1

LTE and LTE-A Overview

1.1 Introduction

Cellular mobile networks have been evolving for many years. As the smartphone market has expanded significantly in recent years and is expected to grow more in the years to come, network evolution needs to keep up with the pace of users' demands. This chapter provides an overview for network operators and interested others on the evolution of cellular networks, with particular focus on 3GPP for the main technologies of WCDMA/UMTS and LTE. In addition, it highlights the interaction of 3GPP with non-3GPP technology (i.e. Wi-Fi).

The initial networks are referred to collectively as the First Generation (1G) system. The 1G mobile system was designed to utilize analog; it included AMPS (Advanced Mobile Telephone System). The Second Generation (2G) mobile system was developed to utilize digital multiple access technology: TDMA (Time Division Multiple Access) and CDMA (Code Division Multiple Access). The main 2G networks were GSM (Global System for Mobile communications) and CDMA, also known as cdmaOne or IS-95 (Interim Standard 95). The GSM system still has worldwide support and is available for deployment on several frequency bands, such as 900 MHz, 1800 MHz, 850 MHz, and 1900 MHz. CDMA systems in 2G networks use a spread-spectrum technique and utilize a mixture of codes and timing to identify cells and channels. In addition to being digital and improving capacity and security, these digital 2G systems also offer enhanced services such as SMS (Short Message Service) and circuit-switched data. Different variations of the 2G technology have evolved to extend the support of efficient packet data services and to increase the data rates. GPRS (General Packet Radio System) and EDGE (Enhanced Data Rates for Global Evolution) systems have evolved from GSM. The theoretical data rate of 473.6 kbps enables operators to offer multimedia services efficiently. Since it does not comply with all the features of a 3G system, EDGE is usually categorized as 2.75G.

The Third Generation (3G) system is defined by IMT2000 (International Mobile Telecommunications). IMT2000 requires a 3G system to provide higher transmission rates in the range of 2 Mbps for stationary use and 348 kbps under mobile conditions. The main 3G technologies are [1]:

WCDMA (Wideband CDMA): This was developed by the 3GPP (Third Generation Partnership Project). WCDMA is the air interface of the 3G UMTS (Universal Mobile Telecommunications System). The UMTS system has been deployed based on the existing GSM communication core network (CN) but with a new radio access technology in the form of WCDMA. Its radio access is based on FDD (Frequency Division Duplex). Current deployments are mainly in 2.1 GHz bands. Deployments at lower frequencies are also possible, such as UMTS900. UMTS supports voice and multimedia services.

TD-CDMA (Time Division CDMA): This is typically referred to as UMTS TDD (Time Division Duplex) and is part of the UMTS specifications. The system utilizes a combination of CDMA and TDMA to enable efficient allocation of resources.

TD-SCDMA (Time Division Synchronous CDMA): This has links to the UMTS specifications and is often identified as UMTS-TDD Low Chip Rate. Like TD-CDMA, it is also best suited to low-mobility scenarios in micro or pico cells.

CDMA2000 (C2K): This is a multi-carrier technology standard which uses CDMA. It is part of the 3GPP2 standardization body. CDMA2000 is a set of standards including CDMA2000 EV-DO (Evolution-Data Optimized) which has various revisions. It is backward compatible with cdmaOne.

WiMAX (Worldwide Interoperability for Microwave Access): This is another wireless technology which satisfies IMT2000 3G requirements. The air interface is part of the IEEE (Institute of Electrical and Electronics Engineers) 802.16 standard, which originally defined PTP (Point-To-Point) and PTM (Point-To-Multipoint) systems. This was later enhanced to address multiple

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issues related to a user's mobility. The WiMAX Forum is the organization formed to promote interoperability between vendors.

Fourth Generation (4G) cellular wireless systems have been introduced as the latest version of mobile technologies. 4G technology is defined as meeting the requirements set by the ITU (International Telecommunication Union) as part of IMT Advanced (International Mobile Telecommunications Advanced).

The main drivers for the network architecture evolution in 4G systems are: all-IP based, reduced network cost, reduced data latencies and signaling load, interworking mobility among other access networks in 3GPP and non-3GPP, always-on user experience with flexible Quality of Service (QoS) support, and worldwide roaming capability. 4G systems include different access technologies:

LTE and LTE-Advanced (Long Term Evolution): This is part of 3GPP. LTE, as it stands now, does not meet all IMT Advanced features. However, LTE-Advanced is part of a later 3GPP release and has been designed specifically to meet 4G requirements.

WiMAX 802.16m: The IEEE and the WiMAX Forum have identified 802.16m as the main technology for a 4G WiMAX system.

UMB (Ultra Mobile Broadband): This is identified as EV-DO Rev C. It is part of 3GPP2. Most vendors and network operators have decided to promote LTE instead.

The evolution and roadmap for 3GPP 3G and 4G are illustrated in Figure 1.1.

The standardization in 3GPP Release 8 defines the first specifications of LTE. The Evolved Packet System (EPS) is defined, mandating the key features and components of both the radio access network (E-UTRAN) and the core network (Evolved Packet Core, EPC). Orthogonal Frequency Division Multiplexing (OFDM) is defined as the air interface, with the ability to support multi-layer data streams using Multiple-Input, Multiple-Output (MIMO) antenna systems to increase spectral efficiency. LTE is defined as an all-IP network topology differentiated over the legacy circuit switch (CS) domain. However, Release 8 specification makes use of the CS domain to maintain compatibility with 2G and 3G systems by utilizing the voice calls Circuit-Switch Fallback (CSFB) technique for any of those systems. Other significant aspects defined in this initial 3GPP release are Self-Organizing Networks (SONs) and Home Base Stations (Home eNodeBs), aiming to revolutionize heterogeneous networks. Moreover, Release 8 provides techniques for smartphone battery saving, known as Connected-mode Discontinuous Reception (C-DRX).

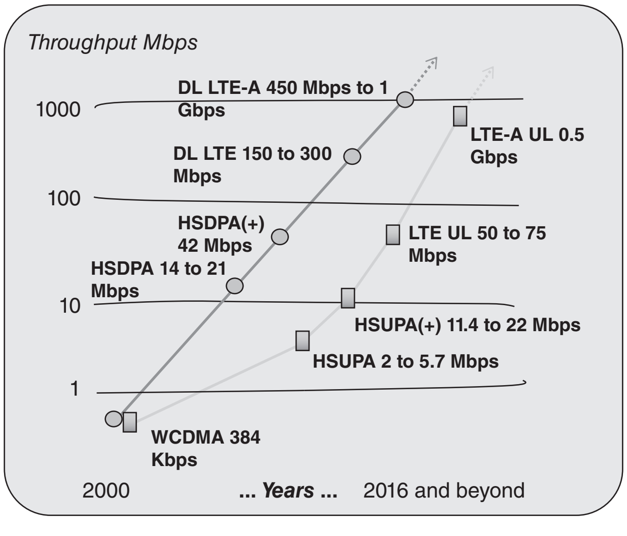


Figure 1.1 3G and 4G roadmap and evolution.

LTE Release 9 provides improvements to Release 8 standards, most notably enabling improved network throughput by refining SONs and improving eNodeB (eNB) mobility. Additional MIMO flexibility is introduced with multi-layer beamforming. Furthermore, CSFB improvements have been introduced to reduce voice call-setup time delays.

The International Telecommunication Union (ITU) has created the term IMT-Advanced (International Mobile Telecommunications-Advanced) to identify mobile systems whose capabilities go beyond those of IMT2000. In order to meet this new challenge, 3GPP's partners have agreed to expand specification scope to include the development of systems beyond 3G's capabilities. Some of the key features of IMT-Advanced are: worldwide functionality and roaming, compatibility of services, interworking with other radio access systems, and enhanced peak data rates to support advanced services and applications with a nominal speed of 100 Mbps for high mobility and 1 Gbps for low-mobility users.

Release 10 defines LTE-Advanced (LTE-A) as the first standard release that meets the ITU's requirements for Fourth Generation, 4G. The increased data rates up to 1 Gbps in the downlink and 500 Mbps in the uplink are enabled through the use of scalable and flexible bandwidth allocations up to 100 MHz, known as Carrier Aggregation (CA). Additionally, improved MIMO operations have been introduced to provide higher spectral efficiency. The support for heterogeneous networks and relays added to this 3GPP release also improves capacity and coverage. Lastly, a seamless interoperation of LTE and WLAN networks is defined to support traffic offload concepts.

Release 11 continues the evolution towards the LTE-A requirements. Enhanced interference cancellation and CoMP (Coordinated Multi-Point transmission)

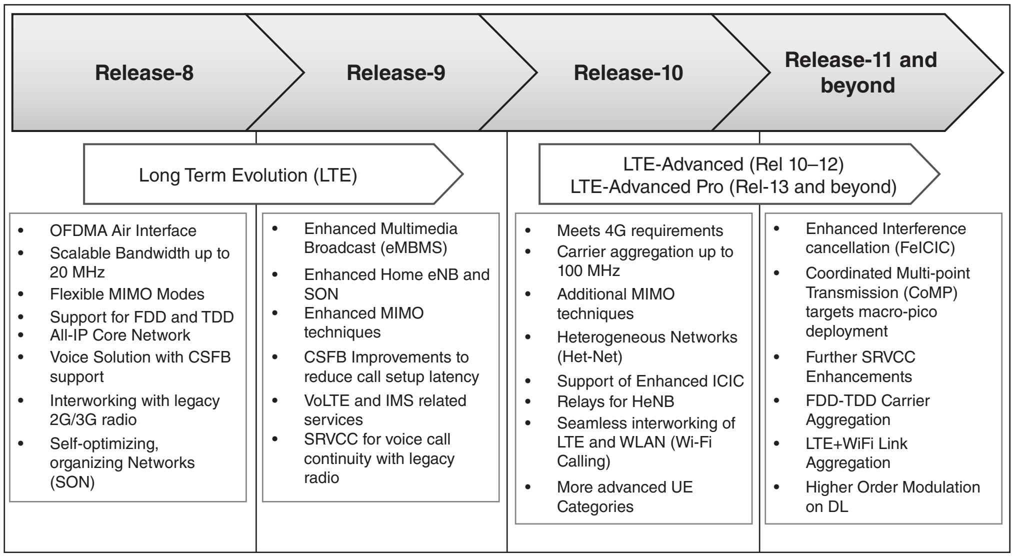


Figure 1.2 3GPP LTE releases.

are means for further improving the capacity in 4G networks.

Key features of 3GPP LTE releases are outlined in Figure 1.2.

1.2 Link Spectrum Efficiency

The Shannon–Hartley theorem states the channel capacity, meaning the theoretical tightest upper bound on the information data rate that can be sent with a given average signal power through a communication channel subject to noise of power:

$$C = B \log_2 \left(1 + \frac{S}{N}\right) \tag{1.1}$$

where

C	is the channel capacity in bits per second
B	is the bandwidth of the channel in hertz
S	is the average received signal power over the bandwidth, measured in watts
N	is the average noise or interference power over the bandwidth, measured in watts
S/N	is the signal-to-noise ratio (SNR)

Therefore, channel capacity is proportional to the bandwidth of the channel and to the logarithm of the SNR. This means that channel capacity can be increased linearly either by increasing the channel bandwidth given a fixed SNR requirement or, with fixed bandwidth, by using higher-order modulations that need a very high SNR to operate.

Spectral efficiency refers to the information rate that can be transmitted over a given bandwidth in a specific communication system, measured in bits/sec/Hz

As mentioned above, the LTE targets higher capacity by using fixed and high bandwidth in a cell and using higher-order modulations that need high SNR to operate, which is achieved by using different MIMO techniques.

As the modulation rate increases, the spectral efficiency improves, but at the cost of the SNR requirement, which makes LTE scalable at different radio conditions.

Then, the spectral efficiency can be defined as follows:

Efficiency = the number of information bits/the total number of symbols.

The number of information bits + parity bits = total number of bits = total number of symbols * modulation order:

$$\text{Spectral efficiency} = \text{Coded bit rate} * \text{Modulation order} \tag{1.2}$$

For example, with LTE, CQI index 1, QPSK, a modulation order of 2, code rate $= 78/1024 = 0.0762$, efficiency $= 0.1523 = 0.0762 * 2$. More specifically, $78/1024 = 0.076$ is the ratio of the information symbols (78) to the total number of symbols (1024). Then, the efficiency is equal to 0.076 * 2 (QPSK modulation, one symbol occupies two information bits)= 0.152. Modulation order = 2 (QPSK), 4 (16QAM), 6 (64QAM). Table 1.1 summarizes the different values of CQI, code rate, and modulation, and the corresponding efficiencies [1].

Table 1.1 Spectrum efficiencies of the LTE system.

LTE CQI	Code Rate	Modulation	Efficiency
1	0.08	2	0.1523
2	0.12	2	0.2344
3	0.19	2	0.3770
4	0.30	2	0.6016
5	0.44	2	0.8770
6	0.59	2	1.1758
7	0.37	4	1.4766
8	0.48	4	1.9141
9	0.60	4	2.4063
10	0.46	6	2.7305
11	0.55	6	3.3223
12	0.65	6	3.9023
13	0.75	6	4.5234
14	0.85	6	5.1152
15	0.93	6	5.5547

1.3 LTE-Advanced and Beyond

The International Telecommunication Union (ITU) has created the term IMT-Advanced to identify mobile systems whose capabilities go beyond those of IMT2000. Table 1.2 provides the IMT-Advanced requirements.

In order to meet this new challenge, 3GPP's partners have agreed to expand the specification scope to include the development of systems beyond 3G's capabilities. Some of the key features of IMT-Advanced are: worldwide functionality and roaming, compatibility of services, interworking with other radio access systems, and enhanced peak data rates to support advanced services and applications with a nominal speed of 100 Mbps for high mobility and 1 Gbps for low-mobility users.

Table 1.2 IMT-Advanced requirements.

Requirements	IMT-Advanced
Spectrum bandwidth	40 MHz
Downlink peak spectrum efficiency	15 bps/Hz (4 streams)
Uplink peak spectrum efficiency	6.75 bps/Hz (2 streams)
Control plane latency	< 100 ms
User plane latency	< 10 ms

Where:
Peak spectrum efficiency is defined in 3GPP as the highest theoretical data rate normalized by the spectrum bandwidth.
Control plane latency is defined in 3GPP as the transition time from Idle mode to Connected mode.
User plane latency is defined in 3GPP as the one-way transit time in RAN for a packet being available at the IP layer.

The requirements for further advancements for Evolved Universal Terrestrial Radio Access E-UTRA (LTE-Advanced) are defined in TR 36.913. The reports that include the requirements of IMT-Advanced and the basis for evaluation criteria were approved in an ITU-R (International Telecommunication Union) Study Group 5 meeting in November 2008. LTE-Advanced targets are provided in Table 1.3. Therefore, LTE-A naturally meets the ITU requirements for IMT-Advanced.

Average spectrum efficiency is defined as the aggregate throughput of all users normalized by bandwidth and divided by the number of cells. This requirement is essential for operators in terms of capacity and cost per bit. Cell edge user throughput is defined as the 5% point of CDF of average user throughput normalized by bandwidth, assuming ten users in a cell. Average and cell-edge requirements are summarized in Table 1.4. Base coverage urban (shown in bold font in the table) is used as a benchmark, which is a similar model to 3GPP "Case 1" (see ITU-R IMT.EVAL).

In order to support higher peak data rates in the uplink and downlink, LTE-Advanced improved many of the features introduced in Release 8 and Release 9 and introduced new features such as carrier aggregation, enhanced Inter-Cell Interference Coordination (eICIC) for HetNets, and relay nodes. Carrier aggregation extends the maximum bandwidth in the downlink/uplink by aggregating two to five carriers. Each carrier to be aggregated is referred to as a Component Carrier (CC). Since Release 8 carriers have a maximum bandwidth of 20 MHz, CA allows for a maximum transmission bandwidth of 100 MHz (5 × 20 MHz). A pre-Release 10 UE can access

Table 1.3 LTE-Advanced targets versus LTE targets.

Requirements	LTE Targets	LTE-A Targets
Spectrum bandwidth	1.4–20 MHz	Wider than LTE, e.g. 100 MHz
Downlink peak data rate	300 Mbps	1 Gbps
Downlink peak spectrum efficiency	15 bps/Hz (4 streams)	30 bps/Hz (8 streams)
Uplink peak data rate	75 Mbps	500 Mbps
Uplink peak spectrum efficiency	3.75 bps/Hz (1 stream)	15 bps/Hz (4 streams)
Control plane latency	< 100 ms	<50 ms
User plane latency	5 ms	5 ms

Table 1.4 Average and cell-edge requirements.

