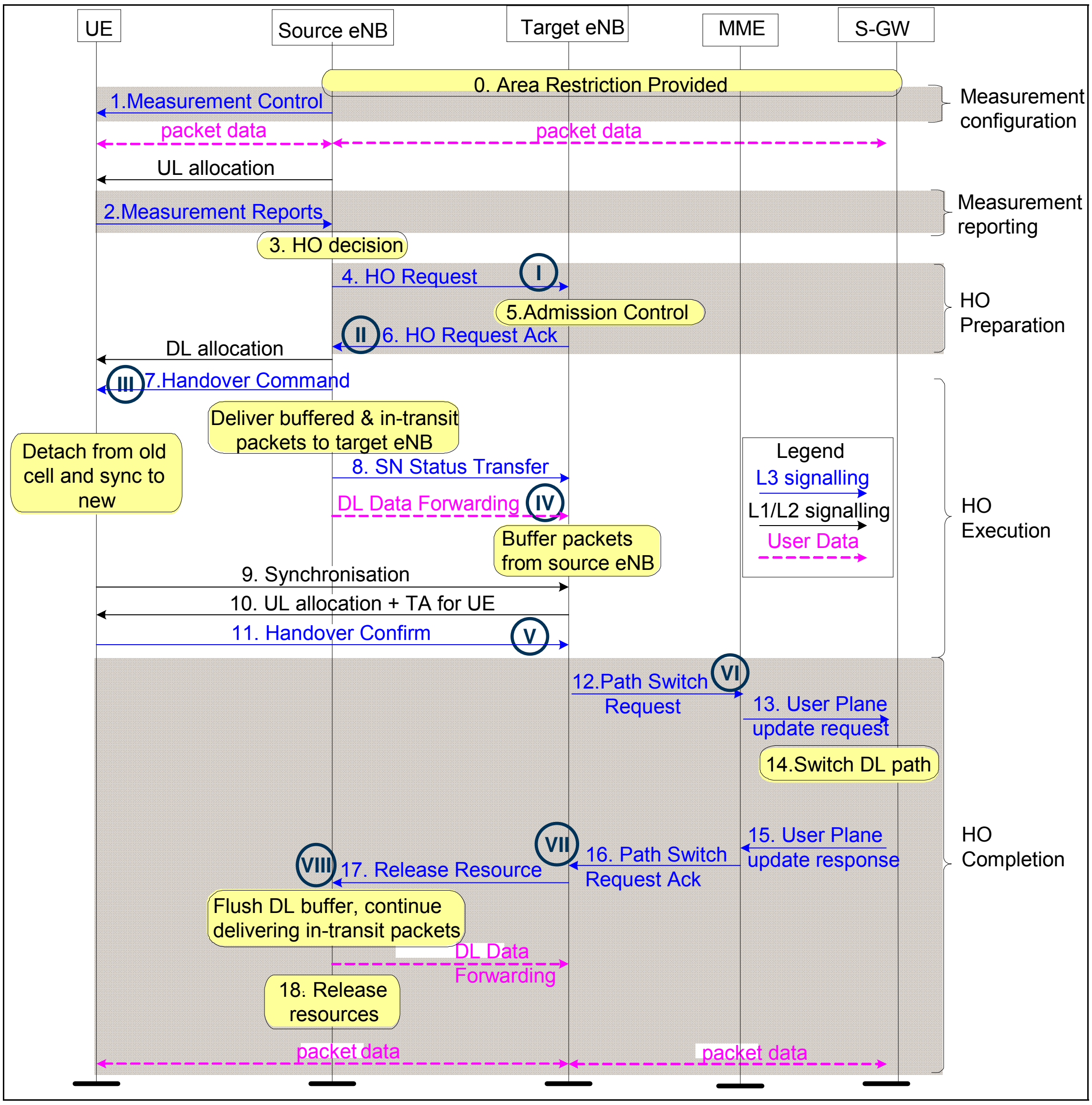


Figure 4-8. Intra LTE Handover (within one MME-pool).

1. The source eNB configures the UE measurement procedures according to the area restriction information.

2. The UE is triggered to send a MEASUREMENT REPORT according to the rules set by the measurement configuration.

3. Based on the measurement report the source eNB decides to perform a handover and selects the target cell.

4. The source eNB issues a HANDOVER REQUEST message to the target eNB passing necessary information to prepare the HO at the target side (UE X2 signalling context reference at source eNB, UE S1 EPC signalling context reference, target cell ID, RRC context including the C-RNTI of the UE in the source eNB, AS-configuration (excluding physical layer configuration), EPC bearer context and physical layer ID of the source cell + MAC for possible RLF recovery). UE X2 / UE S1 signalling references enable the target eNB to address the source eNB and the EPC. The EPC bearer context includes necessary RNL and TNL addressing information, and QoS profiles of the EPC bearers.

5. Admission Control may be performed by the target eNB dependent on the received EPC bearer QoS information to increase the likelihood of a successful HO, if the resources can be granted by target eNB. The target eNB configures the required resources according to the received EPC bearer QoS information and reserves a C-RNTI and optionally a RACH dedicated preamble. The AS-configuration to be used in the target cell can either be specified independently (i.e., an “establishment”) or as a delta compared to the AS-configuration used in the source cell (i.e., a “reconfiguration”).

6. Target eNB prepares the handover with L1/L2 and sends the HANDOVER REQUEST ACKNOWLEDGE to the source eNB. The HANDOVER REQUEST ACKNOWLEDGE message includes a transparent container to be sent to the UE as part of the Handover Command. The container includes the new C-RNTI, optionally a dedicated RACH preamble, indication of the expiry time of the dedicated RACH preamble and possibly some other parameters i.e. access parameters, SIBs, etc. The HANDOVER REQUEST ACKNOWLEDGE message may also include RNL/TNL information for the forwarding tunnels, if necessary.

NOTE: As soon as the source eNB receives the HANDOVER REQUEST ACKNOWLEDGE, or as soon as the transmission of the handover command is initiated in the downlink, data forwarding may be initiated.

7. The source eNB generates the HANDOVER COMMAND (RRC message) towards the UE. The HANDOVER COMMAND includes the transparent container, which has been received from the target eNB. The source eNB performs the necessary integrity protection and ciphering of the message.

8. The source eNB sends the SN STATUS TRANSFER message to the target eNB to convey the uplink PDCP SN receiver status and the downlink PDCP SN transmitter status of EPC bearers for which PDCP status preservation applies. The uplink PDCP SN receiver status includes at least the PDCP SN of the next expected in-sequence UL SDU (upper window edge) and may include a list of the PDCP SN of the out of sequence missing UL SDUs that the UE needs to retransmit in the target cell, if there are any such SDUs. The downlink PDCP SN transmitter status indicates the next PDCP SN that the target eNB shall assign to new SDUs, not having a PDCP SN yet. The source eNB may omit sending this message if none of the EPC bearers of the UE shall be treated with PDCP status preservation.

9. After receiving the HANDOVER COMMAND, UE performs synchronisation to the target eNB and accesses the target cell via RACH following a contention-free procedure if a dedicated RACH preamble was allocated in HANDOVER COMMAND or following a contention-based procedure if no dedicated preamble was allocated.

10. Network responds with UL allocation and timing advance.

11. When the UE has successfully accessed the target cell, the UE sends the HANDOVER CONFIRM message (C-RNTI) to the target eNB to indicate that the handover procedure is completed for the UE. The target eNB verifies the C-RNTI sent in the HANDOVER CONFIRM message.

12. The target eNB sends a PATH SWITCH message to the MME to inform it that the UE has changed cell.

13. The MME sends a USER PLANE UPDATE REQUEST message to the Serving Gateway to trigger the switch of the DL tunnels (optionally the UL tunnel endpoints may also be changed).

14. The Serving Gateway switches the downlink data path to the target side and can release any U-plane/TNL resources towards the source eNB.

15. User Plane update response sent to the MME
16. The MME confirms the PATH SWITCH message with the PATH SWITCH ACK message (optionally including new UL tunnel endpoint in case they have been changed).
17. By sending RELEASE RESOURCE the target eNB informs the source eNB about the successful completion of the handover and triggers the release of resources.
18. Upon reception of the RELEASE RESOURCE message, the source eNB can release radio and C-plane related resources associated to the UE context. However, the data forwarding may be still be ongoing even after that point.

Measurements

The UE measurements necessary for the handover are configured from the source eNB via RRC. It is generally assumed that downlink measurements, done by the UE, are used for the handover decision (measurements performed by the source eNB may also assist the decision). The reporting can be done on an event triggered and/or periodic basis.

However, the UE is also required to detect and measure neighbor cells itself, since no neighbor cell list is configured in the measurement command for intra-LTE mobility (for inter-frequency measurements at least the carrier frequencies need to be indicated in the measurement configuration). The measurement configurations that need to be indicated for inter-system measurements depend on the target system type and may include neighbor cell lists

Depending on whether the UE needs transmission/reception gaps to perform the given measurement, measurements are classified as gap assisted or non-gap assisted. The required gap patterns are allocated by the eNB and configured in the UE.

UE handover measurements included in LTE standard are:

- RSRP (Reference Symbol Received Power- mean measured power per reference symbol)
- RSRQ (Reference Symbol Received Quality)

Investigations in standardization work are ongoing to possibly include other measurements (RS-SINR, RSRP/E_UTRA carrier RSSI). It is however assumed below that RSRP is typically used for best cell evaluation according to present status of standardization. RSRQ can be used for Bad LTE coverage measurements e.g. to trigger start of gap assisted measurements.

The handover evaluation algorithm proposed in this document is based only on handover measurements on mean DL channel performance. In TDD systems the channel path gain is the same in DL and UL. The measurement filter time constant must be set to properly weight large scale fading impact. Fast fading is not considered in handover while it is assumed that the fading coherence time is to short relative to handover execution time and exploring the frequency selective channel in UE scheduling will reduce the fast fading problem. The possible imbalances in DL and UL path gain due to non-compensated feeder losses, incorrect reference symbol power and alike deteriorates handover performance but simulations has shown that the level of impact is relatively low. Concerning UL measurements it is for FFS if including UL interference level will gain to handover performance.

<u>Best cell DL measurement setup in UE</u>

The following configured information is assumed to be included in UE measurement setup (to be standardized):

- Trigger condition for event that start measurement reporting.
- Trigger condition for stop measurement reporting
- Type of measurements
- Time between periodic reporting
- L3 measurement filtering parameters. Offset, time to trigger and hysteresis
- Measurement bandwidth [1)]

[1)] The UE handover measurements perform estimations on received cell reference symbols power. While cells may have different bandwidths the UE must be informed on the bandwidth the measurements shall use (that is the bandwidth that is covered by all cells).

The following UE DL measurement report event is setup:

Event: “Change of best cell” (other cell is better than source cell).

- Is reported when $RSRP_{Candidate} > RSRP_{SourceCell} + bestCellThreshold + bestCellHysteres/2$
- Starts periodic BestCell measurement reports
- Stops periodic measurement reports when no candidate cells fulfills $RSRP_{Candidate} > RSRP_{SourceCell} + bestCellThreshold – bestCellHysteres /2$

It is assumed that UE cannot distinguish Intra- MME cells from Inter-MME cells and may not handle cell specific thresholds (i.e. do not have neighbor cell information). The threshold for event triggers must therefore be the minimum threshold that covers all neighbor cell threshold settings. The cell unique thresholds are then applied in eNB.

The UE finds intra frequency cells and detects the identities by their synchronization signals. The UE performs handover measurements on detected cells reference symbols, filters and evaluates measurement results with respect to event conditions. If condition for start event is met a measurement report to source RBS and BestCellEvaluation is sent. If parameter TimeToTrigger is set the event is considered not to be fulfilled until the event condition is fulfilled during the TimeToTrigger. Then the event report is sent. Periodic reporting results in measurement reports being sent periodically as long as condition for stop event is not met.

Concept:

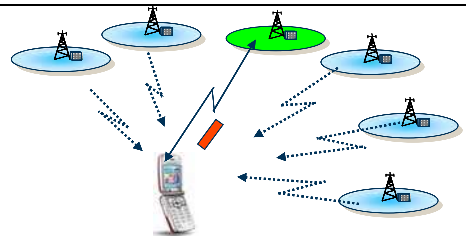
UE measures, evaluate and reports standardized ”events”

Events are used for triggering network actions e.g. handover

Standardized events and parameters controlled by the network is used by the UE e.g. Offsets, hysteresis, averaging time, thresholds..

UE sends report only when network is interested in the information i.e only when event criteria is fulfilled.

Figure 4-9. Event triggered measurement reporting.



UE measures on cells and reports only when it according to event criteria is important (WCDMA, LTE..)

+ UE transmit reports immediately and only when Network configured ”event criteria” are fulfilled.

Typical events:

- A neighbour cell becomes **offset** better than serving cell (A3)

- Serving cell becomes worse than an **absolute threshold** (A2)

- ...

Figure 4-10. Event triggered measurement reporting.

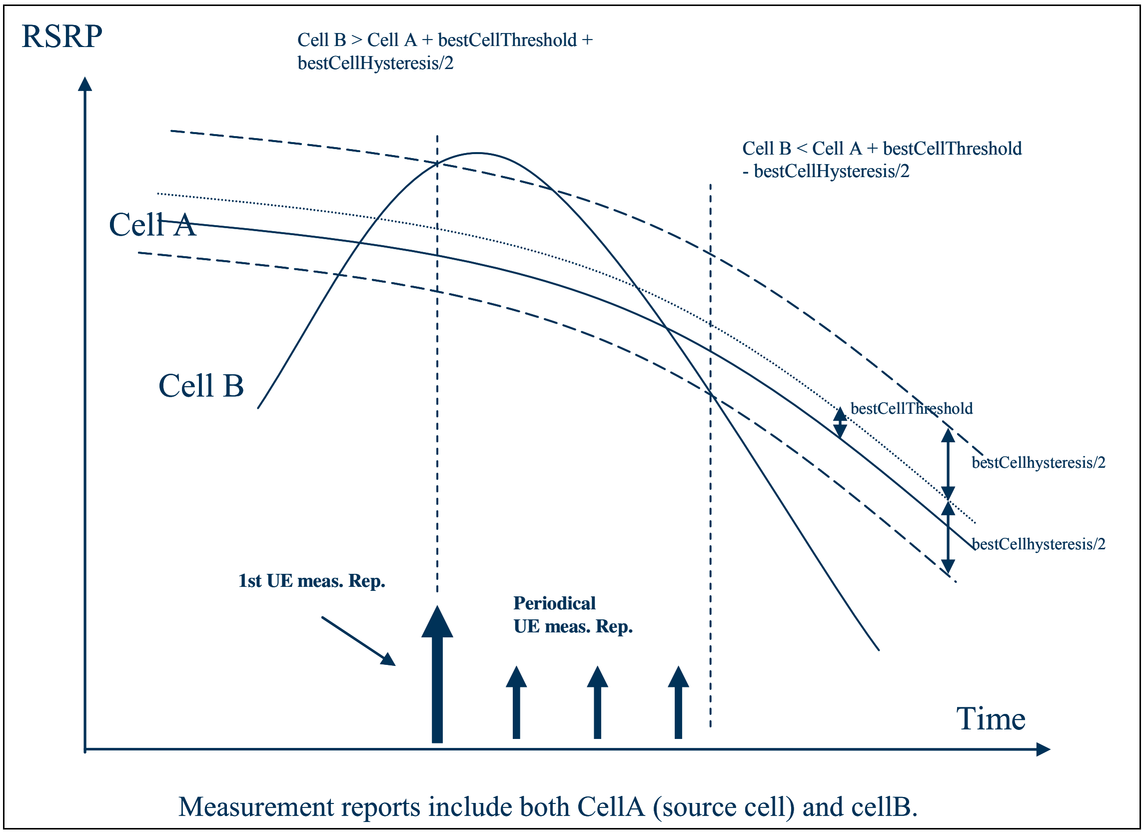


Figure 4-11 Event triggered periodical reporting.

Once the RRC_CONNECTION setup has been completed, the user equipment monitors the RSRP of the serving cell. When the serving cell RSRP drops below a parameter defined threshold, set by the `sMeasure` parameter, the user equipment commences RSRP and RSRQ measurements (depending on configuration) on the serving and surrounding cells. The user equipment is configured to send an event triggered measurement report when one or several intra frequency cells are measured to be better than the current serving cell by a parameter defined margin.

When a measurement report is received by the serving RBS the intra frequency handover process commences. The serving RBS evaluates the measurement reports and then determines the most suitable handover candidate cell, which is then referred to as the target RBS.

The serving RBS communicates with the target RBS via the X2 interfaces and attempts to set up the handover. If no X2 interface is defined then the signaling is conducted via the S1 interface.

If the target RBS is able to accommodate the handover request it assigns the required resources and send this information to the serving RBS so that the information can be forwarded to the user equipment. The user equipment then attempts the handover to the target cell using the assigned resources.

The user plane data flow from the S-GW is redirected to the target RBS once the user equipment has successfully attached. The original serving RBS is then informed of the successful handover and it releases the resources assigned to the user equipment.

If the target RBS is unable to accept the handover attempt then it will send the HANDOVER PREPARATION FAILURE message to the serving RBS. When this occurs the serving RBS reevaluates the handover candidate list and attempts to set up the handover to the next best candidate RBS.

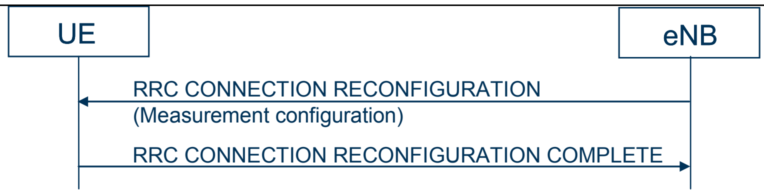
If no suitable handover candidate cell exists then the call continues on the serving cell.

A diagram showing the Intra-LTE handover process is available in TS 36.300 Section 10.

A parameter `bestCellReleaseActive` is available that can over ride the Intra LTE Handover feature. When this parameter is set to TRUE the RBS will send the user equipment a release message when the EventA2 criteria are fulfilled. This will allow the user equipment to return to idle mode in order to reacquire the best serving cell.

Measurement Configuration

Measurement configuration information is sent to the user equipment in *RRCConnectionReconfiguration* messages. A new version of this message is sent to the user equipment whenever there is an update of the handover parameter information. For example, this may occur when the user equipment completes a handover to a cell with different handover parameters.



- **Measurement objects** *(measObjectToAddModifyList, measObjectToRemoveList)*
  - The objects which the UE shall perform the measurement on e.g. a carrier frequency or a list of neighbouring cell offsets or IRAT neighboring cells.
- **Reporting configurations** *(reportConfigToAddModifyList, reportConfigToRemoveList)*
  - Reporting criterion: periodical or event-triggered reporting
  - Reporting format: quantities (e.g. number of cells to report)
- **Measurement identity** *(measIdToAddModifyList, measIdToRemoveList)*
  - List of measurement identities, each identity links one measurement object with one reporting configuration. This is the reference number in the measurement report.
- **Quantity configurations** *(quantityConfig)*
  - The quantity the UE shall measure as well as the associated filtering parameters.
  - E.g. RSRP (Reference Signal Received Power) , RSRQ (Reference Signal Received Quality).
  - One quantity for intra freq, one for inter and one for each RAT type
- **Measurement gaps** *(measGapConfig)*
  - Configuration of periods that the UE may use to perform measurements i.e. no UL and DL transmissions are scheduled.

Figure 4-12. Measurement configuration.

By default, user equipment in the LTE network detect suitable neighbor cells without the assistance of a list of neighbor cells sent by the serving RBS. User equipment are expected to blindly detect suitable handover candidates and the subsequent handover evaluation is undertaken using generic offset values. The exception to this occurs when specific handover offset values are defined between neighboring cells by the network operator. When specific cell offset relationships exist, this information is sent to the user equipment in *RRCConnectionReconfiguration* messages by the RBS.

The *RRCConnectionReconfiguration* message can also contain a list of cells for which handover is not allowed. These cells are identified by their Physical Cell Identity or by a range of Physical Cell Identities.

- Event A1: Serving becomes better than absolute threshold;
- **Event A2: Serving becomes worse than absolute threshold**
- **Event A3: Neighbour becomes amount of offset better than serving**
- Event A4: Neighbour becomes better than absolute threshold;
- Event A5: Serving becomes worse than absolute threshold1 AND Neighbour becomes better than another absolute threshold2.
- Periodic reporting

Figure 4-13. 3GPP events - intra and inter frequency.

The user equipment uses parameters sent by the RBS to determine when to perform handover measurements. Measurements commences on the serving and neighboring cells when the RSRP of the serving cell falls below the value defined in the `sMeasure` parameter. The user equipment detects neighboring cells via intra frequency searches.

Event A3

The user equipment uses either RSRP or RSRQ measurements to determine whether to enter the EventA3 condition. The `triggerQuantityA3` parameter is used to configure whether RSRP or RSRQ values are used to trigger EventA3.

Measurements of RSRP and RSRQ are performed on the serving and detected neighboring cells. The measured values of RSRP and RSRQ can then be filtered based upon the settings of the `filterCoefficientEUtraRsrp` and `filterCoefficientEUtraRsrq` parameters. The filter averages a number of measurements in order to filter out the impact of large scale fast fading.

The user equipment then uses an offset value, `a3offset`, and a hysteresis value, `hysteresisA3`, to determine whether to trigger the EventA3. Non default offset relationships use the value `cellIndividualOffsetEUtran` instead of `a3offset` for the particular cell relationship.

The formula used by the user equipment for evaluating entry to EventA3 is shown below:

$$Mn - HysteresisA3 > Ms + a3offset$$

Mn = measured value of the neighboring cell (either RSRP or RSRQ)

Ms = measured value of the serving cell (either RSRP or RSRQ)

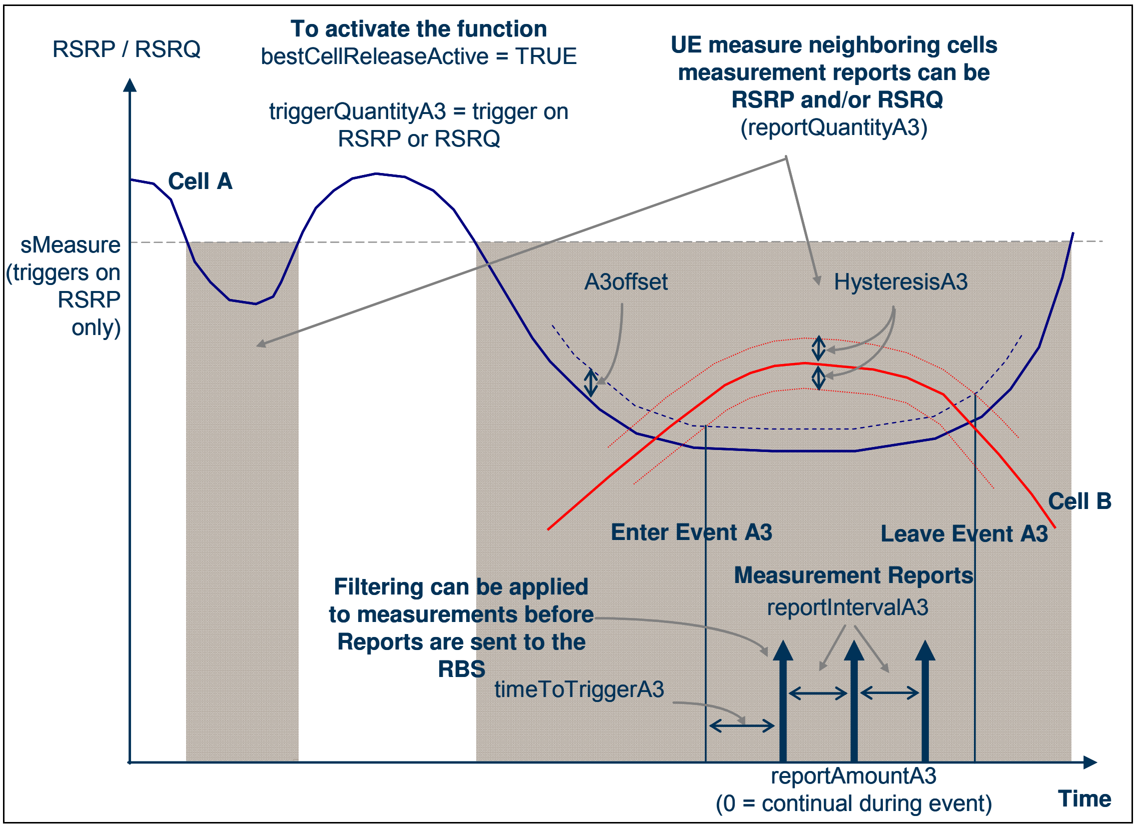
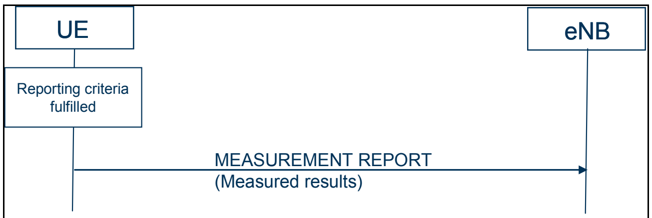


Figure 4-14. Event A3 - Neighbor becomes amount offset better than serving.

Once EventA3 is triggered, the user equipment will wait a predetermined time (`timeToTriggerA3`) before it commences sending measurement reports to the serving RBS. These measurement reports contain measurements for the serving cells and up to three detected intra frequency neighbor cells. The `reportQuantityA3` parameter indicates whether RSRP or RSRQ measurements, or both, are to be included in the measurement reports.



- Reporting criteria
  - Reporting threshold
  - Hysteresis
  - Time-to-trigger
  - Reporting interval
- Measured results
  - Event id
  - Cell identity
  - Measured measurement quantity

Figure 4-15. Measurement reporting.