Scenario	Downlink and Uplink	Antenna Configuration	LTE Targets [a)]	LTE-A Targets [a)]	IMT-Advanced [b)]
Average spectrum efficiency (bit/s/Hz/cell)	DL	2 × 2	1.69	2.4	—
		4 × 2	1.87	2.6	[3, 2.6, **2.2**, 1.1]
		4 × 4	2.67	3.7	—
	UL	1 × 2	0.74	1.2	—
		2 × 4	—	2.0	[2.25, 1.8, **1.4**, 0.7]
Cell-edge user spectrum efficiency (bit/s/Hz)	DL	2 × 2	0.05	0.07	—
		4 × 2	0.06	0.09	[0.1, 0.075, **0.06**, 0.04]
		4 × 4	0.08	0.12	—
	UL	1 × 2	0.024	0.04	—
		2 × 4	—	0.07	[0.07, 0.05, **0.03**, 0.015]

a) Based on radio environment of "Case 1": Inter-cell distance: 500 m, carrier frequency: 2 GHz, bandwidth: 10 MHz, DL Tx power: 46 dBm, penetration loss: 20 dB: mobility speed: 3 km/h (see 3GPP TR 25.814).

b) [Indoor, Microcellular, Base coverage urban, High speed].

one of the component carriers, while CA-capable UEs can operate with multiple component carriers. The CCs can be of the same or different bandwidths, adjacent or non-adjacent CCs in the same or different frequency band, or CCs in different frequency bands. Carrier aggregation can also benefit from both TDD and FDD joint operation. Enhanced MIMO provides higher spatial gains, increased peak data rates, higher spectral efficiency, and increased capacity.

The main goal of heterogeneous networks is to manage traffic between macro and small cell networks. Controlling the interference scenarios within these heterogeneous networks due to different power levels of macro and small cells can be managed with features such as ICIC/eICIC/feICIC and CoMP (Coordinated Multi-Point transmission), which further improve capacity at cell edges.

The Release 8 specification makes use of the CS domain to maintain compatibility with 2G and 3G systems by utilizing the voice calls circuit-switch fallback (CSFB) technique for any of those systems. As LTE has evolved into an all-IP network and IMS implementation has matured, Voice over IP over LTE has been implemented to carry voice packets natively over the LTE network. At an LTE cell edge, the ability to fall back into a circuit-switched network is possible with features such as Single Radio Voice Continuity (SR-VCC). Figure 1.3 summarizes the key features for LTE and LTE-Advanced [1].

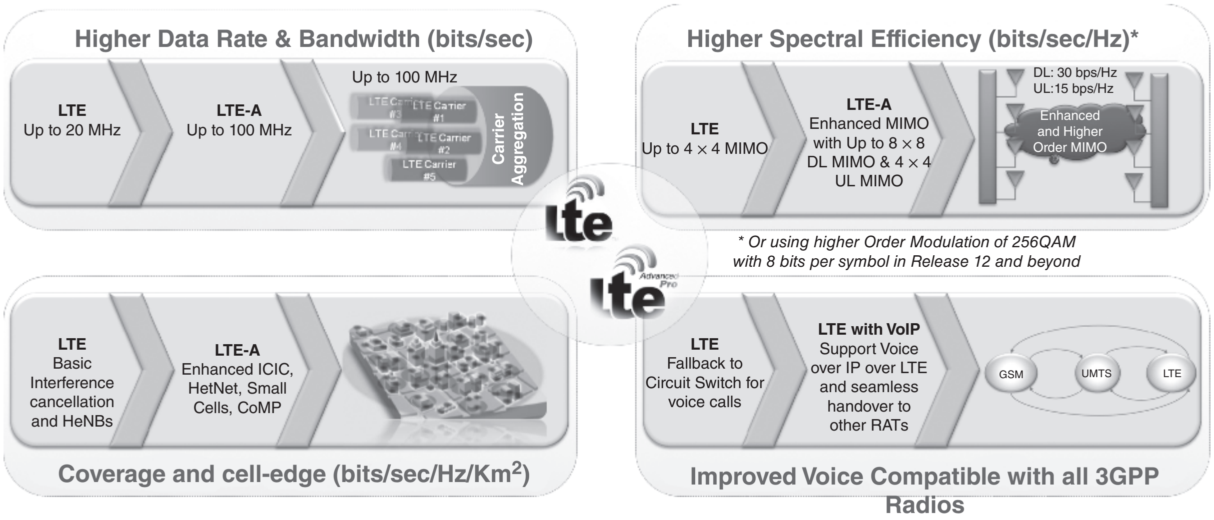


Figure 1.3 Key features for LTE and LTE-Advanced.

1.3.1 LTE and Wi-Fi

There is plenty of spectrum in the 5 GHz band, which is especially suited to small-cell deployments. For the last few years, Wi-Fi has been actively used to offload cellular traffic, and several operators are using it as part of mobile plans. The idea of LTE/Wi-Fi aggregation arose so that smartphones could receive data from a cellular network and a Wi-Fi network at the same time. Therefore, different phases for increasing carrier aggregation in the 5 GHz band have been studied in 3GPP to utilize 5 GHz solely for LTE or jointly with Wi-Fi. The amount of spectrum available in the 5 GHz band per region is summarized in Table 1.5.

The two main options for LTE to use the 5 GHz band are as follows:

LAA (Licensed Assisted Access): A standalone LTE operation in unlicensed spectrum. Several challenges occur with this implementation. In particular, there is a need for eNB and access points (AP) to be collocated, which requires new devices. This would allow operators to benefit from the additional capacity available from the unlicensed spectrum, particularly in hotspots and corporate environments. With LAA, the extra spectrum resource, especially on the 5 GHz frequency band, can complement licensed-band LTE operation to provide additional data plane performance. The use of this technology has prompted regulators to study the feasibility of this deployment and the impact of LTE on Wi-Fi spectrum. However, it is expected that the feature will gain strong momentum in the upcoming years, especially as it brings a substantial capacity boost from the unlicensed band, if it is proven that the quality of service for the end user is not impacted by the interference situation between the two bands.

Table 1.5 5 GHz available spectrum per region.

Region	Estimated Bandwidth Available (MHz)
America	580
Europe and Japan	455
China	325

LWA (LTE–Wi-Fi Aggregation): Dual connectivity between LTE and Wi-Fi. LWA can be enabled at the radio level and can split the data plane traffic so that some LTE traffic is tunneled over Wi-Fi and the rest runs over LTE. The Wi-Fi data rate can go up to 867 Mbps in 802.11ac and the LTE currently being deployed with 300 to 450 Mbps (two- or three-carrier aggregation), and when both are aggregated, the total aggregated throughput can go beyond 1 Gbps. This is, in some networks, called Giga LTE (G-LTE).

LAA and LWA are summarized in Figure 1.4, and comparisons are provided in Table 1.6.

Other forms of LTE/Wi-Fi aggregation are Multi-Path TCP (MPTCP) and a simple HTTP range retrieval request, but neither is necessarily 3GPP standardized:

Multi-Path TCP (MPTCP): TCP subflows are created for each different network. Flow control is operated for each subflow. The advantages of this method are good aggregation performance and the ease of configuration in the network (it may require a proxy server to apply multiple kinds of services which are non-MPTCP capable). An MPTCP scheduler selects a path for each packet based on the network condition. Each subflow controls each congestion window size and the packet loss on one network does not affect the quality of other networks. The disadvantage of this implementation is that not all kinds of applications can benefit from it, especially UDP-type applications.

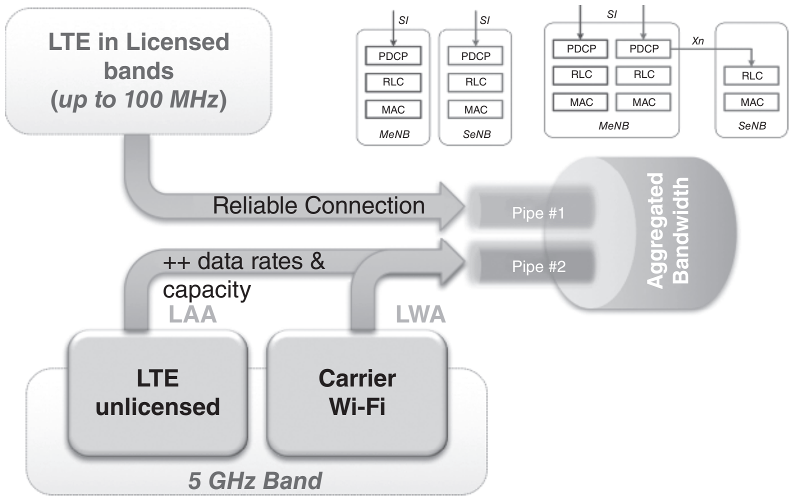


Figure 1.4 LTE with LAA and LWA.

Table 1.6 LAA versus LWA.

Targets	LAA (Licensed Assisted Access)			LWA (LTE–Wi-Fi Aggregation)
3GPP	R10 based	R13	R14	R13
Unlicensed physical layer	Uses LTE on 5 GHz band for higher data rates			Uses Wi-Fi on 5 GHz band for higher data rates
Deployment	Collocated or through backhaul		Collocated or dual-connectivity	Dual-connectivity
Listen before Talk (LBT)	eNodeB Best effort	eNodeB New design	UE listen before talk	802.11
Regulation	LBT not needed in US, Korea, China	LBT needed in Europe and Japan	UE listen before talk fully complied	Wi-Fi widely accepted

HTTP range retrieval request: A client on a device requests half of some data be sent to one network and the rest to another network. This implementation is considered a quick implementation that does not require modification on the device side, but it is only applicable to HTTP traffic.

1.3.2 Wi-Fi Calling

Voice over Wi-Fi is becoming an integral part of the evolution of VoIP in general. One of the advantages set for VoWiFi is its seamless handover with LTE and potentially with CS networks (3G/2G). This is because the 3GPP defines interfaces between the LTE core network (EPS) and the Wi-Fi core network.

The benefits of VoWiFi are as follows:

Wi-Fi is a long-living ecosystem: Smartphone users are still comfortable using Wi-Fi; Wi-Fi is already carrying the bulk of smartphone data consumption and is easy to deploy in Wi-Fi hotspots.

It complements LTE services: Once IMS is being invested in, VoWiFi will be easy to integrate. VoLTE and VoWiFi can work together over EPC. There is added value in cases where VoLTE coverage is not continuous.

There is significant business potential: VoWiFi helps to solve the challenge of indoor access for mobile users when it can extend the coverage over LTE and 2G/3G networks. It also reduces or eliminates roaming costs because calls may be treated as being local.

It provides new service opportunities: Mobile operators need the offering of Wi-Fi services as a differentiator from over-the-top (OTT) clients. VoWiFi is now available to users almost exclusively from over-the-top (OTT) clients for smartphone users. Figure 1.5 illustrates VoWiFi for trusted and untrusted Wi-Fi networks.

We summarize the untrusted and trusted VoWiFi services as follows:

Untrusted access to EPC for VoWiFi services:

The device establishes a dedicated IPSec tunnel to an evolved Packet Data Gateway (ePDG) element located at the edge of the EPC.

The ePDG establishes a PMIPv6 or GTPv2 tunnel (i.e. on the S2b interface) to the P-GW in the EPC.

This IPSec tunnel transfers both signaling and media related to the operator services.

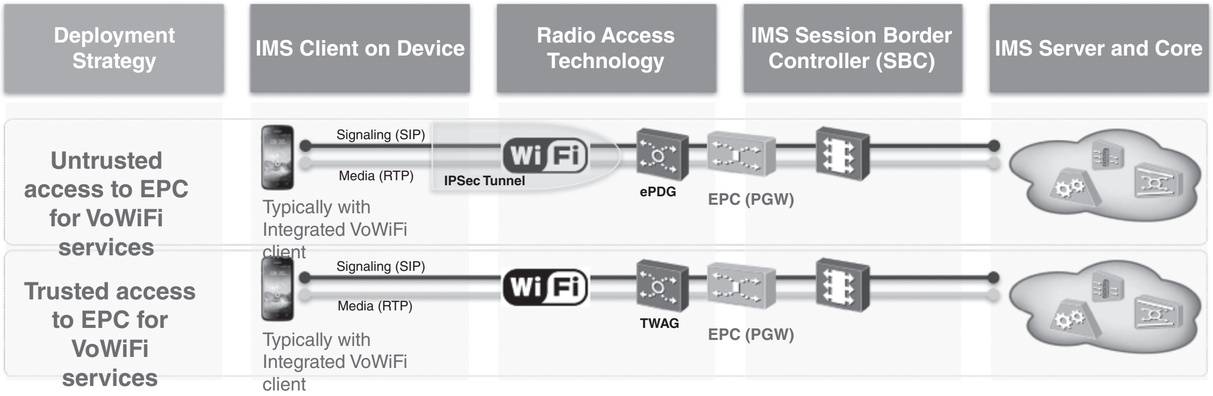


Figure 1.5 VoWiFi for trusted and untrusted 3GPP networks.

- Enables mobility between Wi-Fi and LTE access networks whether or not a call is in progress.
  - Mobility is performed at the EPC level, preserving the IP address allocated for the device.

Trusted access to EPC for VoWiFi services:

- Wi-Fi access points are connected to a Trusted WLAN Access Gateway (TWAG) network function that connects to EPC services via a standard interface (S2a interface).
- Supports multiple APN/PDN,
  - Allowing APN-specific traffic to be offloaded directly to the Internet without routing it to the EPC and only IMS APN is sent to the EPC.
- Enables mobility between Wi-Fi and LTE access networks.

EPC mobility scenarios could enable subsequent call continuity to CS networks with Single Radio Voice Continuity (eSRVCC), or directly to a CS network through Dual Radio VCC (DR-VCC). The VoWiFi deployment choice should address preferences such as the existing network architecture and interface (including security), mobility requirements, and device implementations.

1.3.2.1 QoS Challenges in VoWiFi

In 3GPP radio access (2G/3G/4G), the voice quality can be guaranteed to some extent, but Wi-Fi access brings new challenges:

- Wi-Fi is operating on unlicensed radio bands, which means that resources may not be allocated and higher interference can therefore be experienced.
- Multiple users and applications sharing the same Wi-Fi network cause congestion and potentially low-bandwidth broadband connectivity.
- Wi-Fi access to the operator voice core may be over ISP networks and therefore not managed by the 3GPP network operator.

Therefore, packet losses, jitter, or latency in the packet delivery can cause degradation of the voice quality. QoS architecture in Wi-Fi access is based on packet prioritization and not on resource reservations as in the case of VoLTE. It requires additional IP DSCP marking in the transport layer, and can be available with trusted/untrusted solutions only.

1.3.3 Internet of Things (IoT)

The transition to 5G has started and will continue until 2020. During the cellular evolution to 5G, aspects of the intermediate defining steps have become important. The Internet of Things (IoT) and the migration between multiple radio access technologies (3GPP and non-3GPP) are defining the path towards 5G.

The Internet of Things defines the method for intelligently connected devices and systems to leverage and exchange data between small devices and sensors in machines and objects. IoT concepts and working models have started to spread rapidly, which is expected to provide a new dimension for services that improve the quality of consumers' lives and the productivity of enterprises. The IoT effort started with the concept of machine-to-machine (M2M) solutions to use wireless networks to connect devices to each other and through the Internet, in order to deliver services that meet the needs of a wide range of industries. The IoT must deal with several challenges involving massive numbers of cheap devices providing low energy consumption and connected in a wider range, referred to as a Low-Power Wide Area (LPWA). Therefore, the IoT is typically classified into:

1) IoT connectivity in unlicensed spectrum.
2) Cellular IoT in licensed spectrum.

Many technologies are emerging to deal with these two categories, including:

- **Unlicensed networks:** For short-range scenarios, we have technologies such as Bluetooth Low Energy, Wi-Fi, IEEE802.11ah, IEEE802.15.4, ZigBee, and Z-wave. For long-range scenarios there are Sigfox, Weightless, OnRamp, LoRa, and ETSI LTN.
- **Cellular IoT in licensed spectrum:** LTE evolution for Machine-Type Communication (MTC), narrowband LTE, and the GSM evolution of IoT referred to as Extended-Coverage GSM (EC-GSM).

The main targets for low-power, wide-area (LPWA) networks are:

- Enhanced coverage (path loss ~164 dB).
- Very low power consumption (battery life > 10 years).
- Low data rate and high capacity core network (signaling and network entity optimization).
- Massive numbers of very low-cost devices.

We can summarize the IoT networks as follows:

- Wide area
  - Unlicensed spectrum LPWA (non-3GPP)
    - Sigfox (uplink only)
    - Semtech LoRa (uplink, downlink)
    - Neul Weightless
  - Licensed spectrum (3GPP but not C-IoT)
    - GSM (7B GSM connections today)
  - Short range in unlicensed spectrum
  - Bluetooth Low Energy, Wi-Fi, IEEE802.11ah, ZigBee, Z-Wave.

Some IoT technologies are based on standard protocols supported by industry alliances like the LoRa Alliance and Weightless SIG, some are based on proprietary protocols, and some are standards in progress. The forthcoming IoT networks under 3GPP can be summarized as follows:

- Cellular IoT in licensed spectrum
  - 3GPP eRAN (Release 12/13).
    - LTE evolution for MTC (machine-type communication).
      - Category 1 but it does not meet the IoT requirement (battery/cost/range).
      - Release 12 with Category 0.
      - Release 13 to meet LPWA requirement (Category M).
    - NB-CIoT and NB-LTE.
      - Will be evolved into NB-IoT as per latest 3GPP RAN meeting, and is expected to be released with 3GPP Release 13.
  - 3GPP GERAN (Release 13).
    - GSM evolution: upgrade of GSM by using one carrier for IoT with Extended-Coverage GSM (EC-GSM) is expected with 3GPP Release 13.