Measurement reports are sent periodically whilst the EventA3 condition is active. The parameter `reportIntervalA3` determines the time interval between measurement reports. The parameter `reportAmountA3` indicates how many reports to send; a value of 0 indicates that the reports should be sent indefinitely whilst the EventA3 condition is active.

The user equipment uses the same offset and hysteresis values to determine when to leave EventA3 when the serving cell improves in RSRP or RSRQ relative to the neighboring cells. The formula used by the UE is shown below:

$$Mn + HysteresisA3 < Ms + a3offset$$

Mn = measured value of the neighboring cell (either RSRP or RSRQ)

Ms = measured value of the serving cell (either RSRP or RSRQ)

The Measurement Reports will be Event triggered and resent periodically as long as the event is fulfilled.

Event A2

Event A2 follows a similar principle as event A3.

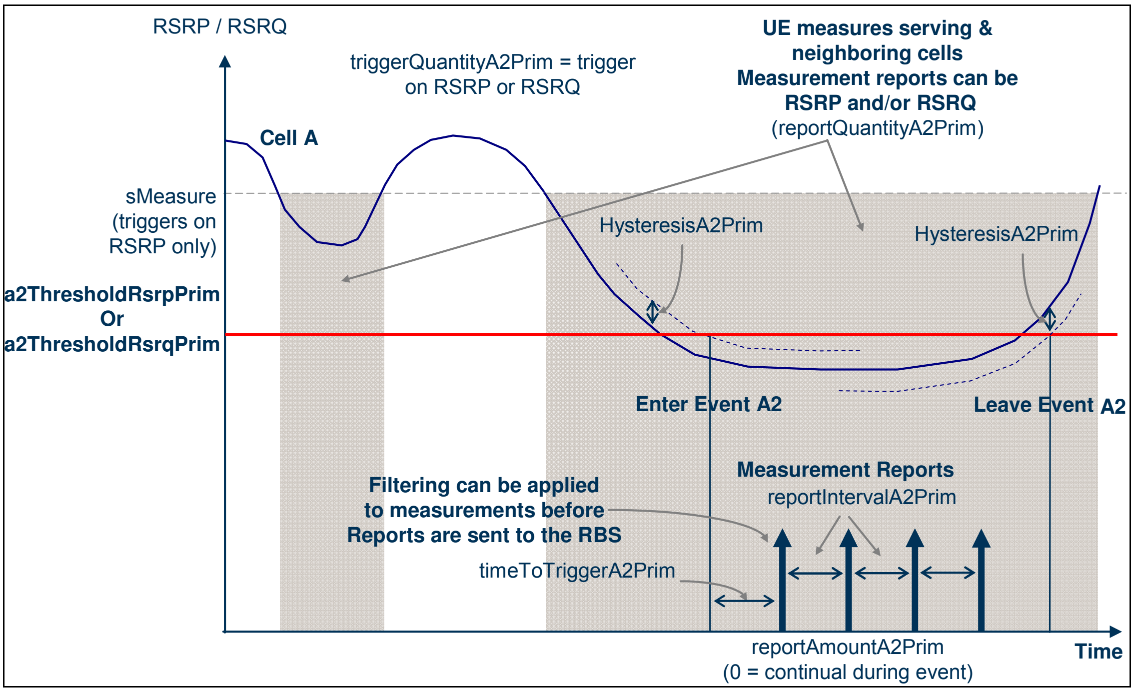


Figure 4-16. Event A2 - Serving becomes worse than absolute threshold.

Inequality A2-1 (Entering condition)

$$Ms + HysteresisA2 < Thresh$$

Inequality A2-2 (Leaving condition)

$$Ms - HysteresisA2 > Thresh$$

The variables in the formula are defined as follows:

Ms is the measurement result of the serving cell, not taking into account any offsets.

HysteresisA2 is the hysteresis parameter for this event (i.e. *hysteresis* as defined within *reportConfigEUTRA* for this event).

Thresh is the threshold parameter for this event (i.e. *a2-Threshold* as defined within *reportConfigEUTRA* for this event).

Ms is expressed in dBm in case of RSRP, or in dB in case of RSRQ.

HysteresisA2 is expressed in dB.

Thresh is expressed in the same unit as ***Ms***.

Events for IRAT HO

- Event B1: Neighbour becomes better than absolute threshold;
- Event B2: Serving becomes worse than absolute threshold1 AND Neighbour becomes better than another absolute threshold2.
- Periodic reporting

Figure 4-17. 3GPP events for IRAT.

HANDOVER EVALUATION AND EXECUTION

When a measurement report is received by the RBS the Best Cell Evaluation process is used to perform the handover evaluation. This process performs handover evaluations based on the filtered downlink channel measurements contained in the measurement report.

- Evaluates if one or more intra frequency cell is better than current serving cell.
- Use event triggered and periodical reporting from UE
- No measurement list sent to UE (UE search for all 504 physical cell id and reports the cell(s) fulfilling the event criteria).
- UE Event Trigger controlled by:
  - L3 filtering (How much averaging is done before event evaluation)
  - Offset (How much better in dB)
  - Time to trigger (For how long)

Figure 4-18. Best cell evaluation.

The Best Cell Evaluation process maintains a list of the cell candidates reported by the user equipment in the measurement reports. The list is updated whenever measurement reports are received by the serving cell. The process ranks the serving and handover candidate cells using the appropriate offset and hysteresis values in order to determine the best candidate cell. If the serving cell is the highest ranked cell then the user equipment remains on the serving cell.

If another cell is identified as the best candidate cell then the serving RBS sends a request over the X2 link to the target RBS requesting the allocation of resources to facilitate the handover. If there is no X2 connection between the serving and target RBS then the handover signalling will be transmitted via the S1 interface and the MME. Alternately, if the `Automated Neighbor Relations` feature is activated then the serving RBS will create the neighbor cell relationship and establish a X2 link to the target RBS prior to facilitating the handover.

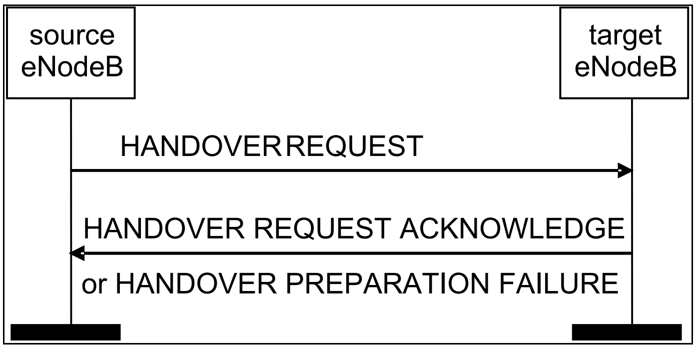


Figure 4-19. Handover preparation.

The target RBS performs admission control and if it is able to accept the handover it reserves cell resources required for the user equipment. The target RBS sends the information to the serving RBS for forwarding to the user equipment.

Upon receiving a positive acknowledgement to the handover request, the serving RBS completes any ongoing HARQ processes and sends a handover direction to the user equipment.

If the target RBS informs the serving cell that it is unable to accept the handover, the parameter `minBestCellHoAttempts` , determines the number of attempts for handover to a cell better than the serving one, before handover is attempted to the next best cell. If there is no next best cell in the UE, report handover to the best cell is attempted repeatedly.

Best Cell Evaluation

The proposed solution for Best cell evaluation in the eNB makes it possible to:

- Set handover threshold relative to source cell
- Handle both intra-MME and inter-MME cells in evaluation
- Set different handover thresholds for intra-MME handovers and inter-MME handovers.
- Set cell specific offsets relative to handover threshold to compensate for cell DL/UL imbalance or to offset handover region.
- If best cell handover proposal is rejected and another cell that also have higher quality than the source cell is available that cell is proposed for handover.

A neighbor list is configured in the eNB that contains cell-ID, Inter/Intra-MME relation, cell specific offset, etc.

BestCellEvaluation keeps a list with best cell candidates. The list is updated based on measurement reports. The size of the list should correspond to the max number of cell measurements that UE can report in a message report. The Best cell candidate list can contain both Intra and Inter MME LTE cells. A proposal for handover is trigged when current source cell no longer is best cell.

If BestCellEvaluation receives a measurement report while it already processes other measurement report the new report will be buffered. When starting a UE best cell evaluation the latest buffered measurement report will be considered.

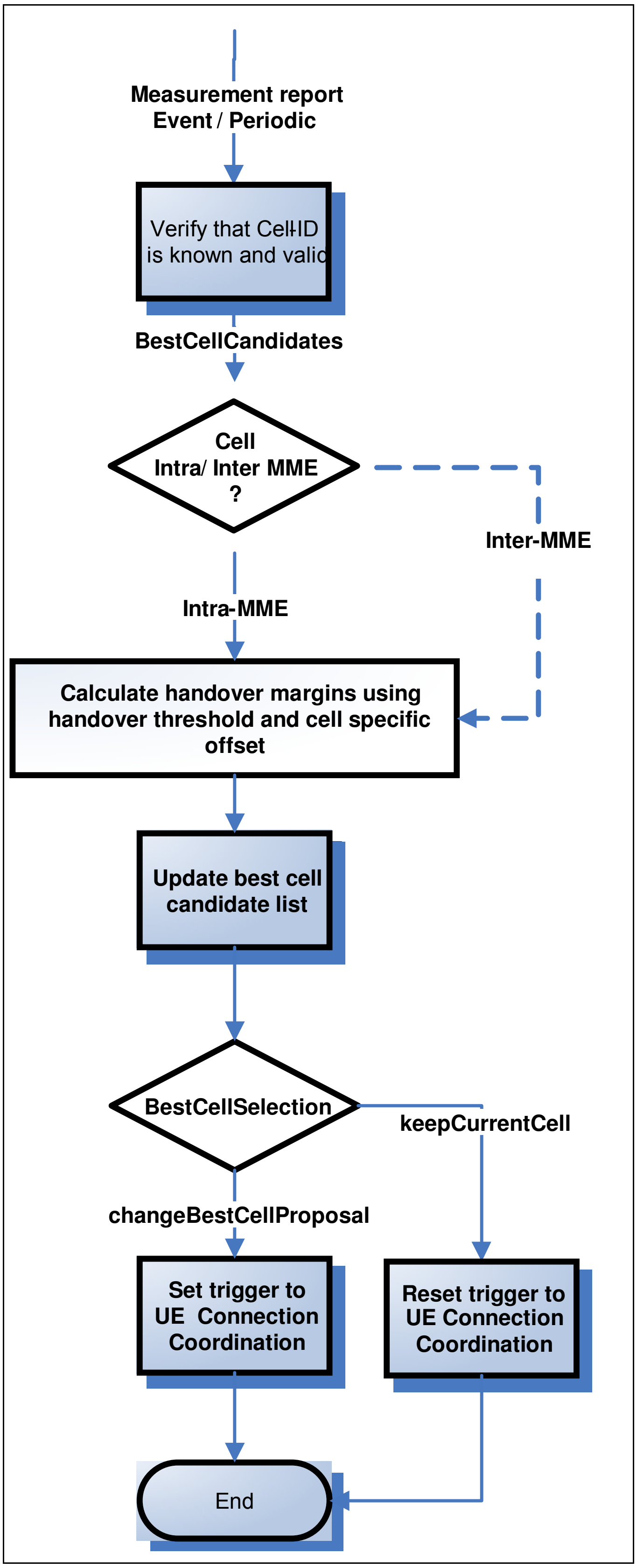


Figure 4-20. Best Cell Evaluation.

1. The received measurement report is validated. Cell-ID's are checked against configured information. If a cell is unknown the corresponding measurement is discarded. The unknown cell is reported to O&M to possibly update the neighbor cell list.

2. Different handover thresholds may be set for cells within the same MME and for cells in a neighbor MME. This makes it possible to have a general threshold for Inter MME handovers that is higher than for intra-MME handovers. Information on inter-/intra-MME relations is available in RBS neighbor list. A cell specific offset to handover threshold may also be defined to modify threshold for a specific cell. Handover threshold and cell specific offset is applied to candidate cell estimates to find handover margin

handoverMargin =
$RSRP_{Candidate}$ -
($RSRP_{SourceCell}$+handoverThreshold+cellSpecificOffset)

3. BestCellCandidate list is generated in order of handover margin.

4. The cell with positive and highest handoverMargin is selected as best cell. If there are no cell that fulfills this requirement current source cell is best cell.

5. If another cell than current source cell is best cell a trigger to the handler for UE connection is sent indicating that an HO proposal for UE is available. If current source cell is best cell a possible buffered and not handled trigger in UE connection coordination is reset.

A summary of connected mode mobility is shown below.

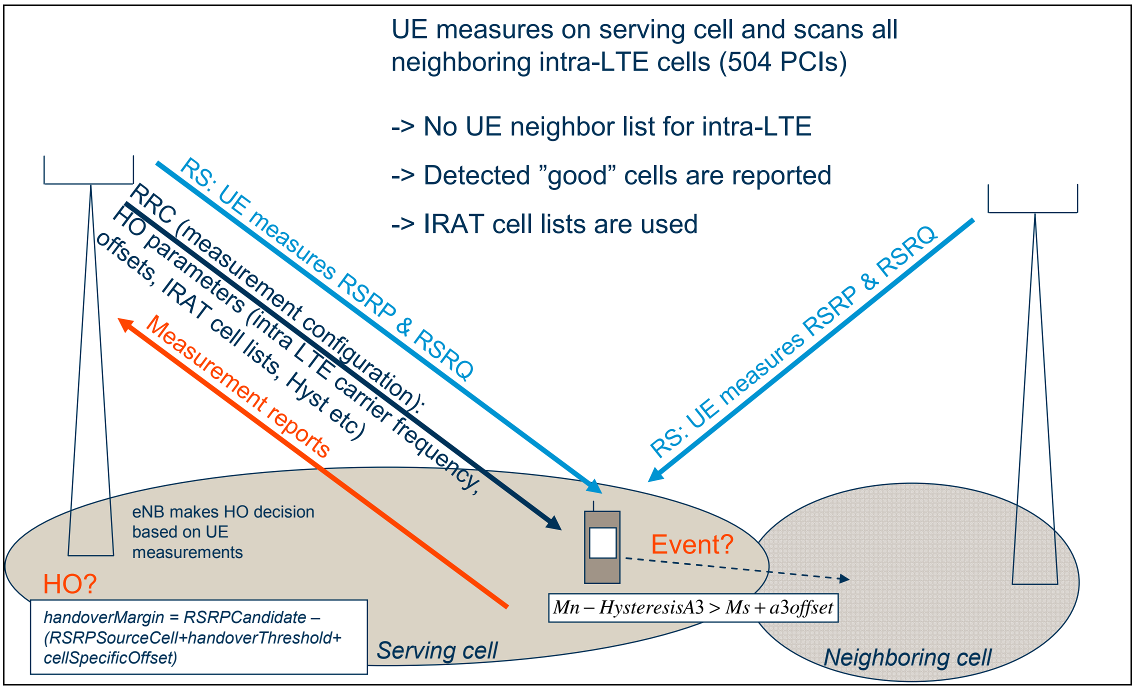


Figure 4-21. Connected mode mobility.

Handover execution

The handover execution starts when the serving RBS sends an *RRCConnectionReconfiguration* message to the user equipment telling it to perform a handover.

The handover execution ends when the user equipment successfully accesses the target RBS and sends a Handover Confirm message.

Once the user equipment has successfully connected to the target RBS, the target RBS notifies the MME and S-GW that the handover has occurred. The MME and S-GW switch the bearer from serving RBS to target RBS which then becomes the serving RBS. The RBS informs the source RBS that the handover is complete.

The bearer between S-GW and the RBS is setup per RBS and not per cell. If the UE is moving to a cell in the same RBS then there is no switching of the bearers.

When a valid measurement report is received the reported cell identities are checked against the list of neighbor cells. If a reported cell identity is unknown the corresponding measurement is discarded and the unknown cell identity is reported to the Automatic Neighbor Relationship process for a possible update of the cell's neighbor list. The Automatic Neighbor Relationship process will request that the user equipment obtain the unique Cell Global Identifier of the unknown cell so that a handover relationship and X2 link can be established.

Intra-LTE handover via the X2 link is only possible between cells that are connected to the same MME pool.

Inter MME handover

When the cells are in different MME pools, an inter MME handover takes place. See Figure 4-22.

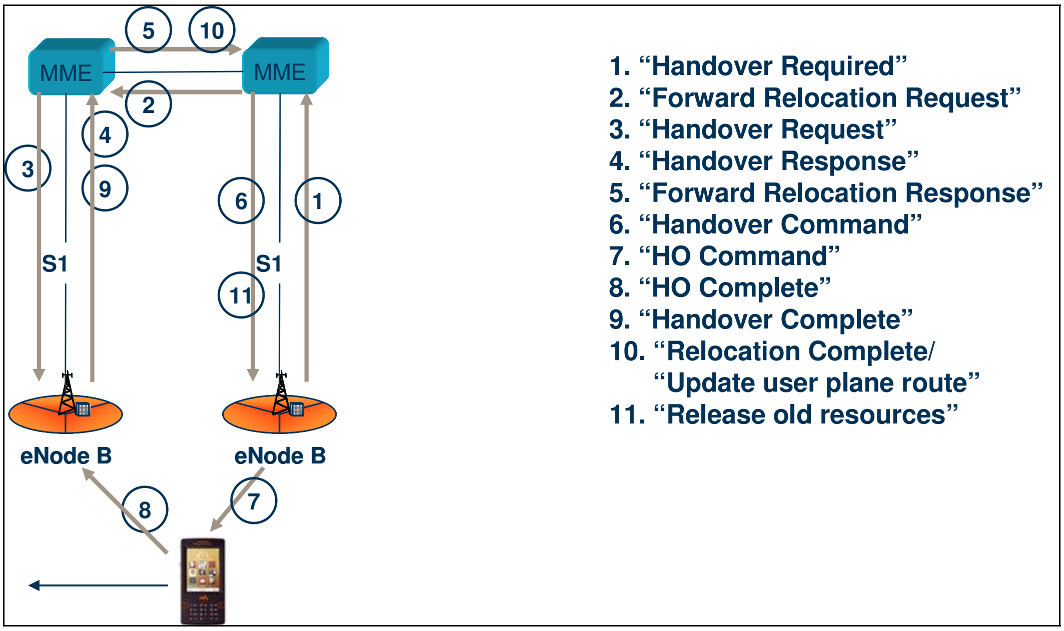


Figure 4-22. Inter MME Handover.

User plane handling

Packet forwarding guarantees that no packets will be lost during the handover execution (packets may still get lost on the transport network). Downlink PDCP SDUs that could not be successfully sent from the source eNB to the UE prior to the handover and the rest of the incoming SDUs on S1 will be forwarded to the target eNB. The forwarding is done for PDCP SDUs, i.e., for IP packets. This means that partially received segments of an SDU, i.e., RLC PDUs and the RLC status are not forwarded, instead the HARQ/ARQ state is reset at the target eNB.

- **Direct packet forwarding** (SGw not involved) may re-use S1 or X2 IPSec tunnels or use its own connection. Applicable for both S1 HO and X2 HO.
- **Indirect packet forwarding** (SGw involved) Applicable for S1 HO case only, re-use of S1 IPSec tunnels.

Figure 4-23. Packet forwarding.

For **RLC_AM bearers** the continuity of the PDCP SN is maintained during the handover both in uplink and downlink direction, which ensures the in-sequence delivery of SDUs received in source cell and SDUs retransmitted in target cell and avoids duplicate SDUs. The source eNB forwards all downlink SDUs with their PDCP SN indicated that have been sent to the UE in the source cell but have not been acknowledged. The SDUs that have not been PDCP processed in the source at the time of the handover, including SDUs incoming on S1 are forwarded without a PDCP SN.

Uplink PDCP SDUs received out of sequence at the source are also forwarded to the target to be reordered with SDUs resent by the UE in the target cell. Note that uplink and downlink SDUs are forwarded in separate tunnels on X2. Uplink SDUs received in-sequence are delivered toward the S-GW by the source eNB.

The source eNB also sends its PDCP transmitter/receiver status to the target in the SN STATUS TRANSFER message on X2. The transmitter status includes the next to be assigned PDCP SN in the downlink, while the receiver status includes the PDCP SN of the next in-sequence expected uplink SDU plus the PDCP SNs of the uplink missing SDUs, which the UE is supposed to retransmit in the target cell.

After the UE arrives to the target cell a PDCP status report can be exchanged between the UE and the eNB. The status report provides information about the potential SDUs that need to be retransmitted and indicates the PDCP SN of the next in-sequence SDU that the sender should continue the transmission after the retransmitted SDUs.

For **RLC_UM bearers** the PDCP SN is reset during the handover and an in-sequence cumulative forwarding method is used, where no PDCP SDUs are retransmitted in the target cell. This means that the source eNB forwards downlink PDCP SDUs in-sequence starting from the first SDU which has not been sent in the source cell (any SDUs that have been at least attempted to send in the source cell is not going to be resent in the target cell).

In the uplink the source eNB releases the in-sequence received SDUs toward the S-GW and discards any out of sequence received SDUs. Consequently the source eNB does not forward uplink data to the target eNB. The UE PDCP entity does not attempt to retransmit any PDCP SDU in the target cell for which transmission had already started in the source cell. Instead UE PDCP entity starts the transmission with new PDCP SDU’s.

In-order delivery

After the downlink path is switched at the Serving GW downlink packets on the forwarding path and on the new direct path may arrive interchanged at the target eNB. The target eNB should first deliver all forwarded packets to the UE before delivering any of the packets received on the new direct path. The method employed in the target eNB to enforce the correct delivery order of packets is an implementation specific detail, outside the scope of the standard.

However, in order to assist the reordering function in the target eNB, the Serving GW shall send one or more tagged empty packets on the old path immediately after switching the path for each EPC bearer of the UE. The tagged packet shall not contain user data, they are only used to indicate the end of the packet stream. The tagging can be indicated in the GTP header. After completing the sending of the tagged packets the GW shall not send any further user data packets via the old path. Upon receiving the tagged packets by the source eNB, the source eNB shall forward the packet unchanged toward the target eNB.

Maintaining security

During mobility the security context is transferred from the source to the target eNB at handover preparation. New security keys are derived in the target cell based on the security keys at the source cell (more specifically based on an eNB specific base-key). Both the target eNB and the UE perform this same key generation process autonomously to obtain the new keys.

The Hyper Frame Number (HFN) and the PDCP SN, which together compose the sequence number input to the ciphering algorithm, are maintained continuous during the handover at least for RLC_AM data bearers. The source eNB sends the current HFN, together with the PDCP SN to the target eNB in the SN Status Transfer message, as we have seen above. (For RLC_UM bearers and for signaling bearers the HFN and PDCP SN are reset after the handover).

The UE and the eNB can start using the new security keys in the target cell immediately after the handover without any further reconfiguration signaling. It is enough to signal only the selected ciphering algorithm and the identifier of the base key set (obtained during initial authentication and used to derive ciphering and integrity keys) in the HO Command.

Error cases

Error cases during the handover process, i.e., when the UE fails to synchronize at the target eNB are handled via the common radio link recovery RRC procedure. We note that a radio link failure may occur basically at any time during the ECM-CONNECTED state of the UE, when it loses the serving cell. The handover failure can be seen as a special case of the RL failure where the RL failure occurs after the UE has received a HO command, which has ordered the UE to switch to a target cell but the UE has failed to access that cell. Although the triggering criteria for the regular RL failure and for the handover failure case will be typically different, the RRC recovery mechanism used will be the same.

During the RRC recovery mechanism the UE selects a suitable cell and sends an RRC message requesting the reestablishment of the connection. The UE identifies itself with the old C-RNTI (valid in the source cell) plus the physical cell ID of the source cell. If the eNB where the UE performs the recovery has the UE context either because the handover has been prepared to that eNB or because the UE returns to a cell of the source eNB, the connection can be reestablished. In all other cases the connection reestablishment is rejected and the UE is pushed to ECM-IDLE after which the UE needs to perform a Service Request to reestablish the connection.

IDLE MODE TASKS

The idle mode tasks can be subdivided into four processes:

- PLMN selection;
- Cell selection and reselection;
- Location registration;
- Support for manual CSG (Closed Subscriber Group) ID selection.

The relationship between these processes is illustrated in the Figure 4-24.