For the unlicensed networks, some of the highlighted technologies have already been deployed and meet the four factors for LPWA (long range, very low power, low data rate, and very low cost). . For 3GPP evolution of cellular IoT, the LTE-MTC is defined with the first version released with 3GPP Release 8 based on Category 1 but it does not meet the IoT requirement (battery/cost/range). This idea took an additional turn by providing a new Release 12 Category 0. The ongoing enhanced version (eMTC) is under evaluation in Release 13 to meet the LPWA requirement (i.e. Category M).

On the other hand, narrowband LTE introduces two underlying technologies being discussed in 2015/2016 3GPP Release 13: NB-CIoT and NB-LTE, where the main difference lies in the physical layer. It is expected that the two will merge and provide a final version referred to as NB-IoT. This technology is targeting three different modes such as utilizing the spectrum currently being used by GERAN systems as a replacement for one or more GSM carriers (standalone operation). The second mode utilizes the unused resource blocks within an LTE carrier's guard band (guard-band operation). The final mode utilizes resource blocks within a normal LTE carrier (in-band operation). The NB-IoT should support the following main objectives:

- 180 kHz UE RF bandwidth for both downlink and uplink.
- OFDMA on the downlink with either 15 kHz or 3.75 kHz subcarrier spacing.
- For the uplink, two options will be considered: FDMA with GMSK modulation, and SC-FDMA (including single-tone transmission as a special case of SC-FDMA).
- A single synchronization signal design for the different modes of operation, including techniques to handle overlap with legacy LTE signals while reducing the power consumption and latencies.
- Utilization of the existing LTE procedures and protocols and relevant optimizations to support the selected physical layer and core network interfaces targeting signaling reduction for small data transmissions.

EC-GSM has been introduced as cellular system support for ultra-low-complexity and low-throughput Internet of Things. It targets the following:

- **Re-using existing designs:** Only changing them when necessary to comply with the study item objectives; a reduction in functionality in the GERAN specification to minimize implementation effort and complexity.
- **Backward compatibility and co-existence with GSM:** Multiplexing traffic from legacy GSM devices and CIoT devices on the same physical channels. No impact on the radio units already deployed in the field. Speed the same as supported today (in normal coverage).
- **Achieving extended coverage:** Provide EC by using control channels with blind repetitions and data channels: blind repetitions of MCS-1 (lowest MCS in EGPRS) and HARQ retransmissions. EC has different coverage classes (CCs). The total number of blind transmissions for a given CC can differ between different logical channels.

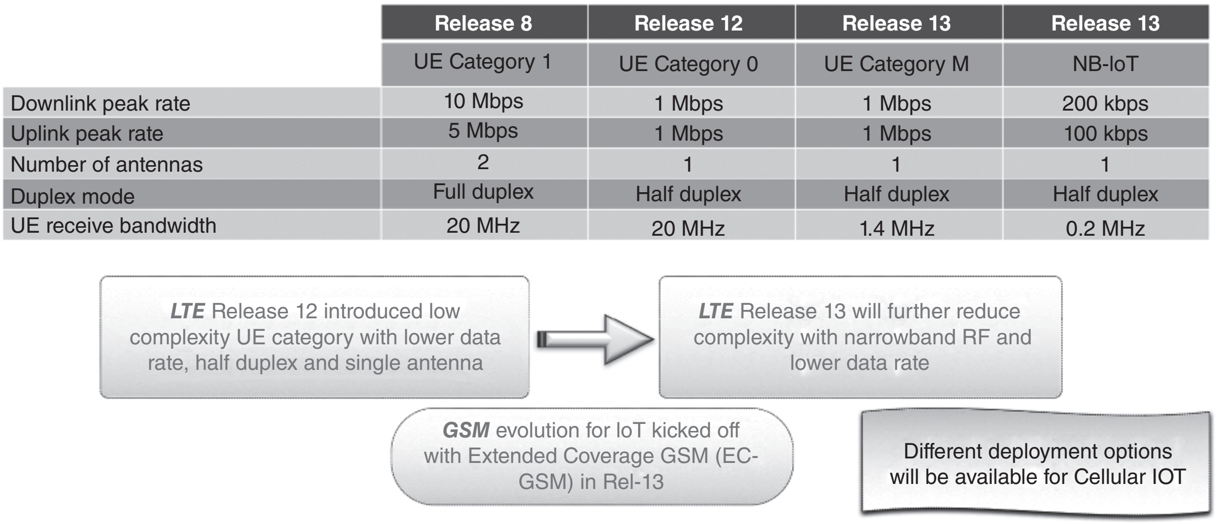
Figure 1.6 summarizes the LTE UE categories with differing 3GPP evolutions.

With the developments in cellular networks, the doors have been opened wide for the development of 5G architecture and its requirements. The envisioned market space for 5G technology is driven by requirements to enhance the mobile broadband smartphone, with a massive range of machine-type communication and LPWA growth, and the need to provide ultra-reliable, low-latency communications. 3GPP expects the evolution to start from Release 14/15 and is aiming to meet the IMT2020 requirements in Release 16. Figure 1.7 summarizes the main targets for 5G, and the main use cases are summarized in Figure 1.8.

1.4 Evolved Packet System (EPS) Overview

3GPP Release 8 is the starting point when defining the standardization for the Long Term Evolution (LTE) specifications:

- The Evolved Packet System (EPS) is defined, mandating the key features and components of both the radio access network (E-UTRAN) and the core network (Evolved Packet Core, EPC).
- Orthogonal Frequency Division Multiplexing (OFDM) is defined as the air interface.



	Release 8	Release 12	Release 13	Release 13
	UE Category 1	UE Category 0	UE Category M	NB-IoT
Downlink peak rate	10 Mbps	1 Mbps	1 Mbps	200 kbps
Uplink peak rate	5 Mbps	1 Mbps	1 Mbps	100 kbps
Number of antennas	2	1	1	1
Duplex mode	Full duplex	Half duplex	Half duplex	Half duplex
UE receive bandwidth	20 MHz	20 MHz	1.4 MHz	0.2 MHz

LTE Release 12 introduced low complexity UE category with lower data rate, half duplex and single antenna

LTE Release 13 will further reduce complexity with narrowband RF and lower data rate

GSM evolution for IoT kicked off with Extended Coverage GSM (EC-GSM) in Rel-13

Different deployment options will be available for Cellular IOT

Figure 1.6 Different LTE UE categories for IoT.

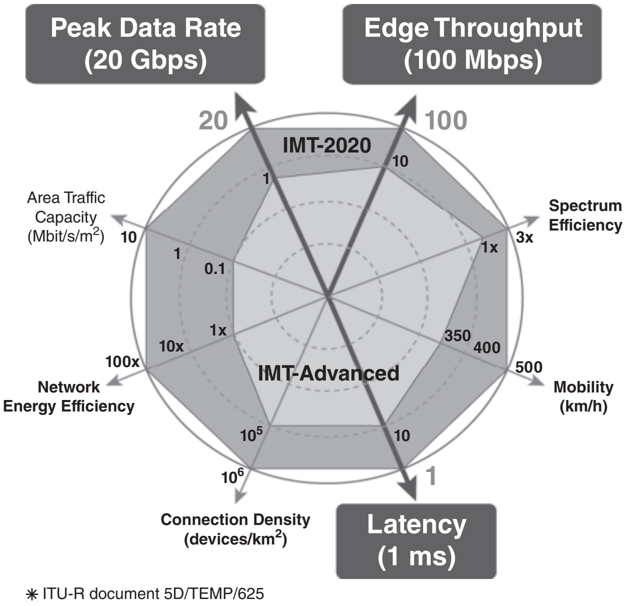


Figure 1.7 Main targets for 5G compared to IMT-Advanced.

- In OFDM, the carriers are packed much closer together (subcarriers).
- This increases spectral efficiency by utilizing a carrier spacing that is the inverse of the symbol or modulation rate.

LTE uses a variable channel bandwidth of 1.4, 3, 5, 10, 15, or 20 MHz.

LTE radio access is designed to operate in two main modes of operation: FDD (Frequency Division Duplex) and TDD (Time Division Duplex).

- In *FDD*, separate uplink and downlink channels are utilized, enabling a device to transmit and receive data at the same time.
- *TDD* mode enables full-duplex operation using a single frequency band and time division multiplexing for the uplink and downlink signals.

Figure 1.9 summarizes FDD and TDD operation. The FDD system:

Can operate in full-duplex or half-duplex modes.

Half-duplex FDD is where the mobile can only transmit or receive; i.e.

- The user cannot transmit and receive at the same time.
- There is reduced mobile complexity since no duplex filter is required.

TDD mode enables full-duplex operation using a single frequency band and time division multiplexing of the uplink and downlink signals. The basic principle of TDD is to use the same frequency band for transmission and reception but to alternate the transmission direction in time. This is a fundamental difference compared to FDD, where different frequencies are used for continuous UE reception and transmission. Like FDD, LTE TDD supports bandwidths from 1.4 MHz up to 20 MHz depending on the frequency band. One advantage of TDD is its ability to provide asymmetrical uplink and downlink allocation. Depending on the system, other advantages include dynamic allocation, increased spectral efficiency, and the improved use of beamforming techniques. This is due to having the same uplink and downlink frequency characteristics.

Since the bandwidth is shared between the uplink and downlink and the maximum bandwidth is specified to be 20 MHz in Release 8, the maximum achievable data rates are lower than in LTE FDD. Therefore, to improve LTE TDD performance, it can be seen that FDD + TDD joint operation (carrier aggregation) will be useful in markets using TDD.

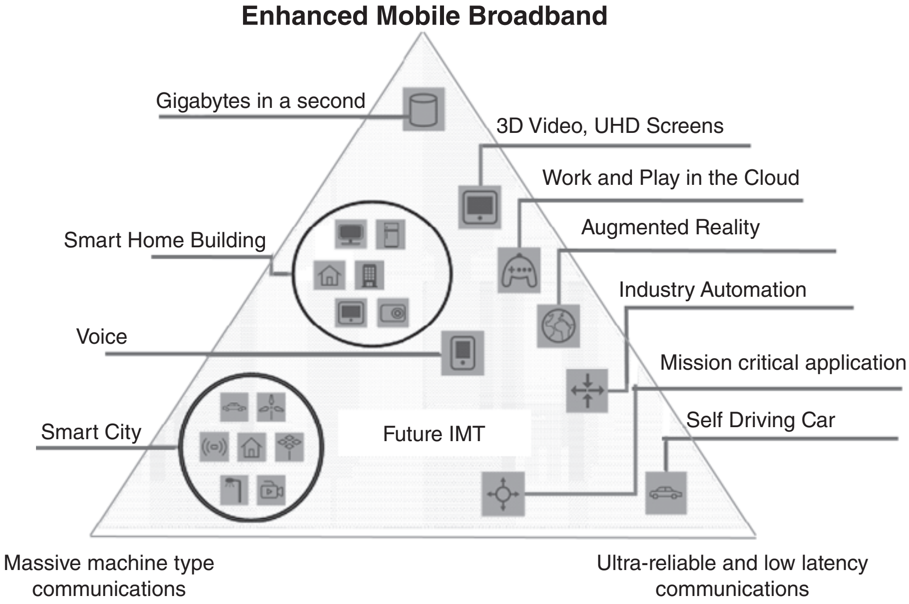


Figure 1.8 Main use cases for 5G.

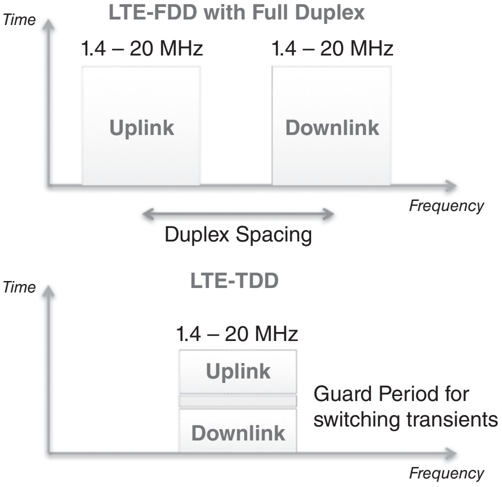


Figure 1.9 FDD and TDD operation.

It is worth noting that the same receiver and transmitter processing capability can be used with both TDD and FDD modes, enabling faster deployment of LTE. However, in an FDD UE implementation, this normally requires a duplex filter when simultaneous transmission and reception is facilitated. In a TDD system, the UE does not need such a duplex filter.

One of the main factors in any cellular system is the deployed frequency spectrum. 2G, 3G, and 4G systems offer multiple band options. The frequency band choice depends on the regulator in each country and the availability of spectrum sharing among network operators in the same country. The device's support for the frequency bands is driven by the hardware capabilities. Therefore, not all bands are supported by a single device. The demands of a multi-mode and multi-band device depend on the market where the device is being sold.

LTE uses a variable channel bandwidth of 1.4, 3, 5, 10, 15, or 20 MHz. Most common worldwide network deployments are in 5 or 10 MHz, given the bandwidth available in the allocated spectrum for the operator. LTE in 20 MHz is being deployed increasingly, especially in bands like 2.6 GHz as well as 1.8 GHz after frequency re-farming.

LTE-FDD requires two center frequencies, one for the downlink and one for the uplink. These carrier frequencies are each given an EARFCN (E-UTRA Absolute Radio Frequency Channel Number). In contrast, LTE-TDD has only one EARFCN. The channel raster for LTE is 100 kHz for all bands. The carrier center frequency must be an integer multiple of 100 kHz.

Tables 1.7 and 1.8 summarize the LTE band allocation for FDD and TDD, respectively.

As was the case with UMTS, LTE supports both FDD and TDD modes. FDD frequency bands are paired, which enables simultaneous transmission on two frequencies: one for the downlink and one for the uplink. The paired bands are also specified with sufficient separations for improved receiver performance. TDD frequency bands are unpaired, as uplink and downlink transmissions share the same channel and carrier frequency. The transmissions in uplink and downlink directions are time-multiplexed. The unpaired bands used in TDD mode start from band 33. Note that band 6 is not applicable to LTE (a UMTS-only band) and bands 15 and 16 are dedicated to ITU Region 1.

1.5 Network Architecture Evolution

Figure 1.10 illustrates the network topologies for 3G/Evolved HSPA/LTE. In a 3G network, prior to the

Table 1.7 LTE-FDD band allocation.

Operating Band	Band Name	Uplink Operating Band (MHz)	Downlink Operating Band (MHz)
1	2100	1920–1980	2110–2170
2	1900	1850–1910	1930–1990
3	1800	1710–1785	1805–1880
4	AWS	1710–1755	2110–2155
5	850	824–849	869–894
7	2600	2500–2570	2620–2690
8	900	880–915	925–960
9	1800	1749.9–1784.9	1844.9–1879.9
10	AWS	1710–1770	2110–2170
11	1500	1427.9–1452.9	1475.9–1500.9
12	700	698–716	728–746
13	700	777–787	746–756
14	700	788–798	758–768
17	700	704–716	734–746
18	800	815–830	860–875
19	800	830–845	857–890
20	800	832–862	791–821
21	1500	1447.9–1462.9	1495.9–1510.9
22	3500	3410–3490	3510–3590
23	2000	2000–2020	2180–2200
24	1600	1626.5–1660.5	1525–1559
25	1900	1850–1915	1930–1995

Table 1.8 LTE-TDD band allocation.

Operating Band	Band Name	Uplink and Downlink Operating Band (MHz)
33	1900	1900–1920
34	2000	2010–2025
35	PCS	1850–1910
36	PCS	1930–1990
37	PCS	1910–1930
38	2600	2570–2620
39	1900	1880–1920
40	2300	2300–2400
41	2500	2496–2690
42	3500	3400–3600
43	3700	3600–3800
44	700	703–803

introduction of the HSPA system, the network architecture is divided into circuit-switched and packet-switched domains. Depending on the service offered to the end user, the domains interact with the corresponding core network entities. The circuit-switched elements are the Mobile services Switching Center (MSC), the Visitor Location Register (VLR), and the Gateway MSC. The packet-switched elements are the Serving GPRS Support Node (SGSN) and the Gateway GPRS Support Node (GGSN).

Furthermore, the control plane and user plane data are forwarded between the core and access networks. The Radio Access Technology (RAT) in the 3G system uses Wideband Code Division Multiple Access (WCDMA). The access network includes all of the radio equipment necessary for accessing the network, and is referred to as the Universal Terrestrial Radio Access Network (UTRAN).

UTRAN consists of one or more Radio Network Subsystems (RNSs). Each RNS consists of a Radio Network Controller (RNC) and one or more NodeBs. Each NodeB controls one or more cells and provides the WCMDA radio link to the UE.

After the introduction of HSPA and HSPA+ systems in 3GPP, some optional changes have been added to the core network as well as mandatory changes to the access network. On the core network side, an evolved direct tunneling architecture has been introduced whereby the user data can flow between the GGSN and the RNC or directly to the NodeB. On the access network side, some of the RNC functions, such as the network scheduler, have been moved to the NodeB side for faster radio resource management (RRM) operations.

Figure 1.11 provides the LTE Evolved Packet System (EPS) network topology. In summary, EPS consists of:

- The E-UTRAN access network (Evolved UTRAN).
  - The E-UTRAN consists of one or more eNodeBs (eNBs).
  - An eNB consists typically of three cells.
  - The eNBs can, optionally, interconnect to each other via the X2 interface.
- The EPC core network (Evolved Packet Core).
  - The EPC core network consists of the main network entities: MME, S-GW, and P-GW.
- The EPS can also interconnect with other radio access networks: 3GPP (GERAN, UTRAN) and non-3GPP (e.g. CDMA, Wi-Fi).

The EPC includes the MME, S-GW, and P-GW entities. They are responsible for different functionalities during a call or registration process. The EPC and the E-UTRAN interconnect with the S1 interface. The S1 interface supports a many-to-many relationship between MMEs, serving gateways, and eNBs.

The MME connects to the E-UTRAN by means of the S1 interface. This interface is referred to as S1-C or S1-MME. When a UE attaches to the LTE network, UE-specific logical S1-MME connections are established. This bearer, known as an EPS bearer, is used to exchange the necessary UE-specific signaling messages between the UE and the EPC.

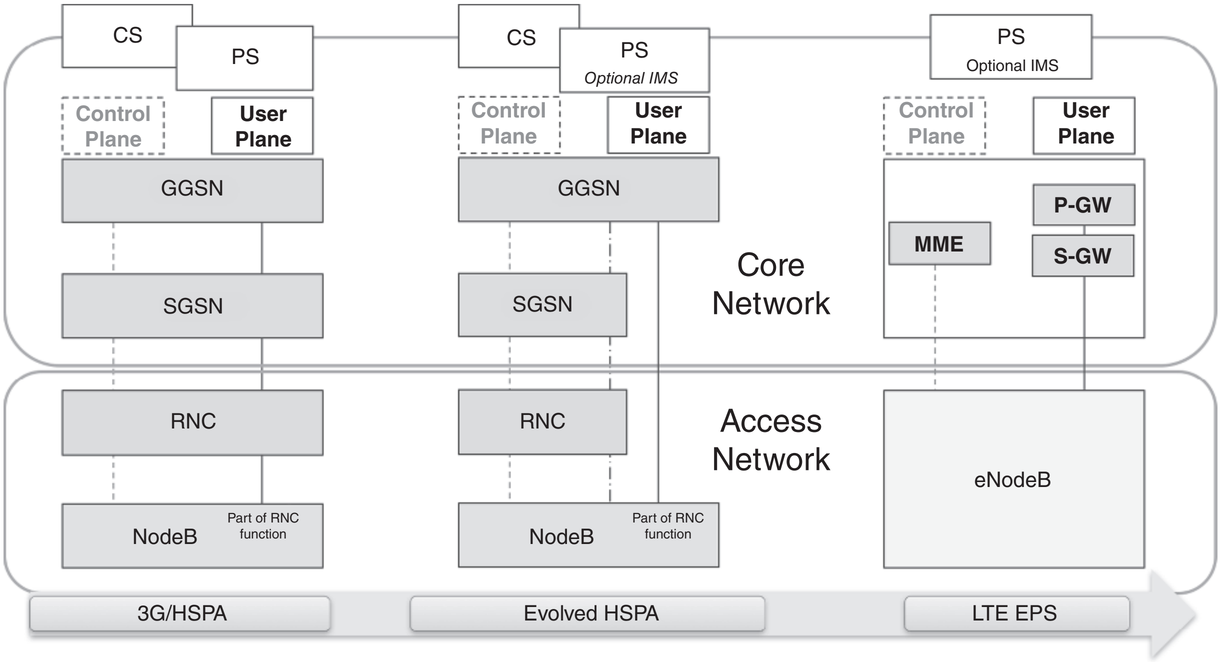


Figure 1.10 3G/Evolved HSPA/ LTE network topology.

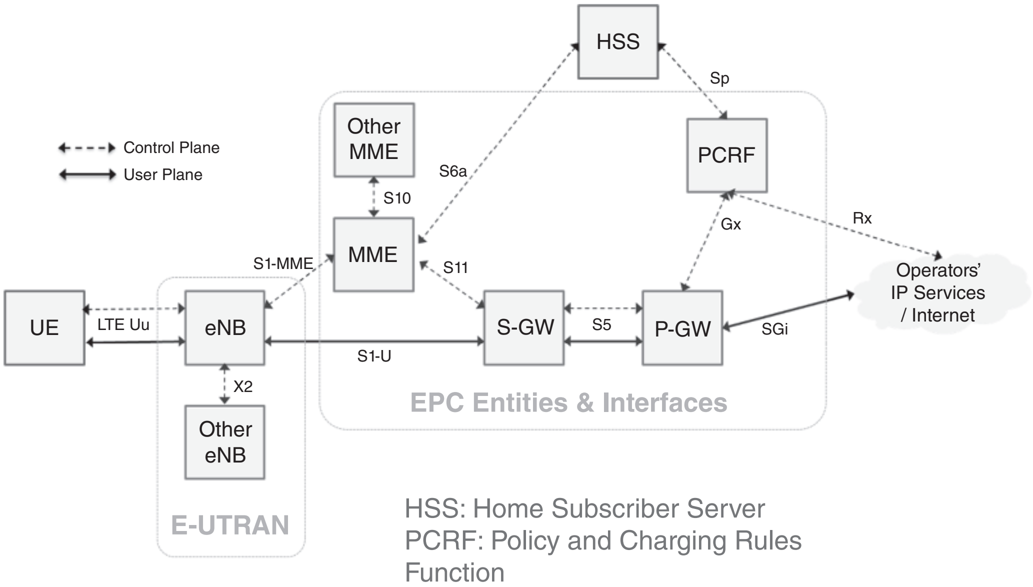


Figure 1.11 LTE/EPS network topology.

Each UE is then assigned a unique pair of eNB and MME identifications during S1-MME control connection. The identifications are used by the MME to send the UE-specific S1 control messages and by the E-UTRAN to send messages to the MME. The identification is released when the UE transitions to Idle state, where the dedicated connection with the EPC is also released. This process may repetitively take place when the UE sets up a signaling connection for any type of LTE call.

The MME and E-UTRAN handle signaling for control plane procedures established for the UE on the S1-MME interface, including:

Initial context setup/UE context release
E-RAB setup/release/modify
Handover preparation/notification
eNB/MME status transfer
Paging UE capability information indication.

The HSS is considered to lie outside the EPC entities and is used to update new EPS subscription data and functions to the EPC. The HSS is located within the HLR of the mobile network and has recently become part of the converged database (CDB) for the entire subscriber services. The PCRF provides QoS policy and charging control (PCC), similar to the 3G PS domain.

The main features of EPS are summarized in Table 1.9.

S1-MME uses S1-AP over SCTP as the transport layer protocol for guaranteed delivery of signaling messages between the MME and the eNodeB. One logical S1-AP connection per UE is established and multiple UEs are supported via a single SCTP association. The following functionalities are conducted in S1-AP:

Setup, modification, and release of E-RABS.
Establishment of an initial S1 UE context.
Paging and S1 management functions.
NAS signaling transport functions between the UE and the MME.
Status transfer functionality.
Trace of active UEs and location reporting.
Mobility functions for UE to enable inter- and intra-RAT HO.

MMEs can also periodically send MME loading information to the E-UTRAN for mobility management procedures. This is not UE-specific information. The S-GW is connected to the E-UTRAN by means of the S1-U interface. After the EPS bearer is established for control plane information, the user data packets start flowing between the EPC and the UE through this interface.

1.6 LTE UE Description

Like that in UMTS, the mobile device in LTE is referred to as the UE (User Equipment) and is comprised of two distinct elements: the USIM (Universal Subscriber Identity Module) and the ME (Mobile Equipment). The ME supports a number of functional entities and protocols including:

RR (Radio Resource): This supports both the control and user planes. It is responsible for all low-level protocols including RRC, PDCP, RLC, MAC, and PHY layers. The layers are similar to those in the eNB protocol layer.

EMM (EPS Mobility Management): A control plane entity which manages the mobility states of the UE; LTE Idle, LTE Active, and LTE Detached. Transactions within these states include procedures such as TAU (Tracking Area Updates) and handovers.

ESM (EPS Session Management): A control plane activity which manages the activation, modification, and deactivation of EPS bearer contexts. These can either be default or dedicated EPS bearer contexts.

The physical layer capabilities of the UE may be defined in terms of the frequency bands and data rates supported. Devices may also be capable of supporting adaptive modulation including QPSK (Quadrature Phase Shift Keying), 16QAM (16 Quadrature Amplitude Modulation), and 64QAM (64 Quadrature Amplitude Modulation). Modulation capabilities are defined separately in 3GPP for the uplink and downlink. The UE is able to support several scalable channels including 1.4 MHz, 3 MHz, 5 MHz, 10 MHz, 15 MHz, and 20 MHz

Table 1.9 Main features of EPS entities.

EPS Element	Element	Basic Functionality
EPC	MME Mobility Management Entity	• Signaling and security control • Tracking area management • Inter core network signaling for mobility between 3GPP access networks • EPS bearer management • Roaming and authentication
	S-GW Serving Gateway	• Packet routing and forwarding • Transport level Quality of Service mapping
	P-GW Packet Data Network (PDN) Gateway	• IP address allocation • Packet filtering and policy enforcement • User plane anchoring for mobility between 3GPP access networks
E-UTRAN	eNodeB Evolved Node B	• Provides user plane protocol layers: PDCP, RLC, MAC, physical and control plane (RRC) with the user • Radio resource management • E-UTRAN synchronization and interface control • MME selection

whilst operating in FDD and/or TDD. The UE may also support advanced antenna features such as MIMO with different numbers of antenna configurations.

The physical layer and radio capabilities of the UE are advertised to the EPS at the initiation of the connection with the eNB in order to adjust the radio resources accordingly. An LTE-capable device advertises one of the categories listed in Table 1.10 according to its software and hardware capabilities. UE categories > 5 are considered part of LTE-A capabilities, with CA starting from Category 6 and above.

It should also be noted that different combinations of 3G and LTE categories can be supported in the same device, depending on the price and the market in which the device is being sold.

The UE categories are summarized in Table 1.10.

Table 1.11 illustrates how to estimate the peak throughput for sample LTE UE categories.

Table 1.11 shows the maximum capability of each category and which factor will limit it. The maximum data rates in each category are presented as the MAX_Throughput {MIMO configuration, higher-order modulation, carrier aggregation combination} that provides whatever maximum throughput is possible. Therefore, using advanced MIMO with advanced higher-order modulation and advanced carrier aggregation bandwidth techniques may or may not be possible simultaneously in every category on one carrier. For 600 Mbps, for example, it can be achieved within Category 11 by:

2 × CC 4 × 4MIMO, or
1 × CC 4 × 4MIMO + 2CC 2 × 2MIMO, or
4 × CC 2 × 2MIMO
1 × CC 4 × 4MIMO 256QAM + 1 × CC 2 × 2MIMO 256QAM, or
3 × CC 2 × 2MIMO 256QAM

As mentioned earlier, some operators around the world are aiming to use the current LTE spectrum and deployment conditions and aggregate it with the Wi-Fi network to achieve Giga LTE. This can happen directly at the LTE protocol stack (LWA), or through application layer aggregations (MP-TCP), especially if the public Wi-Fi network is the operator's own and the core network can be integrated with the EPS network. If 4 × 4 MIMO or 256QAM are not currently supported in the LTE commercial network, the alternative means to reach a 1 Gbps network is to utilize Wi-Fi aggregation with the minimum LTE capabilities possible (2 × 2 MIMO + 2 × CC 64QAM). Figure 1.12 illustrates how to achieve 1 Gbps using LTE evolution either by using LTE-U or LWA.

1.7 EPS Bearer Procedures

The EPS bearer service layered architecture may be described as follows:

Table 1.10 LTE UE categories.

		Downlink			Uplink		
UE Category	**3GPP Release**	**Max. Data Rate [Mbps]**	**Max. Number of Layers**	**Support for 256 QAM**	**Max. Data Rate [Mbps]**	**Support for 64QAM**	**General Description**
Category 0	Rel 12	**1**	**1**	No	**1**	No	Internet of Things
Category 1	Rel 8/9	10	1	No	5	No	
Category 2	Rel 8/9	51	2	No	25	No	Non CA
Category 3	Rel 8/9	102	2	No	51	No	Non CA
Category 4	Rel 8/9	150	2	No	51	No	Non CA
Category 5	Rel 8/9	300	4	No	75	Yes	Non CA
Category 6	Rel 10	301	2 or 4	No	51	No	DL 2 × CC
Category 7	Rel 10	301	2 or 4	No	102	No	UL 2 × CC
Category 8	Rel 10	3000	8	No	1500	Yes	Non CA
Category 9	Rel 11/12	452	2 or 4	No	51	No	DL 3 × CC
Category 10	Rel 11/12	452	2 or 4	No	102	No	DL 3 × CC + UL 2 × CC
Category 11	Rel 11/12	603	2 or 4	Optional	51	No	DL 4 × CC
Category 12	Rel 11/12	603	2 or 4	Optional	102	No	UL 2 × CC
Category 13	Rel 12	391	2 or 4	Yes	150	Yes	DL 2 × CC

2 × CC, 3 × CC, and 4 × CC indicate carrier aggregation with 40, 60, and 80 MHz maximum bandwidth, respectively.
The maximum data rates in each category are presented as the MAX_Throughput {MIMO Configuration, Higher Order Modulation, Carrier Aggregation Combination} that provides whatever maximum throughput possible.

Table 1.11 LTE UE categories throughput estimation.

UE Category	Downlink Max. Data Rate [Mbps]	Downlink Maximum Number of Bits of a DL-SCH Transport Block Received Within a TTI	Maximum DL Through put Calculation
Category 6	301	75376 (2 layers, 64QAM) 149776 (4 layers, 64QAM)	• 2 × CC with 2 × 2 MIMO and **64**QAM = (75376 * 2 Codewords * 2 Carriers)/10^3 = 301 Mbps • 1 × CC with 4 × 4 MIMO and **64**QAM = (149776 * 2 Codewords)/10^3 = 300 Mbps Then, 4 × 4 can't be used with > 20 MHz because it would exceed the category rate.
Category 9	452	75376 (2 layers, 64QAM) 149776 (4 layers, 64QAM)	• 3 × CC with 2 × 2 MIMO and 64QAM = (75376 * 2 Codewords * 3 Carriers)/10^3 = 452 Mbps • l × CC with 4 × 4 MIMO and 64QAM = (149776 * 2 Codewords)/HT^3 = 300 Mbps Then, 4 × 4 can't be used with > 20 MHz because it would exceed the category rate. So, if 4 × 4 MIMO is used, this category acts like Category **6.**
Category 11	603	75376 (2 layers, 64QAM) 97896 (2 layers, 256QAM) 149776 (4 layers, 64QAM) 195816 (4 layers, 256QAM)	• 4 × CC with 2 × 2 MIMO and 64QAM = (75376 * 2 Codewords * 4 Carriers)/10^3= 603 Mbps • 3 × CC with 2 × 2 MIMO and 256QAM = (97896 * 2 Codewords * 3 Carriers)/10^3 = 587 Mbps • 2 × CC with 4 × 4 MIMO and 64QAM = (149776 * 2 Codewords * 2 Carriers)/10^3 = 599 Mbps Then, 256QAM can't be used with > 60 MHz, and 4 × 4 can't be used with > 40 MHz because it would exceed the category rate, and maximum CA is 80 MHz but with 2 × 2 MIMO and 64QAM. ***A combination is also possible (e.g. 2 × CC with 2 × 2MIMO + Third carrier with 4 × 4 MIMO)***
Category 13	391	97896 (2 layers, 256QAM) 195816 (4 layers, 256QAM)	• 2 × CC with 2 × 2 MIMO and 256QAM – (97896 * 2 Codewords * 2 Carriers)/10^3 = 391 Mbps • l × CC with 4 × 4 MIMO and 256QAM = (195816 * 2 Codewords)/10^3 – 391 Mbps Then, 256QAM can't be used with > 40 MHz, and 4x4 can't be used with > 20 MHz because it would exceed the category rate.

MIMO 2 × 2 and 4 × 4 always use two codewords (i.e. two DL-SCH transport blocks received within a TTI) that are spread over two or four layers. See the MIMO section later in this chapter.
Each carrier can transmit the entire maximum number of bits of a DL-SCH transport block received within a TTI.

A radio bearer transports the packets of an EPS bearer between a UE and an eNB. There is a one-to-one mapping between an EPS bearer and a radio bearer.

An S1 bearer transports the packets of an EPS bearer between an eNB and the S-GW.

An S5/S8 bearer transports the packets of an EPS bearer between the S-GW and the P-GW.

UE stores a mapping between an uplink packet filter and a radio bearer to create the binding between an SDF (Service Data Flow) and a radio bearer in the uplink, described later.