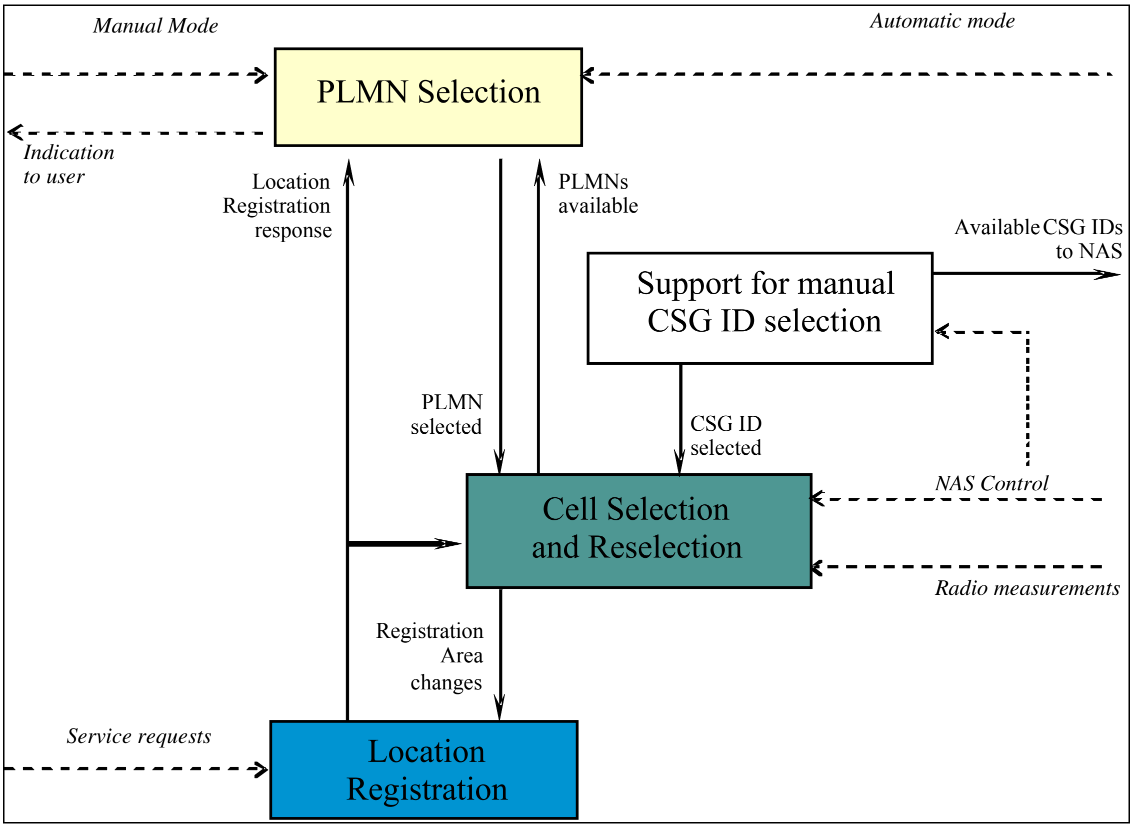


Figure 4-24 Idle Mode Tasks

The UE shall, if necessary, then register its presence, by means of a NAS registration procedure, in the tracking area of the chosen cell and as outcome of a successful Location Registration the selected PLMN becomes the registered PLMN.

If the UE finds a more suitable cell, according to the cell reselection criteria, it reselects onto that cell and camps on it. If the new cell does not belong to at least one tracking area to which the UE is registered, location registration is performed.

If necessary, the UE shall search for higher priority PLMNs at regular time intervals and search for a suitable cell if another PLMN has been selected by NAS.

Search of available CSG IDs may be triggered by NAS to support manual CSG ID selection within the registered PLMN.

If the UE loses coverage of the registered PLMN, either a new PLMN is selected automatically (automatic mode), or an indication of which PLMNs are available is given to the user, so that a manual selection can be made (manual mode).

Registration is not performed by UEs only capable of services that need no registration.

The purpose of camping on a cell in idle mode is fourfold:

a) It enables the UE to receive system information from the PLMN.

b) When registered and if the UE wishes to establish an RRC connection, it can do this by initially accessing the network on the control channel of the cell on which it is camped.

c) If the PLMN receives a call for the registered UE, it knows (in most cases) the set of tracking areas in which the UE is camped. It can then send a "paging" message for the UE on the control channels of all the cells in this set of tracking areas. The UE will then receive the paging message because it is tuned to the control channel of a cell in one of the registered tracking areas and the UE can respond on that control channel.

d) It enables the UE to receive ETWS notifications.

If the UE is unable to find a suitable cell to camp on, or the USIM is not inserted, or if the location registration failed UE enters a "limited service" state in which it can only attempt to make emergency calls.

RRC_IDLE MODE MOBILITY

Cell selection

The principles of PLMN selection in E-UTRA are based on the 3GPP PLMN selection principles. Cell selection is required on transition from EMM_DEREGISTERED to EMM-REGISTERED and from ECM-IDLE or ECM-CONNECTED.

Cell selection:

- The UE NAS identifies a selected PLMN and equivalent PLMNs;
- The UE searches the E-UTRA frequency bands and for each carrier frequency identifies the strongest cell. It reads cell system information broadcast to identify its PLMN(s):
- The UE may search each carrier in turn (“initial cell selection”) or make use of stored information to shorten the search (“stored information cell selection”).
- The UE seeks to identify a suitable cell; if it is not able to identify a suitable cell it seeks to identify an acceptable cell. When a suitable cell is found or if only an acceptable cell is found it camps on that cell and commence the cell reselection procedure:
- A suitable cell is one for which the measured cell attributes satisfy the cell selection criteria; the cell PLMN is the selected PLMN, registered or an equivalent PLMN; the cell is not barred or reserved and the cell is not part of a tracking area which is in the list of “forbidden tracking areas for roaming”;
- An acceptable cell is one for which the measured cell attributes satisfy the cell selection criteria and the cell is not barred;

Transition to RRC_IDLE:

On transition from RRC_CONNECTED to RRC_IDLE, a UE should camp on the last cell for which it was in RRC_CONNECTED or a cell/any cell of set of cells or frequency be assigned by RRC in the state transition message.

Recovery from out of coverage:

The UE should attempt to find a suitable cell in the manner described for stored information or initial cell selection above. If no suitable cell is found on any frequency or RAT the UE should attempt to find an acceptable cell.

Cell reselection

UE in RRC_IDLE performs cell reselection. The principles of the procedure are the following:

- The UE makes measurements of attributes of the serving and neighbour cells to enable the reselection process:
- There is no need to indicate neighbouring cell in the serving cell system information to enable the UE to search and measure a cell i.e. E-UTRAN relies on the UE to detect the neighbouring cells;
- For the search and measurement of inter-frequency neighbouring cells, only the carrier frequencies need to be indicated;
- Measurements may be omitted if the serving cell attribute fulfils particular search or measurement criteria.
- Cell reselection identifies the cell that the UE should camp on. It is based on cell reselection criteria which involves measurements of the serving and neighbour cells:
- Intra-frequency reselection is based on ranking of cells;
- Inter-frequency reselection is based on absolute priorities where UE tries to camp on highest priority frequency available. Absolute priorities for reselection are provided only by the RPLMN and valid only within the RPLMN; priorities are given by the system information and valid for all UEs in a cell, specific priorities per UE can be signalled in the RRC Connection Release message. A validity time can be associated with UE specific priorities.
- For inter-frequency neighbouring cells, it is possible to indicate layer-specific cell reselection parameters (e.g., layer specific offset). These parameters are common to all neighbouring cells on a frequency;
- An NCL can optionally be provided by the serving cell to handle specific cases for intra- and inter-frequency neighbouring cells. This NCL can contain cell specific cell reselection parameters (e.g., cell specific offset) for specific neighbouring cells;
- It should be possible to prevent the UE from reselecting to specific detected neighbouring cells;
- Cell reselection can be speed dependent (speed detection based on UTRAN solution);

- Cell reselection parameters are applicable for all UEs in a cell, but it is possible to configure specific reselection parameters per UE group or per UE.

Cell access restrictions apply as for UTRAN, which consist of access class (AC) barring and cell reservation (e.g. for cells "reserved for operator use") applicable for mobiles in RRC_IDLE mode.

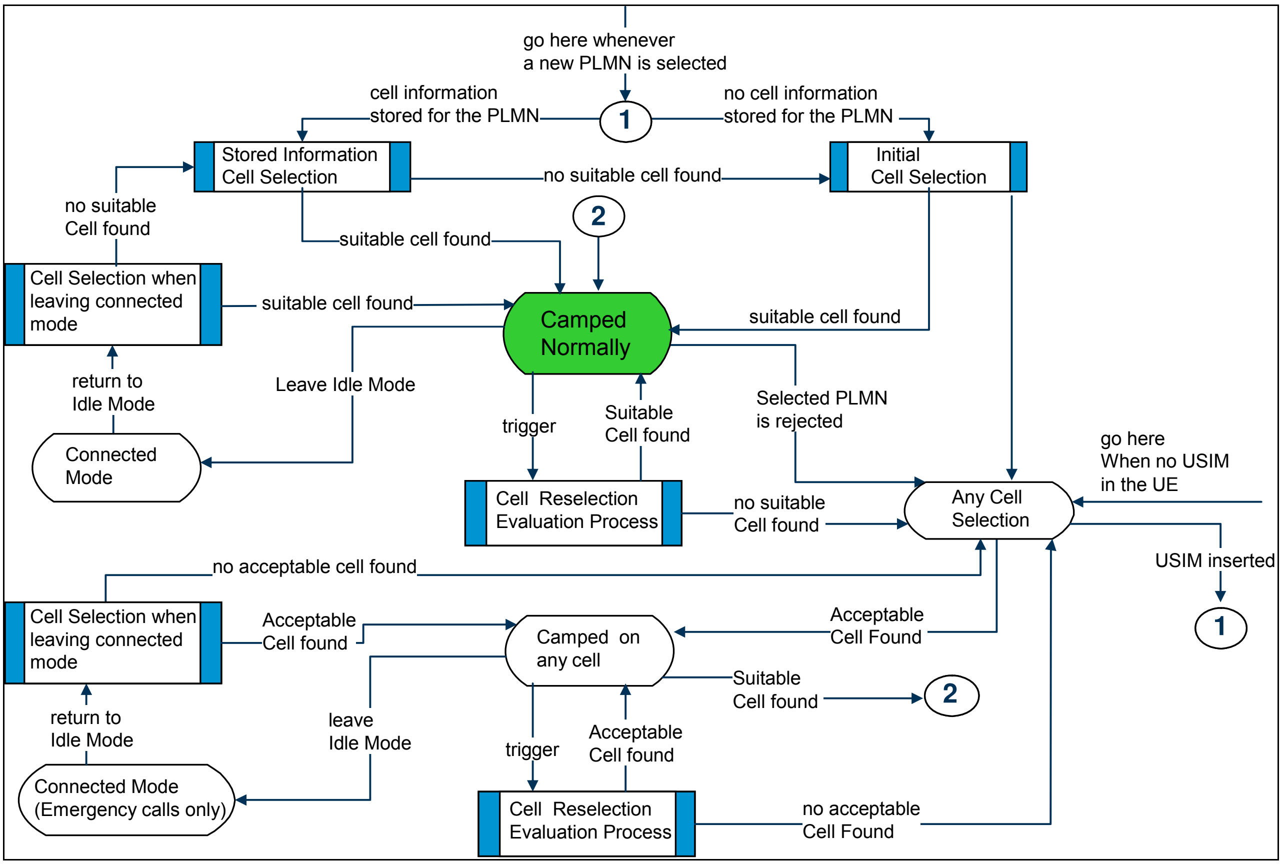


Figure 4-25 Cell Selection

The UE uses one of the following two cell selection procedures:

a) Initial Cell Selection

This procedure requires no prior knowledge of which RF channels are E-UTRA carriers. The UE shall scan all RF channels in the E-UTRA bands according to its capabilities to find a suitable cell. On each carrier frequency, the UE need only search for the strongest cell. Once a suitable cell is found this cell shall be selected.

b) Stored Information Cell Selection

This procedure requires stored information of carrier frequencies and optionally also information on cell parameters, from previously received measurement control information elements or from previously detected cells. Once the UE has found a suitable cell the UE shall select it. If no suitable cell is found the Initial Cell Selection procedure shall be started.

Cell Selection Criterion

The cell selection criterion S is fulfilled when:

$$\boxed{Srxlev > 0}$$

Where:

$$Srxlev = Q_{rxlevmeas} - (Q_{rxlevmin} + Q_{rxlevminoffset}) - Pcompensation$$

Where:

the signaled value QrxlevminOffset is only applied when a cell is evaluated for cell selection as a result of a periodic search for a higher priority PLMN while camped normally. During this periodic search for higher priority PLMN the UE may check the S criteria of a cell using parameter values stored from a different cell of this higher priority PLMN.

Srxlev	Cell Selection RX level value (dB)
$Q_{rxlevmeas}$	Measured cell RX level value (RSRP).
$Q_{rxlevmin}$	Minimum required RX level in the cell (dBm)
$Q_{rxlevminoffset}$	Offset to the signalled $Q_{rxlevmin}$ taken into account in the Srxlev evaluation as a result of a periodic search for a higher priority PLMN while camped normally in a VPLMN [5]
Pcompensation	$max(P_{EMAX} – P_{UMAX}, 0)$ (dB)
P_{EMAX}	Maximum TX power level an UE may use when transmitting on the uplink in the cell (dBm) defined as P_{EMAX} in [TS 36.101]
P_{UMAX}	Maximum RF output power of the UE (dBm) according to the UE power class as defined in [TS 36.101]

When camped on a cell, the UE shall regularly search for a better cell according to the cell reselection criteria. If a better cell is found, that cell is selected. The change of cell may imply a change of RAT.

For normal service, the UE shall camp on a suitable cell, tune to that cell's control channel(s) so that the UE can:

- Receive system information from the PLMN; and
- receive registration area information from the PLMN, e.g., tracking area information; and

- receive other AS and NAS Information; and

if registered:

- receive paging and notification messages from the PLMN; and
- initiate transfer to connected mode.

CELL RESELECTION EVALUATION PROCESS

The UE only performs cell reselection evaluation for E-UTRAN frequencies and inter-RAT frequencies that are given in system information and for which the UE has a priority provided.