A P-GW stores a mapping between a downlink packet filter and an S5/S8 bearer to create the binding between an SDF and an S5/S8 bearer in the downlink.

An eNB stores a one-to-one mapping between a radio bearer and an S1 to create the binding between a radio bearer and an S1 bearer in both the uplink and downlink.

An S-GW stores a one-to-one mapping between an S1 bearer and an S5/S8 bearer to create the binding between an S1 bearer and an S5/S8 bearer in both the uplink and downlink.

Figure 1.13 illustrates EPS bearers. For an EPS bearer to be established:

Initial attach between the UE and the EPC is required to establish signaling and user plane bearers.

EPS security is negotiated at attach and subsequent calls.

Quality of Service for the bearer is negotiated.

1.7.1 EPS Registration and Attach Procedures

The attach procedure usually starts when the UE initiates the request. After establishing an RRC connection, the UE can send an attach request message to the MME. The

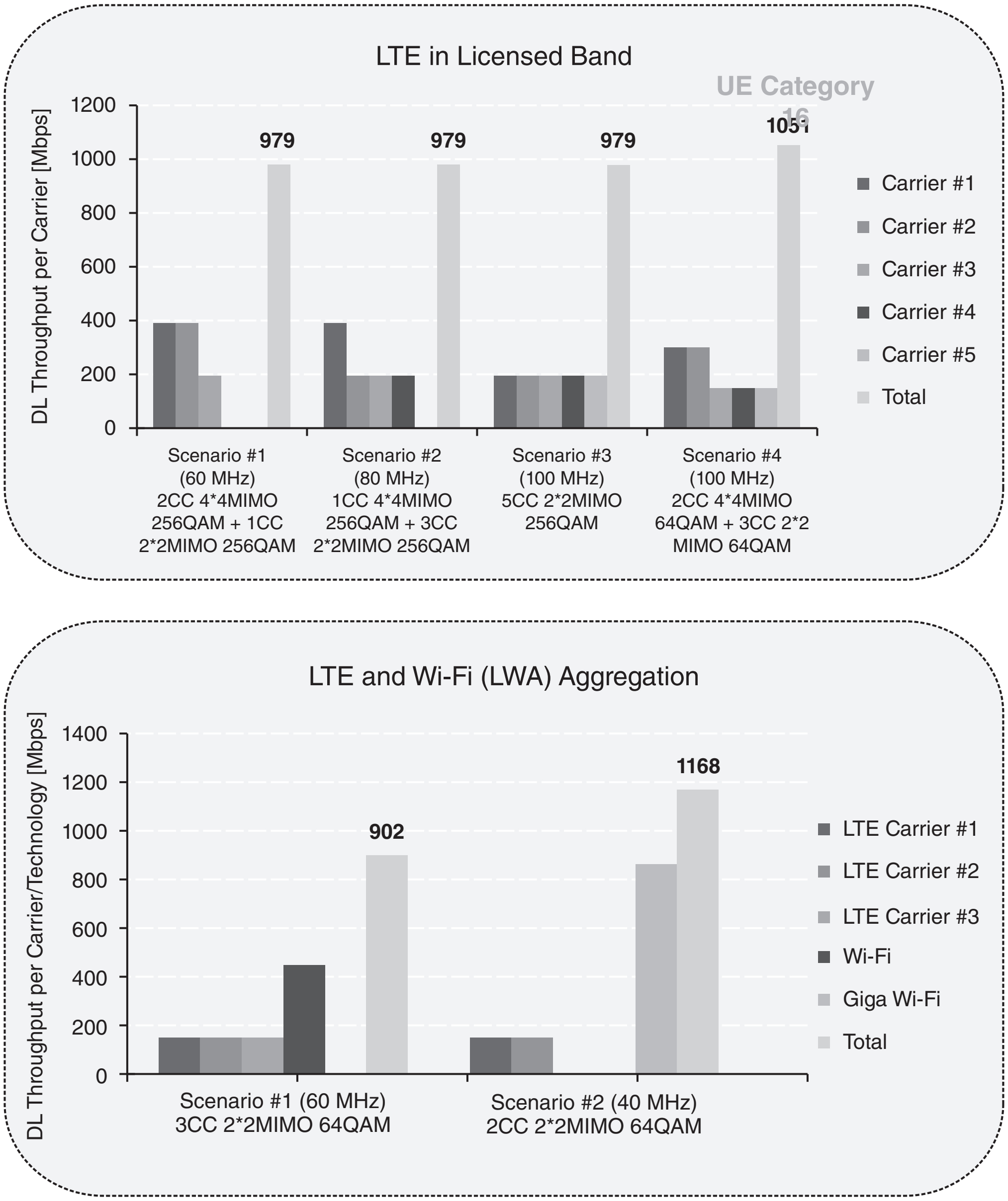
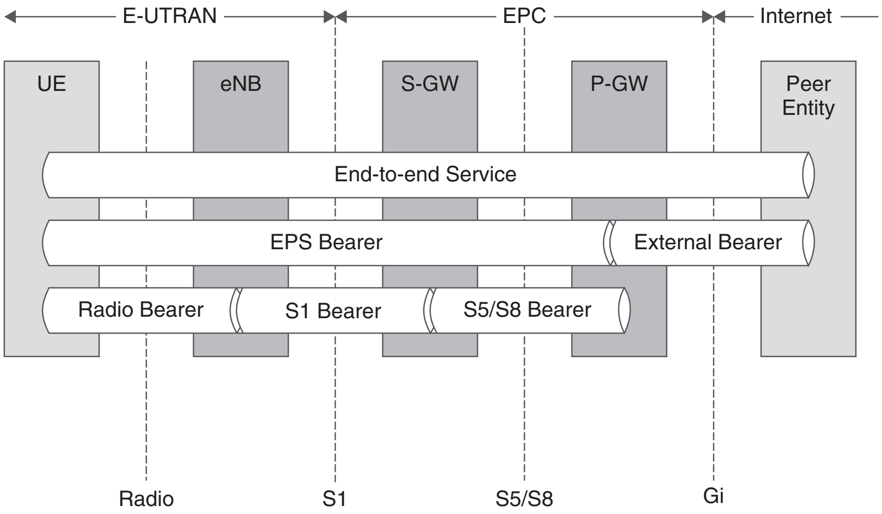


Figure 1.12 Giga LTE roadmap in licensed and unlicensed bands.

Figure 1.13 EPS bearers.



UE also requests PDN connectivity along with the attach request.

After all necessary signaling connections have been established, the EPC may trigger security functions. The HSS (Home Subscriber Service) downloads user subscriber information to the MME, which processes the UE request for default EPS bearer setup. After the default EPS bearer and QoS have been negotiated and agreed to among the MME and S-GW/P-GW, the MME forwards the default bearer setup request to the eNB and UE.

The eNB and the UE then acknowledge the default bearer setup and communicate the attach accept messages to the EPC. The EPS bearer is finally active and data can flow between the UE and the IP network, in both uplink and downlink directions.

At this point, the UE typically registers with a default APN, as per the subscription policies. If an additional APN is available, the process needs to continue setting up another EPS bearer.

Figure 1.14 illustrates the registration and attach procedure in the EPS [2]. When the UE enters LTE coverage or powers up, it first registers with the EPS network through the "Initial EPS Attach" procedure:

Register the UE for packet services in the EPS.
Establish (at a minimum) a default EPS bearer that a UE could use to send and receive the user application data.
IPv4 and/or IPv6 address allocation.

Once the SRBs have been established, control plane messages and parameters are sent to the UE from the EPC or E-UTRAN. The UE will adhere to these parameters to continue the protocol procedures on the access stratum. The parameters sent to the UE in the SRB messages will control all protocol layers for the data transmission.

Due to the mapping between the radio bearer and lower-layer logical channels, up to eight DRBs can be set up to carry user plane data connected to multiple PDNs (for example, they may be divided into one default EPS bearer and seven dedicated EPS bearers, or two default bearers and six dedicated bearers).

In 3G systems, the mobile registers on the network first. Then, based on downlink or uplink activities, the IP address allocation procedure starts as part of "PDP context activation". This procedure is referred to in 3G systems as establishing a PS data call (packet-switched data call). The procedure for a PS data call setup follows that for a circuit-switched call setup. When the user initiates or receives a call, the CS or PS call is established and all resources are then allocated at the call-setup stage.

The LTE procedure, compared to 3G, can provide a significant signaling reduction on the protocol layers and also improves the end user experience in terms of data reactivation after a certain period of inactivity. In 3G, when the user disconnects the data call and then initiates a new one, the PDP context activation may start all over

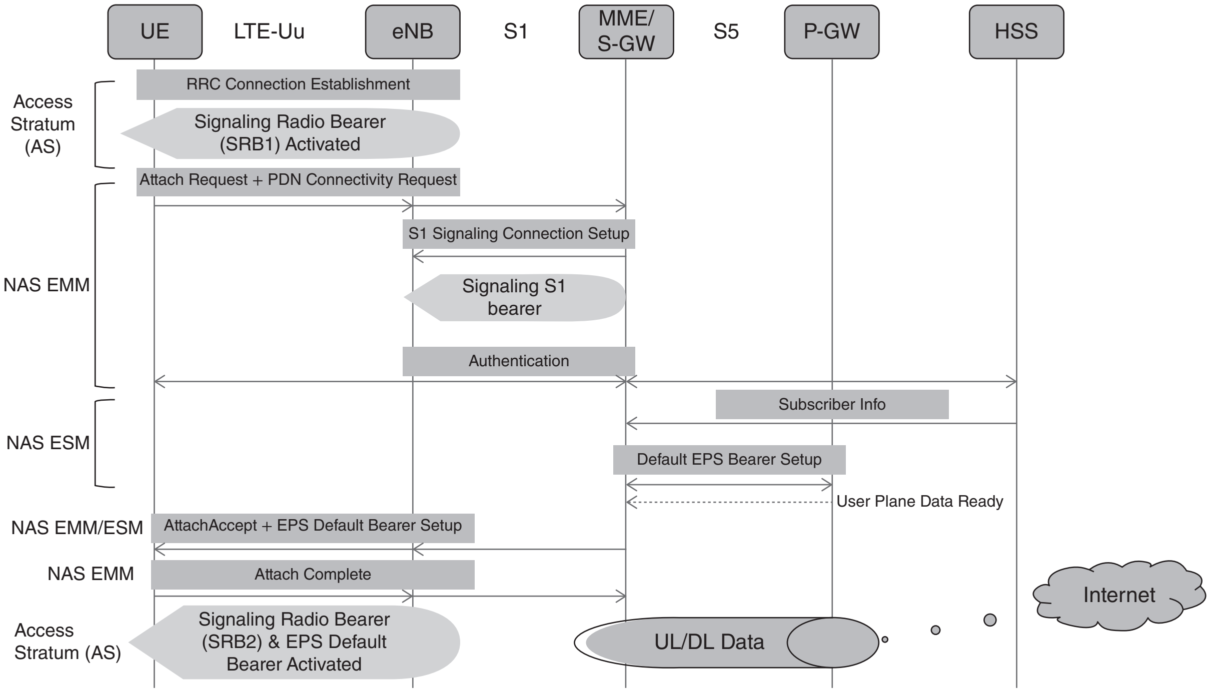


Figure 1.14 Registration and attach procedure in the EPS system.

again. However, in LTE, if the same procedure is done by the user, the call-setup time for a data call is reduced because the default DRB has already been assigned to the user when it first attached to the EPS system.

The dedicated DRB does not necessarily require an extra IP address. The protocol stack uses the Traffic Flow Template (TFT) information to decide what to do with each IP packet. Uplink and downlink traffic are mapped onto proper bearers based on TFT filters configured at the UE and P-GW.

This concept makes the dedicated bearer activation similar to the secondary PDP context activation in 3G that can be used by the IMS, for example, to ensure real-time data are delivered promptly. LTE radio bearers are summarized in Figure 1.15.

1.7.2 EPS Security Basics

Authentication and Key Agreement (AKA) involves interworking with the subscriber's HSS in order to obtain Access Authorization and Accounting (AAA) information to authenticate the subscriber. During AKA, keys are created for AS and NAS integrity protection and ciphering.

The integrity and ciphering procedures involve both NAS and AS:

NAS security context activation provides both integrity protection and ciphering for NAS signaling. The procedure takes place between the UE and the MME.

AS security context activation provides integrity and ciphering protection for RRC signaling in addition to ciphering for user plane data to be sent over the air interface. The procedure takes place between the UE and the eNB.

The MME selects a NAS integrity algorithm and a NAS ciphering algorithm for the UE. The MME is expected to select the NAS algorithms that have the highest priority according to the ordered lists. The selected algorithm is indicated in the NAS Security Mode Command message to the UE and that message also includes the UE security capabilities. The integrity of this message is protected by the MME with the selected algorithm.

The UE verifies that the message from the MME contains the correct UE security capabilities. This enables detection of attacks in the case where an attacker has modified the UE security capabilities in the initial NAS message.

The UE then generates NAS security keys based on the algorithms indicated in the NAS Security Mode Command and replies with an integrity-protected and ciphered NAS Security Mode Complete message. NAS security is activated at this point.

After this point, the eNB creates the AS security context when it receives the keys from the MME. The eNB generates the integrity and encryption keys and selects the highest priority ciphering and integrity protection algorithms from its configured list that are also present in the UE's EPS security capabilities.

Upon receipt of the AS Security Mode Command, the UE generates integrity and encryption keys and sends an AS Security Mode Complete message to the eNB.

Figure 1.16 demonstrates key security basics for the EPS. We can summarize the key security basics as follows:

SRB	Default EPS DRB	Dedicated EPS DRB
• **SRB ID 0** • used to establish the RRC connection request when the UE has transitioned into **connected mode. SRB0 carries** commom control information required to establish the RRC connection • **SRB ID 1** • **used for RRC messages, as well as RRC messages carrying high** priority NAS signaling • **SRB ID 2** • used for RRC carrying low **priority NAS signaling. Prior to** its establishment, low priority signaling is sent on SRB1	• One of the significant changes introduced in LTE is that when the mobile device connects to the network it also implicitly gets an IP address. This is called "Default EPS Bearer Activation" • With the default bearer activation, the packet call is established the same time when the UE attaches to the EPS. This is the concept that makes the LTE's connectivity to be known as "always-on" • Even though the default DRB is enough for the downlink and uplink data transfer, it comes without any quality of Service guarantees	• For real time streaming applications, QoS may be needed especially on the air interface • Such IP packets associated with these types of applications may need to be assigned with a higher priority than other packets, especially when the bandwidth is limited • The dedicated bearer becomes important in order to support different types of applications in EPS network. Dedicated DRB can be set up right after Default DRB

Figure 1.15 LTE radio bearer description.

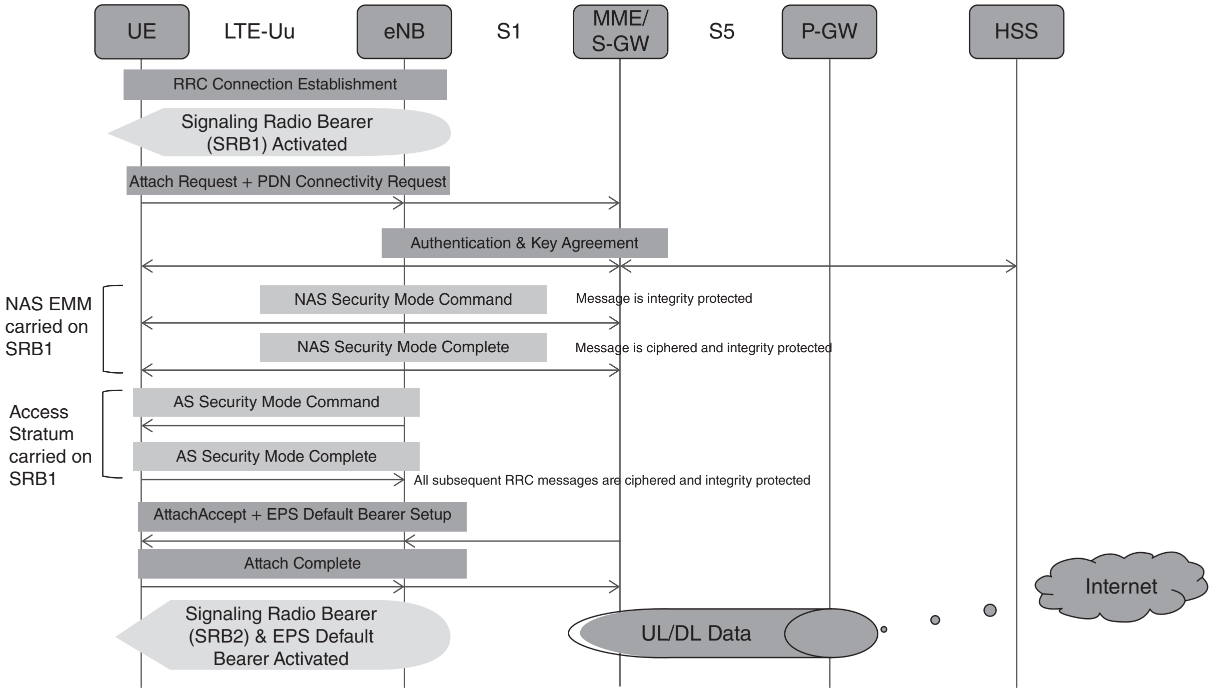


Figure 1.16 EPS security basics.

AKA: To prevent fraud that occurs when a third party obtains a copy of a subscriber's network identification information and uses it to access the system fraudulently.

Ciphering: Used to protect all user data and signaling from being overheard by an unauthorized entity.

Integrity: Protects signaling information from being corrupted. It is a message authentication function that prevents a signaling message from being intercepted and altered by an unauthorized device.

1.7.3 EPS QoS

In order to support a mixture of non-real-time and real-time applications such as voice and multimedia, delay and jitter may become excessive if the flows of traffic are not coordinated. Packet switches should be able to classify, schedule, and forward traffic based on the destination address, as well as the type of media being transported. This becomes possible with QoS-aware systems.

The QoS for data radio bearers is provided to the eNB by the MME using the standardized QoS attributes. Based on these attributes configured by the EPS, the protocol layers between the UE and the eNB can manage the ongoing scheduling of uplink and downlink traffic.

Figure 1.17 summarizes the QoS aspects of EPS. Different QoS Class Identifier (QCI) values are provided in Table 1.12.

1.8 Access and Non-access Stratum Procedures

Figure 1.18 illustrates an overview of the LTE protocol stack. The LTE air interface provides connectivity between the user equipment and the eNB. It is split into a control plane and a user plane. Of the two types of control plane signaling, the first is provided by the Access Stratum (AS) and carries signaling between the UE and the eNB; the second carries Non-Access Stratum (NAS) signaling messages between the UE and the MME, which is piggybacked onto an RRC message. The user plane delivers the IP packets to and from the EPC, S-GW, and PDN-GW.

The structure of the lower-layer protocols for the control and user planes in the AS is the same. Both planes utilize the protocols of PDCP (Packet Data Convergence Protocol), RLC (Radio Link Control), and MAC (Medium Access Control) as well as the PHY (Physical Layer) for the transmission of signaling and data packets.

The NAS is the layer above the AS layers. There are also two planes in the NAS: the higher-layer signaling related to the control plane and the IP data packets of the user plane. NAS signaling exists in two protocol layers, EMM and ESM. The NAS user plane is IP-based. The IP data packets pass directly into the PDCP layer for processing and transmission to or from the user.

Figure 1.17 QoS aspects in EPS.

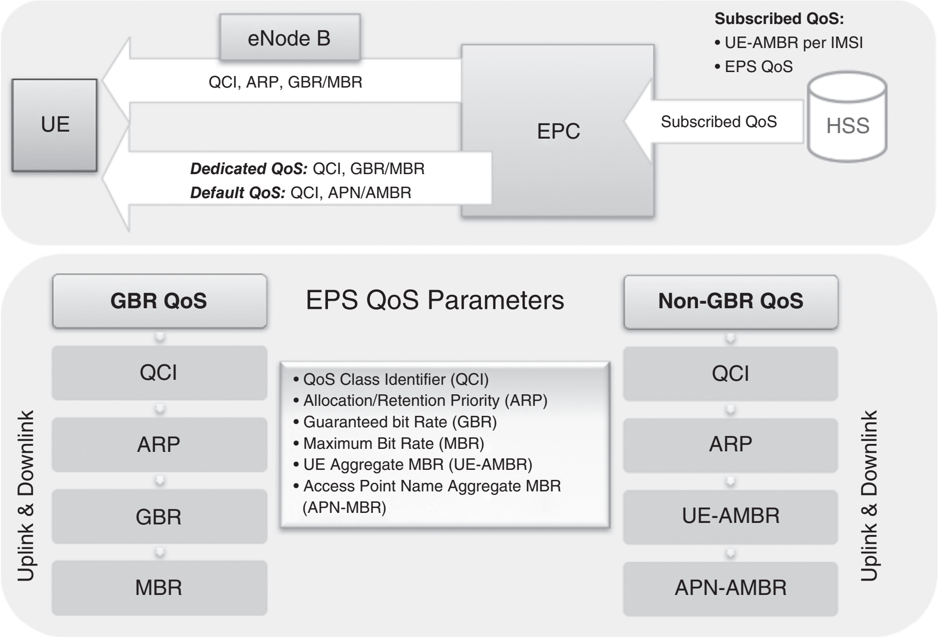


Table 1.12 Different QCI values and corresponding service requirements.

QCI	Resource Type	Priority	Packet Delay Budget (PDB)	Packet Error Loss Rate (PELR)	Examples of Services
1	GBR	2	100 ms	10^{-2}	Conversational voice
2		4	150 ms	10^{-3}	Conversational video (live streaming)
3		3	50 ms	10^{-3}	Real-time gaming
4		5	300 ms	10^{-6}	Non-conversational video (buffered streaming)
5	Non-GBR	1	100 ms	10^{-6}	IMS signaling
6		6	300 ms	10^{-6}	Video (buffered streaming, TCP-based (www, e-mail, ftp, p2p file sharing)
7		7	100 ms	10^{-3}	Voice, Video, Interactive gaming
8		8	300 ms	10^{-6}	Same as QCI 6 but used for further differentiation
9		9	300 ms	10^{-6}	

1.8.1 EMM Procedures and Description

1.8.1.1 Definitions

Attach: Used by the UE to attach to the EPC for packet services in the EPS. It can also be used to attach to non-EPS services, for example, CSFB/SMS.

Detach: Used by the UE to detach from EPS services. It can also be used for other procedures such as disconnecting from non-EPS services.

Tracking Area Updating: Initiated by the UE and used for identifying the UE location at eNB level for paging purposes in Idle mode.

Service Request (PS call): Used by the UE to get connected and establish the radio and S1 bearers when uplink user data or signaling is to be sent.

Extended Service Request: Used by the UE to initiate a circuit-switched fallback call or respond to a mobile terminated circuit-switched fallback request from the network, i.e. non-EPS services (CSFB).

GUTI Allocation: Allocate a GUTI (Globally Unique Temporary Identifier) and optionally to provide a new TAI (Tracking Area Identity) list to a particular UE.

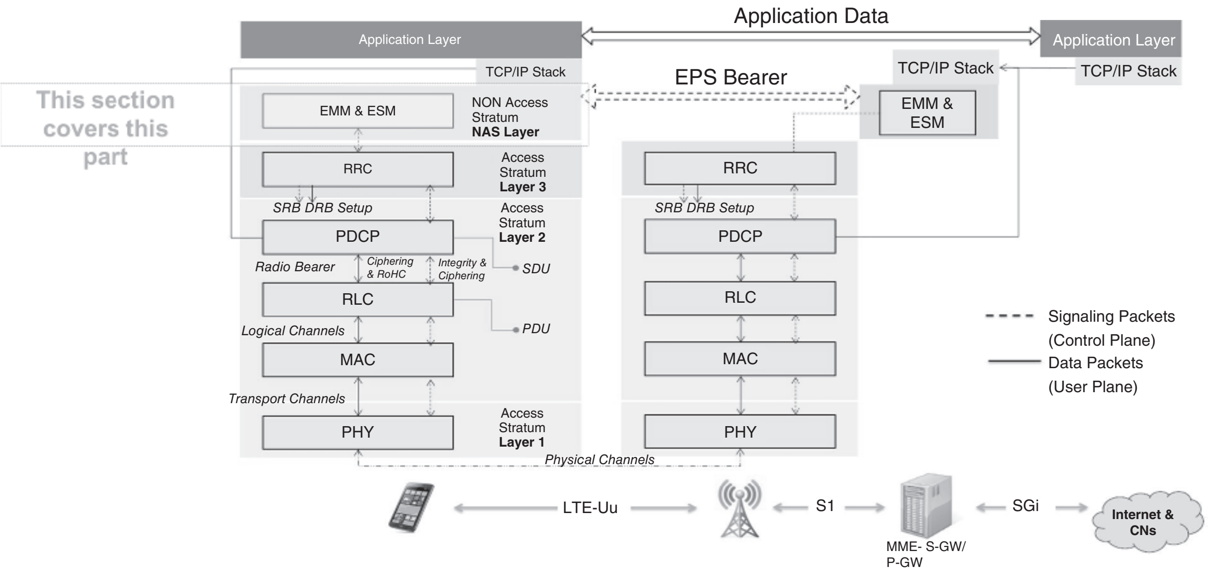


Figure 1.18 LTE protocol stack overview.

Authentication: Used for AKA (Authentication and Key Agreement) between the user and the network.

Identification: Used by the network to request a particular UE to provide specific identification parameters, for example, the IMSI (International Mobile Subscriber Identity) or the IMEI (International Mobile Equipment Identity).

Security Mode Control: Used to take an EPS security context into use and initialize NAS signaling security between the UE and the MME with the corresponding NAS keys and security algorithms.

EMM Status: Sent by the UE or by the network at any time to report certain error conditions.

EMM Information: Allows the network to provide information to the UE.

NAS Transport: Carries SMS (Short Message Service) messages in an encapsulated form between the MME and the UE.

Paging: Used by the network to request the establishment of a NAS signaling connection to the UE. Is also includes the circuit-switched service notification.

1.8.1.2 ESM Procedures and Description

Default EPS Bearer Context Activation: Used to establish a default EPS bearer context between the UE and the EPC.

Dedicated EPS Bearer Context Activation: Establishes an EPS bearer context with specific QoS (Quality of Service) between the UE and the EPC. The dedicated EPS bearer context activation procedure is initiated by the network, but may be requested by the UE by means of the UE-requested bearer resource allocation procedure.

EPS Bearer Context Modification: Modifies an EPS bearer context with a specific QoS.

EPS Bearer Context Deactivation: Deactivates an EPS bearer context or disconnects from a PDN by deactivating all EPS bearer contexts.

UE-Requested PDN Connectivity: Used by the UE to request the setup of a default EPS bearer to a PDN.

UE-Requested PDN Disconnect: Used by the UE to request disconnection from one PDN. The UE can initiate this procedure to disconnect from any PDN as long as it is connected to at least one other PDN.

UE-Requested Bearer Resource Allocation: Used by the UE to request an allocation of bearer resources for a traffic flow aggregate.

UE-Requested Bearer Resource Modification: Used by the UE to request a modification or release of bearer resources for a traffic flow aggregate or modification of a traffic flow aggregate by replacing a packet filter.

ESM Information Request: Used by the network to retrieve ESM information, i.e. protocol configuration options, APN (Access Point Name), or both from the UE during the attach procedure.

ESM Status: Report, at any time, certain error conditions detected upon receipt of ESM protocol data.

Figure 1.19 summarizes the EPS access and non-access strata and we can summarize them as follows:

Access Stratum (AS) resides between the UE and the E-UTRAN.

- Consists of multiple protocol layers: RRC, PDCP, RLC, MAC, and the PHY (physical) layer.
- The AS signaling provides a mechanism to deliver NAS signaling messages intended for control plane procedures as well as the lower-layer signaling and parameters required to set up, maintain, and manage the connections with the UE.

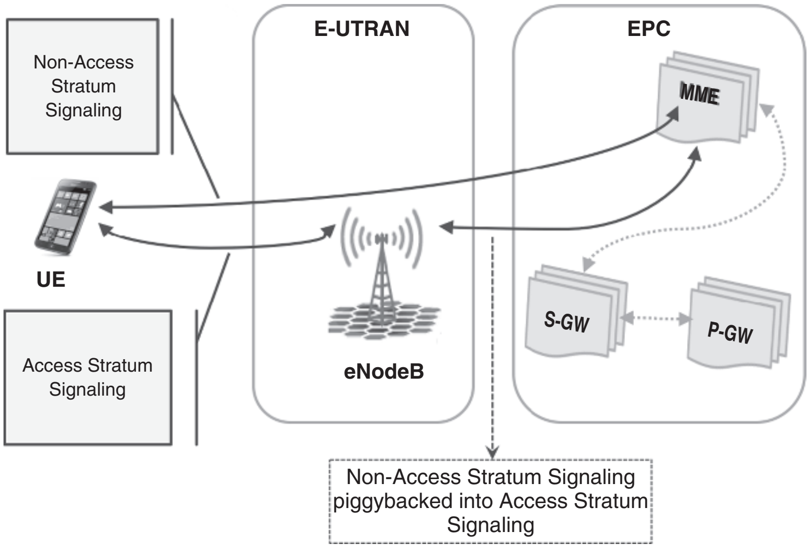


Figure 1.19 EPS access and non-access strata.

Non-Access Stratum (NAS) layer between the UE and the EPC.

Responsible for handling control plane messaging related to the core network.

NAS includes two main protocols: EMM and ESM.

The LTE system is designed to simplify the procedures carried on the EPS. This is possible by designing and assigning the required identifiers at different interfaces within the EPS system. The different identities defined in the EPS system are shown in Figure 1.20. Different types of identifiers are needed between the eNB and the UE as part of the RNTI. These RNTIs are used for different procedures such as paging, random access, and system information on the air interface. A list of EPS identifiers with descriptions and assignments is provided in Table 1.13.

1.8.2 EPS Mobility Management (EMM)

EMM is a control plane entity which manages the mobility states of the UE:

The main EMM function is similar to that in the PS domain of UMTS/GERAN – to provide attach, detach, and TAU (Tracking Area Updates).

NAS security is an additional function of the NAS, providing services to the NAS protocols, for example, integrity protection and ciphering of NAS signaling messages.

LTE has been designed with “ready-to-use” IP connectivity and an “always-on” experience, so there is a linkage between mobility management and session management procedures during the attach procedure.

The success of the attach procedure is dependent on the success of the default EPS bearer context activation procedure.

EMM procedures supported by the NAS protocol in the UE and NW are summarized in Table 1.14. The EMM common procedure can always be initiated whilst a NAS signaling connection exists. Only one UE-initiated, EMM-specific procedure can be running at any time.

1.8.3 Session Management (ESM)

The basic EPS session management (ESM) function is a control plane activity which manages the activation, modification, and deactivation of EPS bearer contexts. These can either be default or dedicated EPS bearer contexts. Table 1.15 summarizes the EMS procedures. The transaction procedure enables the UE to request resources (IP connectivity to a PDN or dedicated bearer resources). The EPS bearer context procedure is always initiated by the NW. The transaction-related procedures are initiated by the UE, with the exception of the ESM information request procedure. The ESM status and notification procedure can be related to an EPS bearer context or to a transaction procedure.

1.8.3.1 Notification Procedure

The network can use the notification procedure to inform the UE about events which are relevant to the upper layer which is using an EPS bearer context or has requested a transaction procedure. If the UE has indicated that it supports the notification procedure, the network may initiate the procedure at any time while a PDN connection exists or a transaction procedure is ongoing.

1.8.3.2 ESM Status Procedure

The purpose of sending the ESM Status message is to report, at any time, certain error conditions detected upon receipt of ESM protocol data. The ESM Status message can be sent by either the MME or the UE.

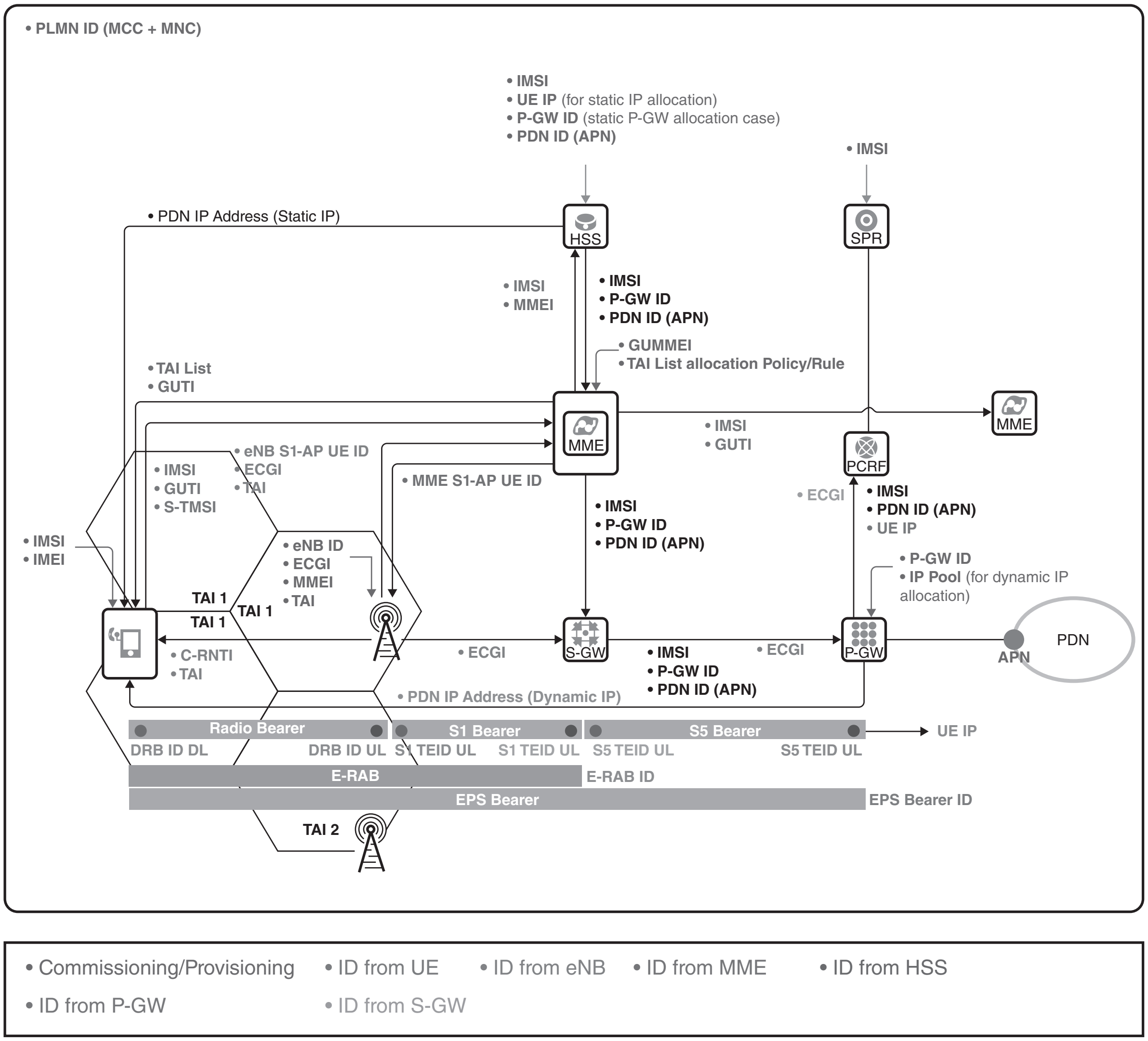


Figure 1.20 EPS identifiers.