The UE does not consider any black listed cells as candidate for cell reselection.

Measurement rules for cell re-selection

When evaluating for reselection purposes UE shall use parameters provided by the serving cell.

If $S_{intrasearch}$ is sent in the serving cell and $S_{ServingCell} > S_{intrasearch}$, UE may choose to not perform intra-frequency measurements in order to limit needed measurements.

If $S_{ServingCell} <= S_{intrasearch,}$ or $S_{intrasearch}$ is not sent in the serving cell UE shall perform intra-frequency measurements.

The cell-ranking criterion R_s for serving cell and R_n for neighboring cells is defined by:

$$R_s = Q_{meas,s} + Q_{Hyst}$$

$$R_n = Q_{meas,n} - Qoffset$$

where:

Q_{meas}	RSRP measurement quantity used in cell reselections.
Qoffset	For intra-frequency: Equals to $Qoffset_{s,n}$, if $Qoffset_{s,n}$ is valid, otherwise this equals to zero. For inter-frequency: Equals to $Qoffset_{s,n}$ plus $Qoffset_{frequency}$, if $Qoffset_{s,n}$ is valid, otherwise this equals to $Qoffset_{frequency}$.

The UE shall perform ranking of all cells that fulfill the cell selection criterion S, but may exclude all CSG (Closed Subscriber Group) cells that are known by the UE to be not allowed.

The cells shall be ranked according to the R criteria specified above, deriving $Q_{meas,n}$ and $Q_{meas,s}$ and calculating the R values using averaged RSRP results.

If a suitable cell is ranked as the best cell the UE shall perform cell reselection to that cell.

In all cases, the UE shall reselect 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 UE camped on the current serving cell.

A summary of idle mode mobility is shown below.

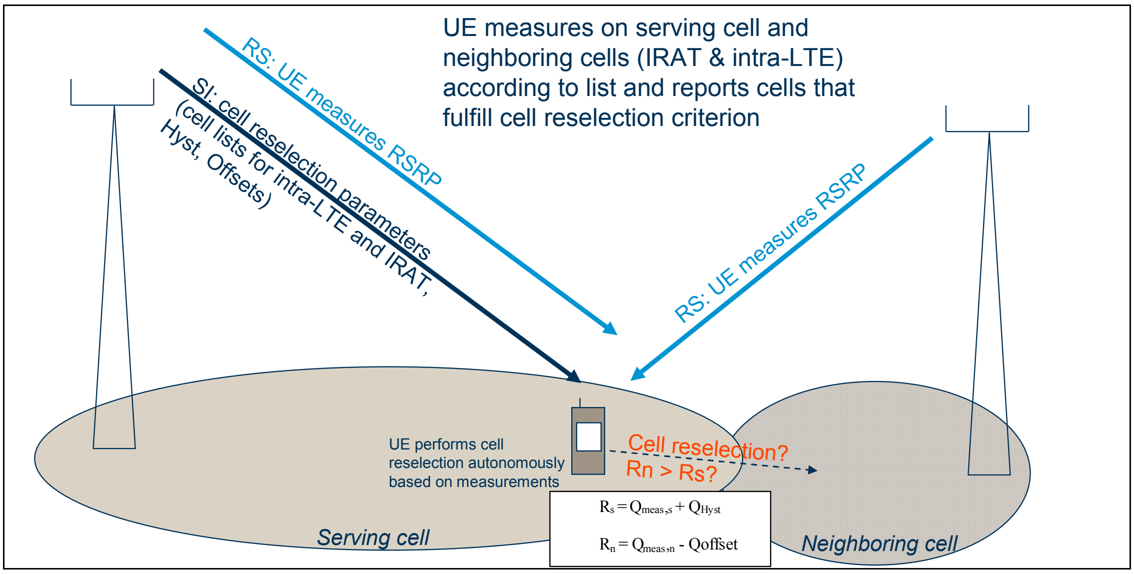


Figure 4-26. Idle mode mobility.

Tracking Area concept

The location of a UE in RRC_IDLE mode is maintained on a Tracking Area (TA) level in the EPC. In SAE/LTE there is only one TA concept defined, as opposed to 3G, where the Routing Area (RA) and UTRAN Registration Area (URA) concepts both exist.

The MME stores the context for idle UEs, which includes the location information of the UE on a TA level, the security context and the context about the established EPC bearers of the UE. Note that the S-GW also preserves the context for idle UEs, which primarily includes the preservation of packet filters corresponding to the existing bearers of the UE. There is no context stored in the eNB about idle UEs. When a UE in ECM-IDLE mode moves into a cell that belongs to a TA different from the one it is currently registered with, it performs a TA Update toward the MME.

In order to avoid excessive TA Update signaling by UEs on tracking area borders the standard supports the so call TA-list concept where multiple TAs can be assigned to the UE. According to this concept each cell belongs to only one TA but the UE can be assigned multiple such TAs.

When the UE enters a cell that does not belong to any of the TA it is currently registered with, it performs a TA Update toward the MME. The MME selects a suitable list of TA's for the UE to camp on and sends this information back to the UE in the TA Update Confirm message.

In case the UE reselects a cell that belongs to a pooling area different from the one where the UE context is located, the network has to perform an MME relocation optionally combined with a GW relocation during the TA Update procedure. When the eNB, where the UE has performed the cell reselection, realizes that it cannot route the TA Update message to the MME where the UE context is located due to being in a different pooling area, it routes the NAS message to a default MME in its own pool. This MME will identify the source MME based on the S-TMSI provided by the UE and will fetch the context from the source MME. When the context fetch is successfully completed it acknowledges the TA Update toward the UE.

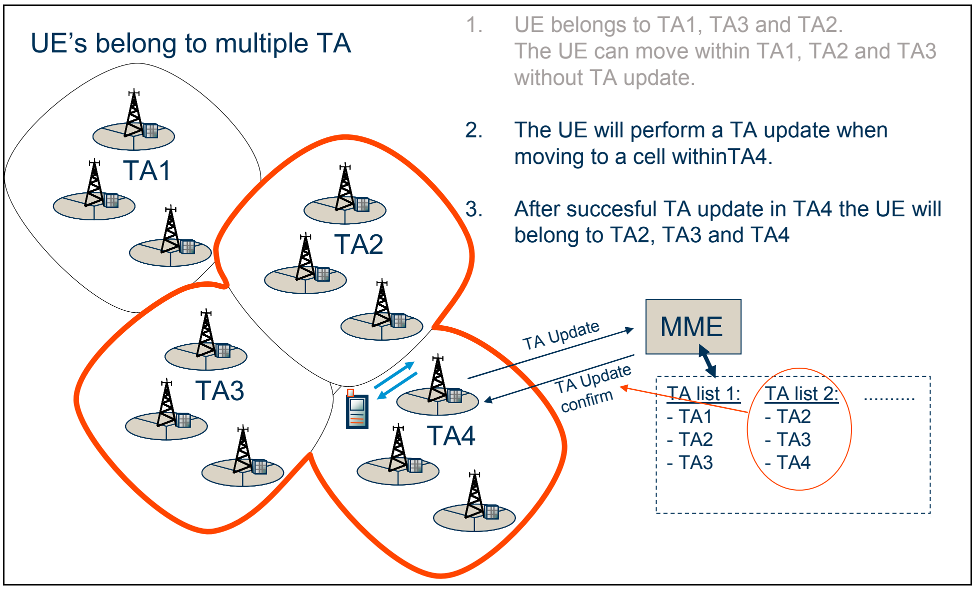


Figure 4-27. Tracking Area concept - multiple tracking areas.

Finally, we note that in RRC_CONNECTED mode the UE does not perform TA Updates as long as it moves within the same pooling area. Only after an S1 handover executed on the border of a pooling area the UE is triggered from the network to perform a TA Update.

INTER-WORKING WITH 3G/2G

This chapter deals with inter-working between LTE (E-UTRAN) and

- 3G (UTRAN)
- 2G (GERAN)

There are in principle two ways of inter-working between LTE and 3G and 2G respectively. The inter-working can be performed by a prepared handover (network controlled) or by a cell re-selection (UE controlled or network assisted). A cell re-selection typically includes signaling with the network but in some cases it may be performed without signaling (i.e., cell change).

The inter working-mechanisms and state transitions described in this chapter assume that the NAS signaling protocols are (at least) compatible enough to map PDP Contexts with EPS Bearers.

State Transitions due to Inter-System Mobility

The agreed state transitions that will be supported between 2G/3G and LTE are shown in Figure 4-28. The methods to execute the supported state transitions are the following:

- Network controlled, prepared handover, for UEs in connected state
- Network controlled Cell Change Order (CCO) with Network Assisted Cell Change (NACC) to GERAN, for UEs in connected state
- UE based cell reselection, for UEs in idle state

The network controlled, prepared handover based state transition is executed via the 2G/3G-LTE inter-system handover procedure, while the cell reselection based state change is executed via a Routing Area Update (LTE to 2G/3G) or via a Tracking Area Update (2G/3G to LTE) procedure.

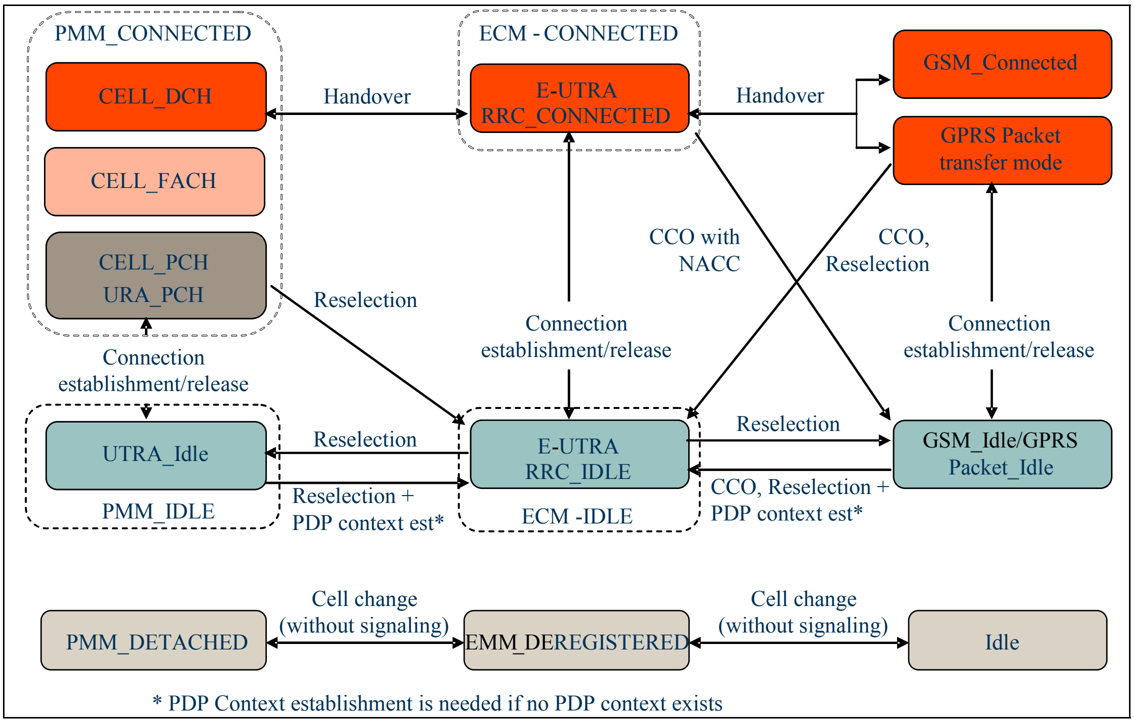


Figure 4-28. Interworking with 2G/3G.

Inter-working mechanisms

This section describes the inter-working mechanisms used for inter-working between LTE and 2G and 3G respectively.

Handover

The handover scheme described in this section is network controlled using preparation signaling, i.e., preparing the resources in the target node before requesting the UE to perform the handover.

The handover scheme includes relocation of the UE context in the sense that the context is removed from the source node (controlling the radio connection) and moved to/re-created in the target node controlling the radio connection (RNC/BSC/eNB). The handover signaling is always performed via the core network.

The handover starts by the source node (RNC/BSC/eNB) requesting handover (relocation) from the connected core network node. The core network node requests resources from the target system. The target system responds back and provides the necessary "Handover Command" to request the UE to change to the configuration of the target system. Once the UE is detected under the target system the target system updates the packet data routing. The sequence at handover from LTE to 3G is schematically shown in Figure 4-29.