1.8.4 EPS Idle and Active States

On the air interface, the UE typically transitions into the RRC Idle state after successfully attaching to the LTE system [3]. The UE remains in this state as long as there are no radio interface downlink or uplink packet activities with the eNB. When a data activity is initiated by a user or an application installed on the device, the UE immediately transits into RRC Connected state and remains in this state until the packet connectivity timer, known as the "User Inactivity timer," expires. The timer is configured in the eNB and is used to monitor the data activity for a user within a timed window. When the timer expires, the eNB releases the RRC connection and immediately triggers the UE's transition to the RRC Idle state.

The concepts of NAS and AS states are also available in 3G systems. In the UMTS air interface, the RRC states can be in either Connected or Idle mode. In Connected mode, the UE can be served in four different states: Cell_DCH, Cell_FACH, Cell_PCH, or URA_PCH. The state transitions in the LTE air interface are simplified to only Idle and Connected modes, avoiding all the timers and optimizations. The RRC-level state transition from Connected to Idle mode targets an improved battery lifetime of the device. The battery consumption is expected to be more efficient in Idle state when there is no connectivity or dedicated resource between the device and the eNB. The UE states are shown in Figure 1.21.

The LTE concept is a little different from the UMTS, as the main target is to keep the LTE system "always on". The user plane data can only flow when all the AS and NAS signaling connections and bearers are in Active/Connected states.

The ECM state and the EMM state are independent of each other. Table 1.16 provides a comparison between EMM and ECM states.

Table 1.13 EPS identifiers.

Identifier	Description	Assignment
IMSI	International Mobile Subscriber Identity	Unique identification of mobile (LTE) subscriber. Network (MME) gets the PLMN of the subscriber.
PLMN ID	Public Land Mobile Network Identifier	Unique identification of PLMN.
MCC	Mobile Country Code	Assigned by regulator.
MNC	Mobile Network Code	Assigned by regulator.
MSIN	Mobile Subscriber Identification Number	Assigned by operator.
GUTI	Globally Unique Temporary UE Identity	Identifies a UE between the UE and the MME on behalf of the IMSI for security reasons.
TIN	Temporary Identity used in Next Update	GUTI is stored in the TIN parameter of the UE's MM context. The TIN indicates which temporary ID to use in the next update.
S-TMSI	SAE Temporary Mobile Subscriber Identity	Locally identifies a UE in short within an MME group (unique within an MME pool).
M-TMSI	MME Mobile Subscriber Identity	Unique within an MME.
GUMMEI	Globally Unique MME Identity	Identifies an MME uniquely in global terms. GUTI contains GUMMEI.
MMEI	MME Identifier	Identifies an MME uniquely within a PLMN. Operator commissions at eNB.
MMEGI	MME Group Identifier	Unique within PLMN.
MMEC	MME Code	Identifies an MME uniquely within an MME group. S-TMSI contains MMEC.
C-RNTI	Cell-Radio Network Temporary Identifier	Identifies a UE uniquely in a cell.
eNB S1AP UE ID	eNB S1 Application Protocol UE ID	Uniquely identifies a UE on the S1-MME interface in the eNB.
MME S1AP UE ID	MME S1 Application Protocol UE ID	Uniquely identifies a UE on the S1-MME interface in the MME.
IMEI	International Mobile Equipment Identity	Identifies an ME (Mobile Equipment) uniquely.
IMEI/SV	IMEI/Software Version	Identifies an ME uniquely.
ECGI	E-UTRAN Cell Global Identifier	Identifies a cell globally. EPC knows the UE location based on the ECGI.
ECI	E-UTRAN Cell Identifier	Identifies a cell within a PLMN.
Global eNB ID	Global eNodeB Identifier	Identifies an eNB globally in the network.
eNB ID	eNodeB Identifier	Identifies an eNB within a PLMN.
P-GW ID	PDN GW Identifier	Identifies a specific PDN-GW. HSS assigns P-GW for PDN connection of each UE.

1.8.5 EPS Network Topology for Mobility Procedures

In the example shown in Figure 1.22, if the UE performs EPS registration from TAI_A, the MMEs send TAC_1 and TAC_2 in the TAI list, implying that the UE can roam around in the eNBs with the TACs belonging to this TAI list without having to re-register with the EPS network. This procedure saves on the signaling load. The UE re-registers with a tracking area update procedure if the UE enters into the coverage areas of eNBs that are part of TAC_3 (in TAI_B) and TAC_4 (in TAI_C).

The TA dimensioning and planning in the network are performed in the optimization stage. TA planning can prevent the ping-pong effect of tracking area updating to achieve optimization between paging load, registration overhead, the UE battery, and an improved paging success rate. In the same example, the paging area for the UE served in TAI_A will be for all cells belonging to TAC_1 and TAC_2, but the registration area will be limited to

Table 1.14 EMM procedures supported by the NAS protocol in both the UE and NW.

EMM Procedure Type	EMM Message
EMM common procedure	GUTI reallocation Authentication Security mode control Identification EMM information
EMM specific procedure	Attach Tracking area updating Detach
EMM connection management procedure	Service request Paging procedure Transport of NAS messages

Table 1.15 EPS session management (ESM).

ESM Procedure Type	ESM Message
Procedures related to EPS bearer contexts	Default EPS bearer context activation Dedicated EPS bearer context activation EPS bearer context modification EPS bearer context deactivation
Transaction-related procedures	ESM status procedure Notification procedure PDN connectivity procedure PDN disconnect procedure Bearer resource allocation procedure Bearer resource modification procedure ESM information request procedure

TAI_A only. TA updating can be either periodical or based on the mobility conditions of the device. An MME area consists of one or more tracking areas. All cells served by an eNB are included in an MME area. There is no one-to-one relationship between an MME area and an MSC/VLR area. Multiple MMEs may have the same MME area (pool area).

- A tracking area corresponds to the concept of the Routing Area (RA) used in UMTS.
- The TA consists of a cluster of eNBs having the same Tracking Area Code (TAC).
  - The TAC provides a means of tracking a UE's location in Idle mode.
  - TAC information is used by the MME when paging an idle UE to notify it of incoming data connections.
- The MME sends the tracking area identity list, abbreviated to the TAI list, to the UE during the TA update procedure or the attach procedure.
  - TA updates occur periodically or when a UE enters a cell with a TAC not in the current TAI list.
- The TAI list makes it possible to avoid frequent TA updates due to ping-pong effects along TA borders.
  - This is achieved by including the old TAC in the new TAI list received at TA update. When the MME pages a UE, a paging message is sent to all cells in the TAI list.

1.9 LTE Air Interface

1.9.1 Multiple Access in 3GPP Systems

UMTS, cdmaOne, and CDMA2000 all use the CDMA air interface. The implementation of the codes and the bandwidths used is different among these systems. UMTS utilizes a 5 MHz channel bandwidth, whereas cdmaOne uses only 1.25 MHz.

The LTE air interface utilizes two different multiple access techniques, both based on OFDM (Orthogonal Frequency Division Multiplexing):

- OFDMA (Orthogonal Frequency Division Multiple Access) – used on the downlink.
- SC-FDMA (Single Carrier-Frequency Division Multiple Access) – used on the uplink.

CDMA and OFDM are summarized in Figure 1.23.

OFDMA on the downlink has the following advantages:

- OFDM is almost completely resistant to multi-path interference due to very long symbol duration.
- Higher spectral efficiency for wideband channels.
- Flexible spectrum utilization.

However, an OFDM system can suffer from high PAPR (Peak-to-Average Power Ratio) when compared to typical single-carrier systems.

OFDMA generates multiple frequencies, used to transmit useful information simultaneously. It increases spectral efficiency by reducing the spacing between the subcarriers that carry different information. Theoretically, this ensures that each subcarrier does not interfere with the adjacent subcarrier. The downlink can use resource blocks freely from different parts of the spectrum.

SC-FDMA was specified for the uplink because of its PA (Power Amplifier) characteristics. An SC-FDMA signal will operate with a lower PAPR, thus increasing the

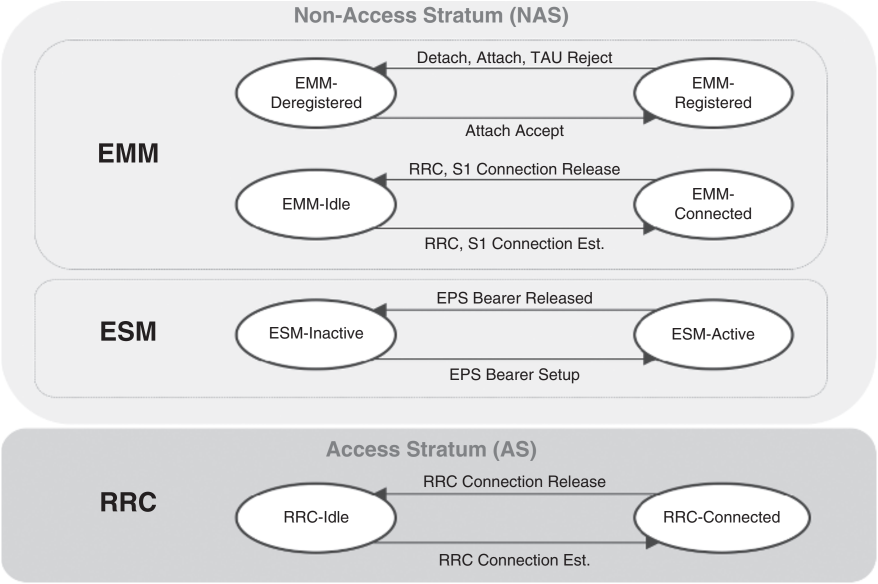


Figure 1.21 EPS Idle and Active states.

Table 1.16 Comparison between EMM and ECM states.

Layer	State	Description
EMM	EMM-Deregistered	The UE is not successfully attached to the LTE network, so the location of the UE is unknown to an MME and hence it is unreachable by an MME. The UE needs to initiate a (combined) attach procedure to establish an EMM context between the UE and the MME.
	EMM-Registered	The EMM context has been established and a default EPS bearer context has been activated in the UE. The UE position is known to the MME with an accuracy of cell level (ECM-Connected) or tracking area level (ECM-Idle).
ECM	ECM-Idle	No NAS signaling connection has been established. The UE will perform a cell selection/reselection procedure.
	ECM-Connected	A NAS signaling connection has been established and the UE has been assigned radio resource. The mobility of the UE is handled by the NW-controlled handover procedure.

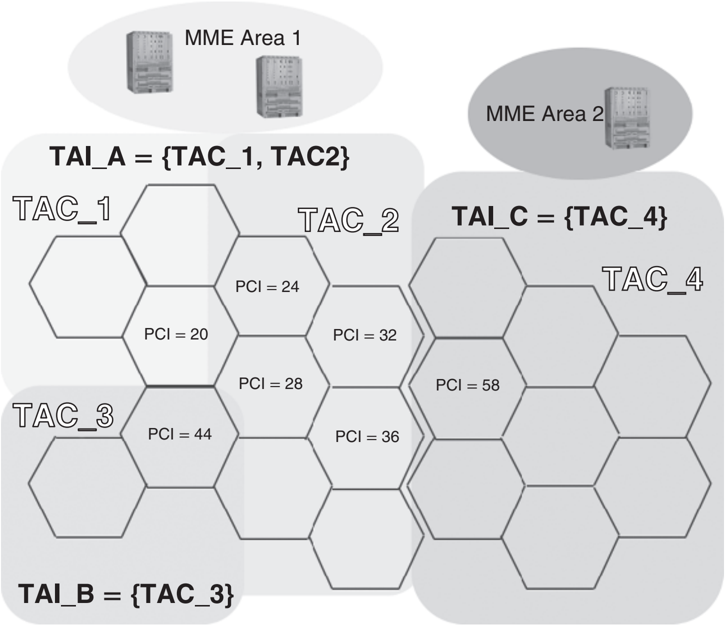
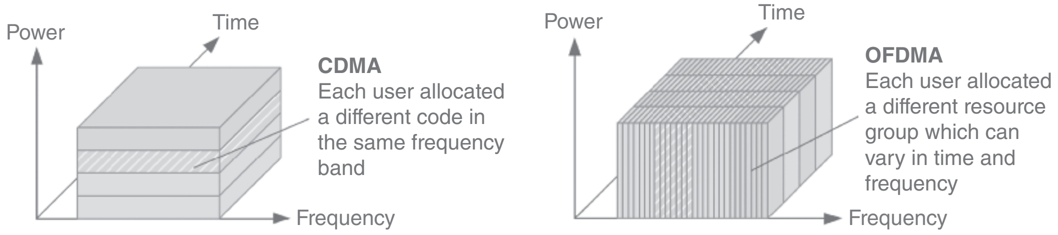


Figure 1.22 EPS network topology.



- The narrowband signals are spread with a wideband code and then transmitted
- The receivers are designed to extract the encoded signal (with the specific code) and treat everything else as noise

- The bandwidth is broken down to smaller units known as “subcarriers”
- These are grouped together and allocated as a resource to a device. The device can be allocated different resources in both the time and frequency domain

Figure 1.23 CDMA and OFDM.

battery life for users, allowing efficient terminal power amplifier design, and providing a better uplink cell coverage.

SC-FDMA produces a waveform associated with a single-carrier system:

Each symbol is sent one at a time, in a similar manner to Time Division Multiple Access (TDMA).

The uplink user-specific allocation is continuous to enable single-carrier transmission.

Figure 1.24 illustrates the difference between OFDMA and SC-FDMA.

1.9.2 Time–Frequency Domain Resources

The LTE air interface has procedures similar to those in HSPA. The main difference is that LTE uses OFDMA instead of WCDMA. This requires changes in the physical layer as well as enhancements in some of the MAC and RLC functionality.

Figure 1.25 shows a possible allocation of the PHY layer downlink channels into the OVSF code tree. In this figure, each channel is assigned a separate OVSF code. For example, the HSDPA channel is assigned spreading factor (SF) 16. All SFs below the used codes of SF 16 will be blocked, as they would not maintain channel orthogonality. Consequently, SF allocation between the channels is important to ensure all channels and users are allocated a separate code when a call is initiated in the cell.

The LTE-FDD frame structure is demonstrated in Figure 1.26. The E-UTRA air interface is based on OFDMA. The LTE-FDD frame structure has the following characteristics:

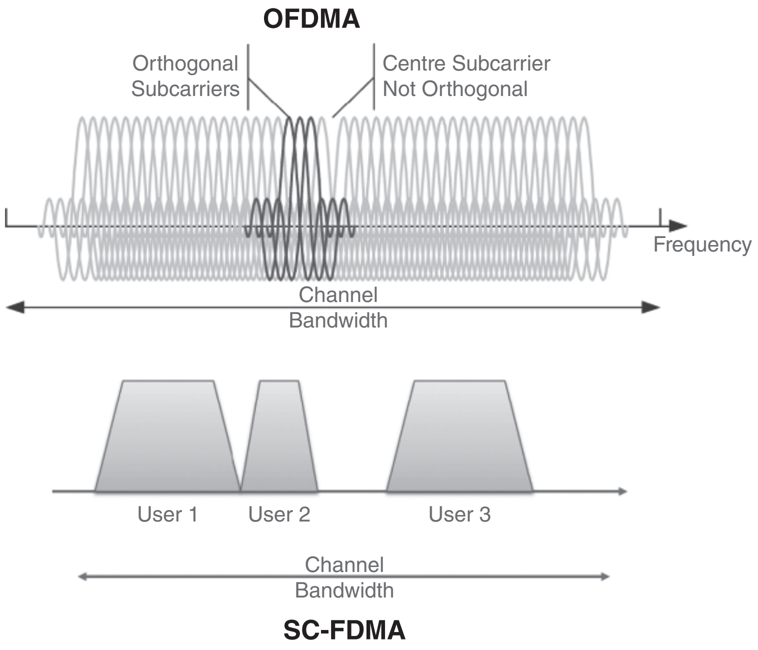


Figure 1.24 OFDMA versus SC-FDMA.