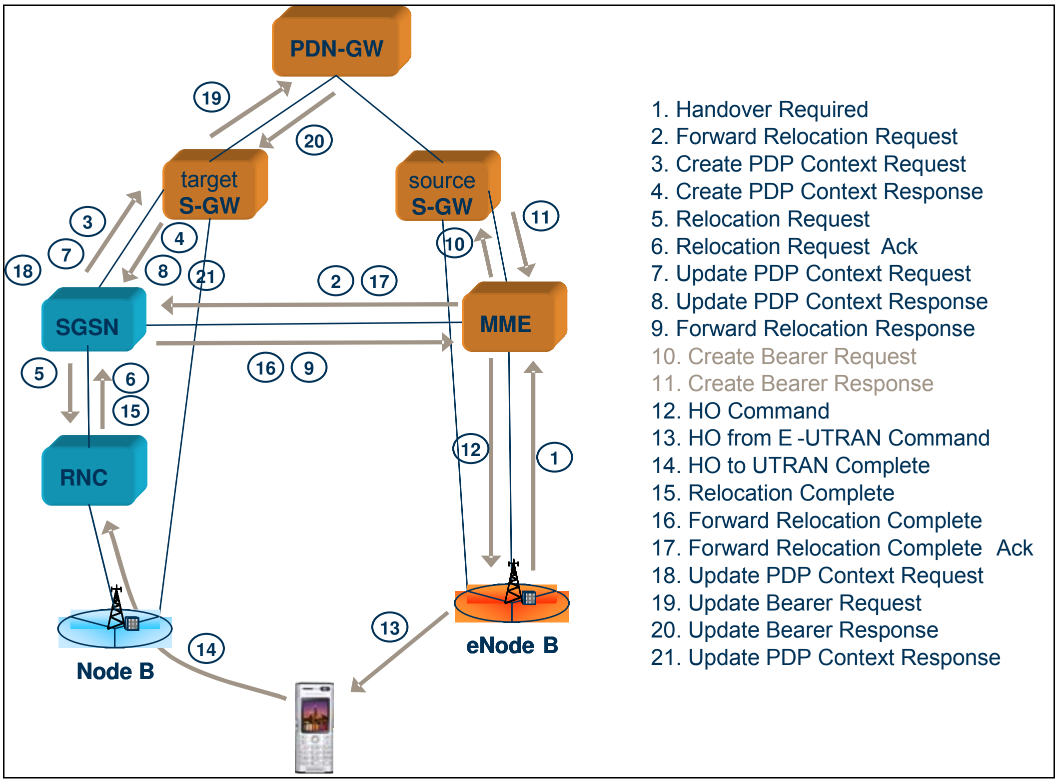


Figure 4-29. LTE to 3G Handover.

The handover example shown in the figure assumes a change of the S-GW, which may not be necessary in all cases.

The user plane is handled via packet forwarding during the handover. This means that the source side (eNB in the example) starts forwarding packets to the target side (to the RNC) at step 12. The forwarding may go directly between the eNB and the RNC if IP connectivity exists between the two nodes. In case direct connectivity is not available between the eNB and the RNC the forwarding can be performed via the S-GW. Then the MME needs to request the allocation of forwarding tunnel endpoints at the source S-GW at step 10-11. These steps are omitted in case of direct forwarding.

The forwarding is performed in-sequence for downlink SDUs that have not been successfully sent in the source system.

We note that the S-GW functionality does not necessarily have to be relocated during the procedure and the S-GW and PDN-GW functionality may reside in the same physical node. (One exception when these two functions are located in separate nodes is the roaming scenario.)

The MME needs to map the EPC bearer QoS parameters to PDP context QoS parameters during the context transfer before sending message 2 (in the LTE to 2G/3G direction). Similarly, in the 2G/3G to LTE direction the MME needs to perform the mapping when it receives the context from the source 2G/3G system.

A similar message sequence diagram applies for the handover from 3G to LTE direction and to the 2G – LTE handover cases as well.

Cell re-selection

Cell re-selection is UE controlled, guided by parameters provided by the network.

Cell re-selection between 3G and LTE is supported for UEs in PMM_IDLE and in ECM-IDLE states, respectively. Cell re-selection between 2G and LTE is supported both in Idle and in ECM-IDLE states, respectively and also in Active and in ECM-CONNECTED states, respectively.

The cell reselection is controlled both on NAS and AS level. The NAS level control in the UE includes such functions as maintaining a priority order of PLMNs and the set of forbidden TAs. The AS level cell reselection parameters such as the priorities of different inter-RAT frequencies and the priorities of different E-UTRAN frequencies can be provided to the UE either via system information broadcast or via dedicated signaling. The RRC release signaling can be used to convey re-selection parameters to the UE upon entering idle state.

The cell re-selection scheme includes relocation of the UE context in the sense that the context is removed from the source node, holding the latest UE context (SGSN/MME) and moved to/re-created in the target node.

The cell re-selection starts by the UE autonomously selecting a cell in the target system, reading the broadcast information in the target cell, and accessing the target system. The target system allocates resources (if needed) and provides a configuration to the UE to be used for the radio connection. The target system requests context transfer from the source system. After the context transfer, the target system updates the packet data routing. The sequence at cell re-selection from LTE to 3G is schematically shown in Figure 4-30.

Note! The messages to update the HLR with the new location of the UE are not shown.) (Note! After step 3 the SGSN may decide to execute “security functions”.

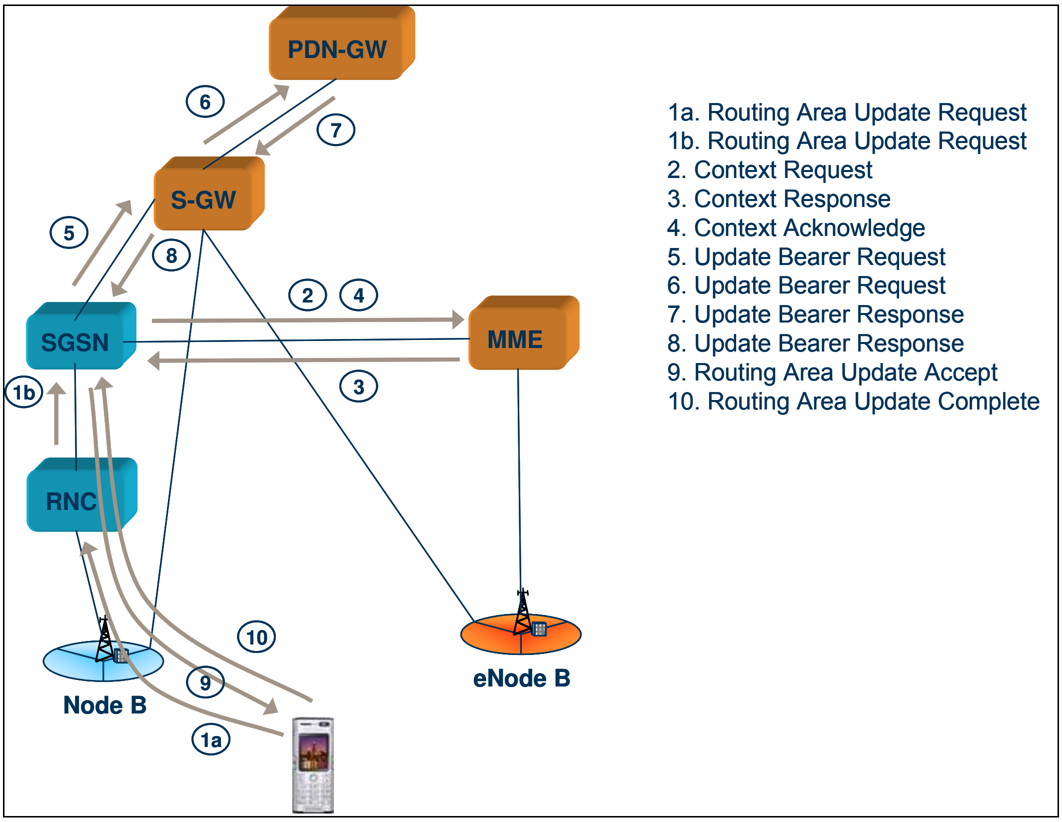


Figure 4-30. LTE to 3G Cell-reselection.

During a cell reselection from 2G/3G to LTE it may become necessary to establish the default EPS bearer connectivity for the UE, immediately after the Tracking Area Update, in case the UE has no activated PDP context in the source 2G/3G system.

In case of cell reselection in "active mode", the user plane is expected to be handled via a hard switch at the S-GW. If any handling of pending user plane packets shall be applied, packet forwarding may be used. However, it is noted that during a cell reselection there is a high risk of losing some packets anyway due to the relatively long delay associated with the cell-reselection process, independent of whether packet forwarding is employed or not.

Inter-working with the CS Domain (in 3G and 2G)

LTE is a packet-only system. However, inter-working with the CS domain is handled by functions as SRVCC (Single Radio Voice Call Continuity) and CS Fallback.

INTER-WORKING WITH CDMA2000

The detailed solution for E-UTRAN to EV-DO handover is based on that the UE pre-registers and reserves resources in EV-DO before it leaves the E-UTRAN cell. The registration and resource reservation signaling is transparently tunneled through E-UTRAN and the MME between the UE and the EV-DO RNC. The control of the handover including measurement control and the trigger for performing the handover is done by the eNB.

CDMA-eHRPD Session Continuity

The purpose of the CDMA-eHRPD Session continuity, coverage triggered feature is to manage the redirection of user equipment in RRC_CONNECTED mode towards a CDMA-eHRPD network when the user equipment measures bad coverage on the LTE network. The redirection is network controlled based upon user equipment measurement reports of the serving LTE cell.

The CDMA-eHRPD Session continuity, coverage triggered feature uses the Event A2 (Serving becomes worse than threshold) measurement process as defined in TS 36.300 and TS 36.331.

The measurement process employed by the user equipment for the evaluation of the serving cell uses parameters sent by the serving RBS to the user equipment. These parameters, which are sent to the user equipment in *RRCConnectionReconfiguration* messages, include a hysteresis values, measurement filtering parameters and time to trigger counters. The hysteresis values and time to trigger counters are included in the evaluation in order to prevent the redirection to the CDMA-eHRPD network being based upon a small number of measurements taken during a rapid fade in the radio link.

The user equipment measurements are reported to the serving RBS which makes the ultimate decision on redirection to the CDMA-eHRPD network. Two types of measurements are used in the handover evaluation process:

• RSRP (Reference Symbol Received Power) which represents the mean measured power per reference symbol

• RSRQ (Reference Symbol Received Quality) which provides an indication of the reference signal quality

The user equipment will inform the RBS when it has bad LTE coverage. The bad coverage release can be set to trigger on the RSRP value, the RSRQ value or both and the measurement reports sent by the user equipment to the RBS contain either or both of these values.

The RBS makes the decision on whether to release the user equipment with redirection to a CDMA-eHRPD network or to handover the user equipment to another LTE cell. The RBS makes the choice depending on the user equipment capabilities and RBS licenses. If the user equipment is released with redirection to a CDMA-eHRPD network, the release message will contain cell information to help the user equipment to find a suitable CDMA-eHRPD cell.

5 Abbreviations

Intentionally Blank

3GPP	3rd Generation Partnership Project
ACIR	Adjacent Channel Interference Ratio
ACK	Acknowledgement
ACLR	Adjacent Channel Leakage Ratio
ACP	Automatic Cell Planning
ACS	Adjacent Channel Selectivity
AES	Advanced Encryption Standard
AGW	Access Gateway
AIF	Auto-Integration Function
AISG	Antenna Interface Standards Group
AM	Acknowledged Mode
AMBR	Aggregate Maximum Bit Rate
A-MPR	Additional Maximum Power Reduction
ANR	Automated Neighbour Relation
APAC	Asia Pacific
API	Application Programming Interface
APN	Access Point Name
ARP	Allocation and Retention Priority
ARQ	Automatic Repeat Request
ARW	Add RBS Wizard
AS	Access Stratum
AS	Application Server
A-SBG	Access SBG
ASC	Antenna System Controller
ASD	Automatic SW Download
ASSL	Adjacent Subcarrier Set Leakage
ASSR	Adjacent Subcarrier Set Rejection
BCCH	Broadcast Control Channel
BCH	Broadcast Channel
BEM	Block Edge Masks
BM-SC	Broadcast-Multicast Service Center
BS	Base Station
BSR	Buffer Status Report
BW	Bandwidth
C/I	Carrier-to-Interference Power Ratio
CA	Certificate Authority
CAPEX	Capital Expenditure
CAZAC	Constant Amplitude Zero Auto-Correlation
CCCH	Common Control Channel
CCE	Control Channel Element
CDD	Cyclic Delay Diversity
CDF	Cumulative Distribution Function
CDMA	Code Division Multiple Access
CE	Carrier Ethernet
CEPT	The European Conference of Postal and Telecommunications Administrations
CM	Configuration Management
CMC	Connection Mobility Control
CMDB	Configuration Management Data Base

CN	Core Network
COMINF	Common O&M Infrastructure
CO-OP	Cooperative Open-OSS Project (interface also called Itf-P2P)
CORBA	Common Object Request Broker Architecture
CP	Cyclic Prefix
CP	Control Plane
CPC	Continous Packet Connectivity
C-plane	Control Plane
CQI	Channel Quality Indicator
CRC	Cyclic Redundancy Check
C-RNTI	Cell RNTI
CS	Circuit Switched
CSCF	Call Session Control Function
CSG	Closed Subscriber Group
CSV	Comma-Separated Values
CTR	Cell TRace
CW	Codeword
CW	Continuous-wave
DCCH	Dedicated Control Channel
DCH	Dedicated Channel
DCI	Downlink Control Information
DCN	Data Communication Network
DFT	Discrete Fourier Transform
DFT-S-OFDM	DTF Spread OFDM
DHCP	Dynamic Host Configuration Protocol
DL	Downlink
DL-SCH	Downlink Shared Channel
DNS	Domain Name Service
DRB	Data Radio Bearer
DRX	Discontinuous Reception
DSCP	Differentiated Services Code Point
DTCH	Dedicated Traffic Channel
DTX	Discontinuous Transmission
DwPTS	Downlink Pilot Time Slot
EBS	Event Based Statistics
ECC	Electronic Communications Committee
ECGI	E-UTRAN Cell Global Identifier
ECM	EPS Connection Management
E-DCH	Enhanced DCH
EHPLMN	Equivalent Home PLMN
EMEA	Europe, Middle East and Africa
EMM	EPS Mobility Management
eNB	E-UTRAN NodeB
eNode B	E-UTRAN NodeB
EPC	Ericsson Policy Control
EPC	Evolved Packet Core
EPS	Evolved Packet System (E-UTRAN and EPC)
E-RAB	E-UTRAN Radio Access Bearer
ETSI	European Telecommunications Standards Institute

ETWS	Earth Quake and Tsunami Warning System
E-UTRA	Evolved UTRA
E-UTRAN	Evolved UTRAN, used as synonym for LTE in the document.
EV-DO	Evolution - Data Optimized
EVM	Error Vector Magnitude
FCC	Federal Communications Commission
FDD	Frequency Division Duplex
FDM	Frequency Division Multiplexing
FDMA	Frequency Division Multiple Access
FEC	Forward Error Correction
FFS	For Further Study
FFT	Fast Fourier Transform
FM	Fault Management
FMX	Fault Management Expert
FQDN	Fully Qualified Domain Name
FS	Frame Structure
FTP	File Transfer Protocol
GBR	Guaranteed Bit Rate
GCL	Generalized Chirp Like
GE	Gigabit Ethernet
GERAN	GSM EDGE Radio Access Network
GGSN	Gateway GPRS Support Node
GMPLS	Generalized Multi-Protocol Label Switching
GNSS	Global Navigation Satellite System
GP	Guard Period
GPRS	General Packet Radio Service
GSM	Global System for Mobile communication
GTP	GPRS Tunneling Protocol
GTP-C	GTP Control
GTP-U	GTP User Data Tunneling
GUI	Graphical user Interface
GUTI	Globally Unique Temporary Identifier
GW	Gateway
HA-CS	High Availability Cluster Solution
HARQ	Hybrid ARQ
HO	Handover
HOM	Higher Order Modulation
HPLMN	Home PLMN
HRPD	High Rate Packet Data
HSDPA	High Speed Downlink Packet Access
HS-DSCH	High Speed Downlink Shared Channel
HSPA	High Speed Packet Access
HSS	Home Subscriber Server
HSUPA	High Speed Uplink Packet Access
HTTP	Hypertext Transfer Protocol
HW	Hardware
IASA	Inter-Access Anchor
ICIC	Inter-Cell Interference Coordination
I-CSCF	Interrogating CSCF

ID	Identifier
IEEE	Institute of Electrical and Electronics Engineers
IETF	Internet Engineering Task Force
IFFT	Inverse FFT
IMEI	International Mobile Equipment Identity
IMS	IP Multimedia Telephony
IMS	IP Multimedia subsystem
IMSI	Individual Mobile Subscriber Identity
IMT	International Mobile Telecommunications
IP	Internet Protocol
IRAT	Inter Radio Access Technology
IS	Integrated Site
ITU	International Telecommunications Union
ITU-R	ITU Radio communication Sector
JSR	Java Specification Request
KPI	Key Performance Indicator
LB	Load Balancing
LCID	Logical Channel ID
LCR	Low Chip Rate
LCR-TDD	Low Chip Rate TDD
LDC	Linear Dispersion Code
LDPC	Low-Density Parity-check Code
LED	Light Emitting Diode
LTE	Long Term Evolution, used as synonym for E-UTRAN in the document.
MAC	Medium Access Control
MBA	Management Based Activation
MBMS	Multimedia Broadcast Multicast Service
MBR	Maximum Bit Rate
MBSFN	Multicast Broadcast Single Frequency Network
MCCH	Multicast Control Channel
MCE	Multi-cell/multicast Coordination Entity
MCH	Multicast Channel
MCS	Modulation and Coding Scheme
MEF	Mobile Entertainment Forum
MGC	Media Gateway Controller
MGW	Media Gateway
MIB	Master Information Block
MIB	Management Information Base
MIMO	Multiple Input Multiple Output
ML-PPP	Multilink point to point protocol
MM	Multi Mediation
MM	Mobility Management
MME	Mobility Management Entity
MMS	Multimedia Messaging Service Managed Objects interface (MOCI)
MMTel	Multi Media Telephony
MOCI	Managed Object Configuration Interface
MOP	Maximum Output Power
MPLS	Multiple Protocol Label Switching
MPR	Maximum Power Reduction

MS	Management Services
MSAP	MCH Subframe Allocation Pattern
MTAS	Multimedia Telephony Application Server
MTCH	Multicast Traffic Channel
MU-MIMO	Multiple User-MIMO
mUPE	MBMS UPE
NACK	Negative Acknowledgement
NAS	Non-Access Stratum
NCC	Network Color Code
NCL	Neighbour Cell List
NCLI	Node Command Line Interface
NCS	Neighbouring Cell Support
NE	Network Element
NEM	Network Element Manager
NGMN	Next Generation Mobile Networks
NGSA	Next Generation Service Assurance
NH	Next Hop Key
NM	Network Management
NMS	Network Management System
NMX	Network level deployment of expert rules
NOC	Network Operations Center
NR	Neighbor cell Relation
NRT	Non Real Time
N-SBG	Network SBG
O&M	Operation and Maintenance
OAM	Operations Administration and Management
OFDM	Orthogonal Frequency Division Multiplexing
OFDMA	Orthogonal Frequency Division Multiple Access
OMC	Operation and Maintenance Center
OOB	Out Of Band
OPEX	Operating Expenditures
OSS	Operation and Support System
OSS-RC	Operation and Support System Radio and Core
OTN	Operator Terminal Network
P(N)CCH	Paging (and Notification) Control Channel
P2P	Peer-to-Peer
PA	Power Amplifier
PAPR	Peak to Average Power Ratio
PAR	Peak to Average Ratio
PARC	Per Antenna Rate Control
PBBTE	Provider Backbone Bridge Traffic Engineering
PBC	Power and Battery Cabinet
PBCH	Physical Broadcast CHannel
PBN	Packet Backbone Network
PBR	Prioritised Bit Rate
PCC	Policy Charging Control
PCCH	Paging Control Channel
PCEF	Policy Charging Enforcement Function
PCFICH	Physical Control Format Indicator CHannel

PCH	Paging Channel
PCI	Physical Cell ID
PCRF	Policy Control and Charging Rules Function
P-CSCF	Proxy - Call Session Control Function
PDCCH	Physical Downlink Control CHannel
PDCP	Packet Data Convergence Protocol
PDN	Packet Data Network
PDP	Packet Data Protocol
PDSCH	Physical Downlink Shared CHannel
PDU	Protocol Data Unit
P-GW	PDN Gateway
PHICH	Physical Hybrid ARQ Indicator CHannel
PHR	Power Headroom Report
PHS	Personal Handy-phone System
PHY	Physical layer
PLMN	Public Land Mobile Network
PM	Performance Management
PMCH	Physical Multicast CHannel
PMI	Precoder Matrix Indicator
PMIP	Proxy Mobile IP
PnP	Plug and Play
PoP	Point of Presence
PRACH	Physical Random Access CHannel
PRB	Physical Resource Block
P-RNTI	Paging RNTI
PS	Packet Switched
PSC	Packet Scheduling
P-SCH	Primary Synchronization Channel
PSK	Pre-Shared Keys
PSTN	Public Switched Telephone Network
PTT	Push to Talk
PUCCH	Physical Uplink Control CHannel
PUSCH	Physical Uplink Shared Channel
QAM	Quadrature Amplitude Modulation
QCI	QoS Class Identifier
QoS	Quality of Service
QPP	Quadrature Permutation Polynomial
QPSK	Quadrature Phase Shift Keying
RA	Random Access
RA	Registration Authority
RAC	Radio Admission Control
RACH	Random Access Channel
RAN	Radio Access Network
RANAP	RAN Application Part
RA-RNTI	Random Access RNTI
RAT	Radio Access Technology
RB	Radio Bearer
RB	Resource Block
RBC	Radio Bearer Control

RBG	Radio Bearer Group
RBS	Radio Base Station
RET	Remote Electrical Tilt
RF	Radio Frequency
RFC	Request For Comment
RI	Rank Indicator
RLC	Radio Link Control
RM	Rate Matching
RNC	Radio Network Controller
RNL	Radio Network Layer
RNTI	Radio Network Temporary Identifier
ROHC	Robust Header Compression
ROP	Recording Output Periods
RPLMN	Registered PLMN
RRC	Radio Resource Control
RRM	Radio Resource Management
RRU	Radio Remote Unit
RS	Reference Symbols
RS	Reference Signal
RSN	Retransmission SN
RT	Real Time
RTCP	RTP Control Protocol
RTP	Real Time Transport Protocol
RTSP	Real Time Streaming Protocol
RU	Resource Unit
RX	Receiver
S1-MME	S1 for the control plane
S1-U	S1 for the user plane
SAE	System Architecture Evolution
SAP	Service Access Point
SB	Scheduling Block
SBC	Session Border Controller
SBG	Session Border Gateway
SCCH	Shared Control Channel
SCCP	Signaling Connection Control Part
SCEP	Simple Certificate Enrolment Protocol
SC-FDMA	Single Carrier – Frequency Division Multiple Access
SCH	Synchronization Channel
S-CSCF	Serving CSCF
SCTP	Streaming Control Transmission Protocol
SDF	Service Data Flow
SDH	Synchronous Digital Hierarchy
SDMA	Spatial Division Multiple Access
SDP	Session Description Protocol
SDU	Service Data Unit
SeGW	Security Gateway
SEM	Spectrum Emission Mask
SFN	System Frame Number
SFP	Small Form factor Pluggable

S-FTP	Secure File transfer protocol
SGSN	Serving GPRS Support Node
S-GW	Serving Gateway
SI	System Information
SIB	System Information Block
SINR	Signal to Interference and Noise Ratio
SIP	Session Initiation Protocol
SIR	Signal to Interference Ratio
SI-RNTI	System Info RNTI
SISO	Single Input Single Output
SLA	Service Level Agreement
SLO	Service Level Objectives
SM	Session Management
SMO	Software Manager Organizer
SMRS	Software Management Repository
SMS	Short Message Service
SN	Sequence Number
SNF	Service Network Framework
SNR	Signal to Noise Ratio
SON	Self Organizing Networks
SOX	Simple Outline XML
S-PARC	Selective PARC
SPID	Subscriber Profile ID for RAT/Frequency Priority
SQL	Structured Query Language
SR	Scheduling Request
SRB	Signaling Radio Bearer
S-SCH	Secondary Synchronization Channel
SSH	Secure Shell
SSL	Secure Sockets Layer
SSLIOP	IIOP over SSL
S-TMSI	SAE-TMSI
SU	Scheduling Unit
SU-MIMO	Single-User MIMO
SW	Soft Ware
TA	Tracking Area
TAS	Telephony Application Server
TAU	Tracking Area Update
TB	Transport Block
TBD	To Be Decided
TCP	Transmission Control Protocol
TDD	Time Division Duplex
TFCI	Transport Format Combination Indicator
TFP	Traffic Forwarding Policy
TFT	Traffic Flow Template
TLP	TEMS LinkPlanner
TM	Transparent Mode
TMA	Tower Mounted Amplifier
TMO	T-Mobile International AG
TMSI	Temporary Mobile Subscriber Identity

TNL	Transport Network Layer
TSP	Ericsson Telecom Server Platform
TTI	Transmission Time Interval
TX	Transmit
UCI	Uplink Control Information
UE	User Equipment
UETR	UE TRace
UL	Uplink
UL-SCH	Uplink Shared Channel
UM	Unacknowledged Mode
UMTS	Universal Mobile Telecommunication System
UP	User Plane
UPE	User Plane Entity
U-plane	User plane
UpPTS	Uplink Pilot Time Slot
URA	UTRAN Routing Area
UTRA	UMTS Terrestrial Radio Access
UTRAN	UMTS Terrestrial Radio Access Network
VoIP	Voice over IP
VPLMN	Visited PLMN
VRB	Virtual Resource Block
WAP	Wireless Access Protocol
WAPECS	Wireless Access Policy for Electronic Communications Services
WCDMA	Wideband Code Division Multiple Access
WDM	Wavelength Division Multiplexing
X2-C	X2-Control plane
X2-U	X2-User plane
XML	Extensible Markup Language

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