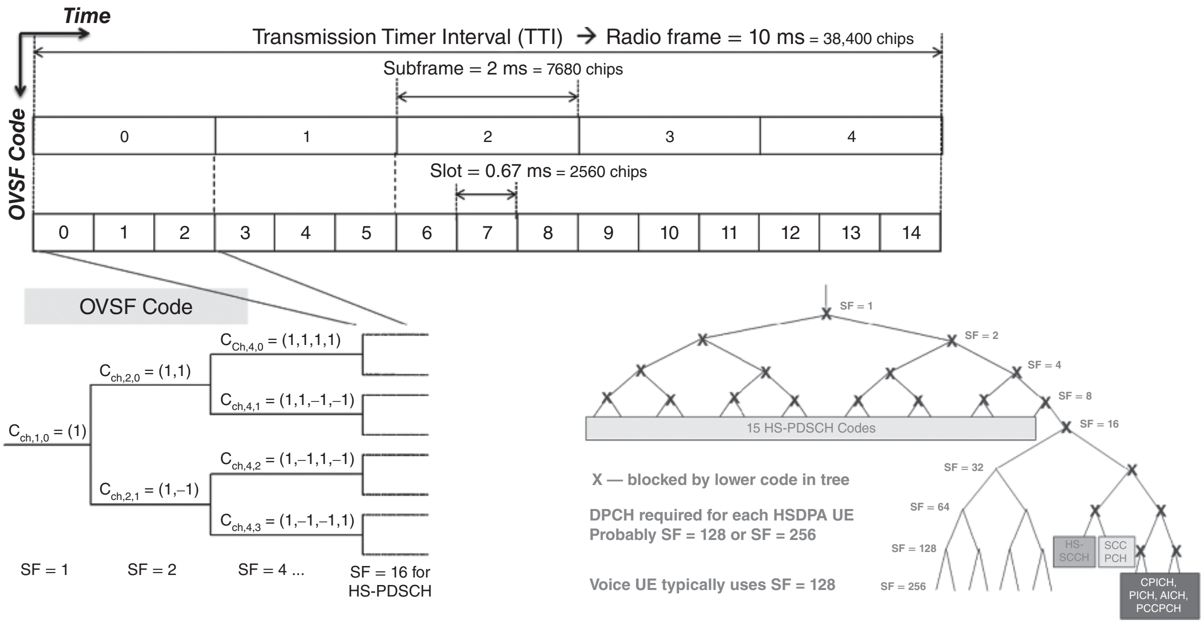


Figure 1.25 WCDMA frame structure.

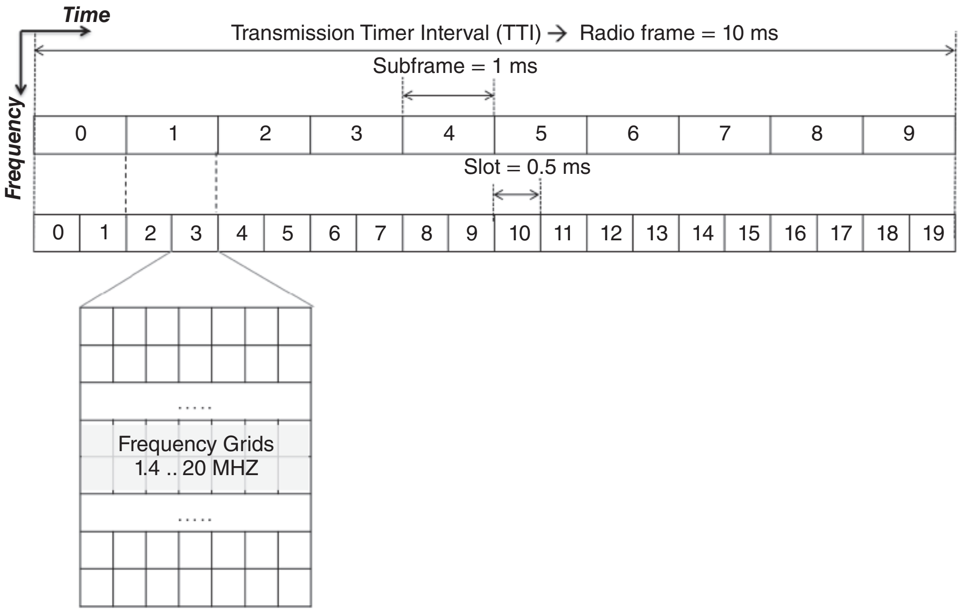


Figure 1.26 LTE-FDD frame structure.

It enables multiple devices to receive information at the same time but on different parts of the radio channel.

In most OFDMA systems, this is referred to as a "subchannel", i.e. a collection of subcarriers.

However, in E-UTRA, the term subchannel is replaced by the term PRB (Physical Resource Block).

A PRB is used in LTE to describe the physical resource in the time/frequency grid.

E-UTRA uses a variable channel bandwidth of 1.4, 3, 5, 10, 15, or 20 MHz with an OFDMA downlink and an SC-FDMA uplink.

Figure 1.27 illustrates physical resource blocks and resource elements (REs) in LTE-FDD. A PRB consists of 12 consecutive subcarriers and lasts for one slot, 0.5 ms. Each subcarrier is spaced by 15 kHz. The N_{RB}^{DL} parameter is used to define the number of RBs (resource blocks) used in the downlink. This is dependent on the channel bandwidth. In contrast, N_{RB}^{UL} is used to identify the number of resource blocks in the uplink. Each RB consists of N_{SC}^{RB} subcarriers, which, for standard operation, is set to 12 or a total of 180 kHz lasting in the 0.5 ms slot. The PRB is used to identify an allocation. It typically

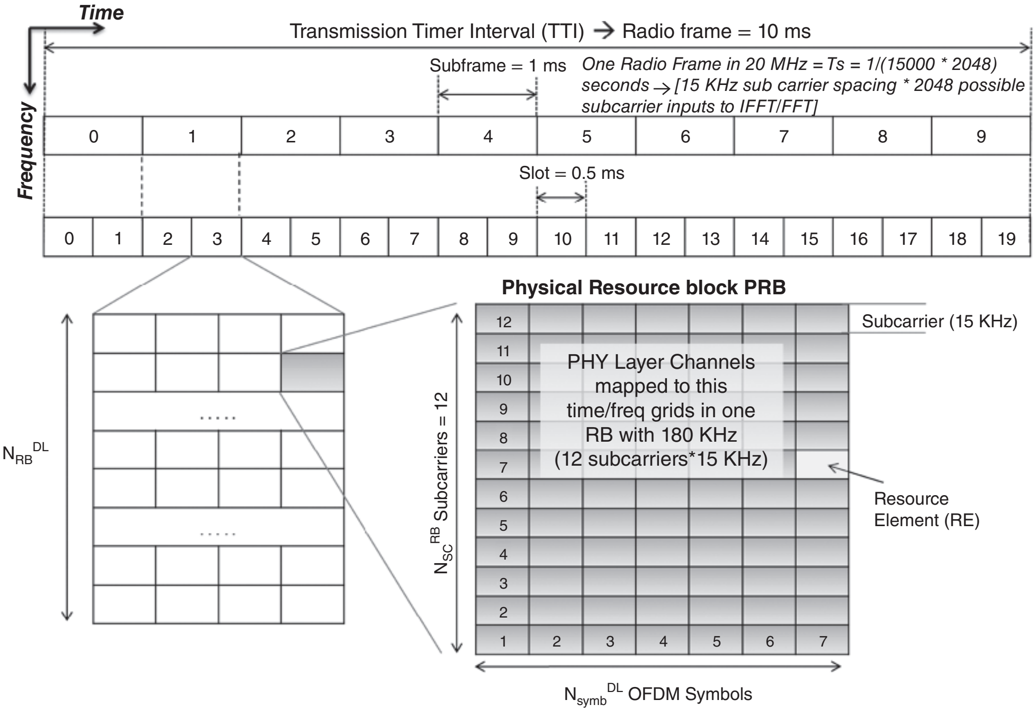


Figure 1.27 Physical resource block and resource element in LTE-FDD.

includes six or seven symbols, depending on whether an extended or normal cyclic prefix is configured [4].

The term RE (resource element) is used to describe one subcarrier lasting one symbol. This can then be assigned to carry modulated information, reference information, or nothing. The RB resources assigned to a specific UE by the eNodeB scheduler can be contiguous, where subcarriers from one RB to another are sequential; this is referred to as a "Localized Virtual Resource Block". Alternatively, the RB resources scheduled to a UE can be distributed in such a way that some resources are continuous and some are assigned a pre-defined distance away; this is referred to as a "Distributed Virtual Resource Block".

For the control information channel, such as the PDCCH, the time/frequency grid shares parts of the bandwidth with the data channels, such as PDSCH. Therefore, the control region is limited up to the first three symbols of the subframe for large bandwidths and up to four symbols for small bandwidths. This allocation is defined by the Control Channel Element (CCE) and the Resource Element Group (REG). Each CCE consists of 36 usable REs derived from 9 REGs * 4 usable REs per REG [5].

Time domain frame arrangements are illustrated in Table 1.17. The type 2 radio frame structure is used for TDD. One key addition to the TDD frame structure is the concept of "special subframes". This includes a DwPTS (Downlink Pilot Time Slot), GP (Guard Period), and UpPTS (Uplink Pilot Time Slot). These have configurable individual lengths and a combined total length of 1 ms. There are various frame configuration options supported for TDD. Configuration options 0, 1, 2, and 6 have a 5 ms switching point and therefore require two special subframes, whereas the rest are based on a 10 ms switching point. In Table 1.17, the letter "D" is reserved for downlink transmissions, "U" denotes subframes reserved for uplink transmissions, and "S" denotes a special subframe with the three fields: DwPTS, GP, and UpPTS.

Frequency domain frame arrangements are shown in Table 1.18. A DC (direct current) subcarrier is located at the center of the frequency band. It can be used by the UE to locate the center of the frequency band. There are two guard bands at the edges of the band to avoid interference with adjacent bands.

The LTE transmission scheme provides a time resolution of 12 or 14 OFDM symbols for each subframe of 1 ms, depending on the length of the OFDM cyclic prefix. The frequency resolution provides for a number of resource blocks ranging from 6 to 100, depending on the bandwidth, each containing 12 subcarriers with 15 kHz spacing. Different types of data occupy the resource elements that make up the resource grid. The various physical channels and signals that constitute the content of the resource grid are described in the next section.

Table 1.17 Time domain frame arrangements.

Component	Configuration		
Frame types	FS-1: Used for LTE-FDD UL and DL FS-2: Used for LTE-TDD where DL and UL are sharing the same frame		
Frame	10 ms		
Subframe	1 ms (= the “TTI”, Time Transmission Interval)		
Slot	0.5 ms		
	Normal Cyclic Prefix	Extended Cyclic Prefix	MBSFN [a)]
# OFDM symbols/slot	7	6	3
Cyclic prefix length (μs)	5.2 for first symbol 4.69 for other symbols	16.67	33.3

a) MBSFN is used for multimedia broadcast over a single-frequency network (eMBMS).

Table 1.18 Frequency domain frame arrangements for different BW.

Component	1.4 MHz	3 MHz	5 MHz	10 MHz	15 MHz	20 MHz
Guard band	~22%	10%	10%	10%	10%	10%
Subcarrier spacing (kHz)	15	15	15	15	15	15
DC subcarrier	1	1	1	1	1	1
# of resource blocks	6	15	25	50	75	100
# of subcarriers (without DC)	72	180	300	600	900	1200
Total bandwidth available (MHz)	1.1	2.7	4.5	9	13.5	18

The RG for channels greater than 1.4 MHz is illustrated in Figure 1.28. Each resource element contains the modulated symbol for three different types of information contained in the physical resource grid:

User data: Physical layer channels carrying data for the users.

Variable allocation and bandwidth depending on user data demand and available cell capacity.

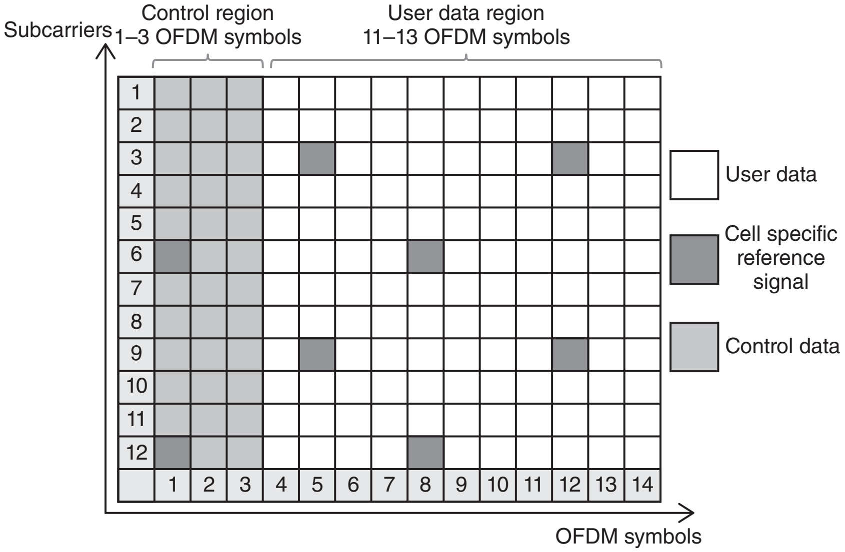


Figure 1.28 Resource grid arrangements.

Reference or synchronization signals: Physical layer channels carrying the pilot or sync channels.
  Fixed allocation and bandwidth depending on the number of antennas configured.
Control information/region: Physical layer channels carrying control-related information needed to decode the user data channels.
  Variable bandwidth depending on channel conditions and cell capacity.

Total user throughput depends on the overhead that the control information and reference signals occupy from the total bandwidth available.

In an OFDM time–frequency grid, up to four symbols of the frame are used for the control channels. These channels are PCFICH, PHICH, and PDCCH. The standard allows dynamic or static symbol assignment. The PDCCH capacity depends on the channel BW (the number of REs) and the required RE for the scheduled UE. The PDCCH consists of Control Channel Elements (CCEs), each CCE is 36 REs. The CCEs form the control region per subframe and can occupy up to four symbols. The number of supported users will depend on the available number of CCEs that can serve the control channel assigned to schedule user data channels for each user. Note the following:

The control region is arranged by:
  Control Channel Elements (CCEs) and the Resource Elements Group (REG).
  Each CCE consists of 36 usable REs derived from 9 REGs * 4 usable REs per REG.
  The total number of CCEs available in the cell depends on the system bandwidth and the number of OFDM symbols allocated for control information in a subframe.
This bandwidth is signaled dynamically in each subframe:
  1, 2, or 3 OFDM symbols/subframe for bandwidths above 1.4 MHz.
  2, 3, or 4 OFDM symbols/subframe for bandwidths of 1.4 MHz.

A dedicated physical channel called the PCFICH is used to indicate to the UE this information.

1.10 OFDM Signal Generation

Figure 1.29 illustrates downlink physical layer processing [5]. MIMO builds on Single Input, Multiple Output (SIMO), also called Receive Diversity (RxD), as well as Multiple Input, Single Output (MISO), also called Transmit Diversity (TxD). Both of these techniques seek to boost the SNR in order to compensate for signal degradation. As a signal passes from Tx to Rx, it gradually weakens, while interference from other RF signals also reduces the SNR. In addition, in dense urban environments, the RF signal frequently encounters objects which alter its path or degrade the signal. Multiple-antenna systems can compensate for some of the loss of SNR due to multi-path conditions by combining signals that have different fading characteristics, as the path from each antenna will be slightly different.

However, SIMO or MISO systems may not be fully suitable for the high-speed data rates promised in 3GPP's next generation of cellular systems. Therefore, the full version of MIMO can achieve benefits in terms of both increased SNR and throughput gains. MIMO in 3GPP exploits several concepts such as spatial multiplexing, transmit diversity, beamforming, and multi-user MIMO. All these techniques fall into two categories: open loop or closed loop.

A MIMO system utilizes the space and time diversity in a multi-path rich environment and creates multiple parallel data transmission pipes on which data can be carried:

The data pipes are realized with proper digital signal processing.
A transmission pipe does not correspond to an antenna transmission chain or any one particular signal path.
The rank of the MIMO system is limited by the number of transmitting or receiving antennas, whichever is lower.
Codewords, layers, antenna ports, and pre-coding are described below.

The *pre-coding* stage performs the mapping of the complex-valued modulation symbols onto each layer for transmission. Pre-coding allows the adjustment of the

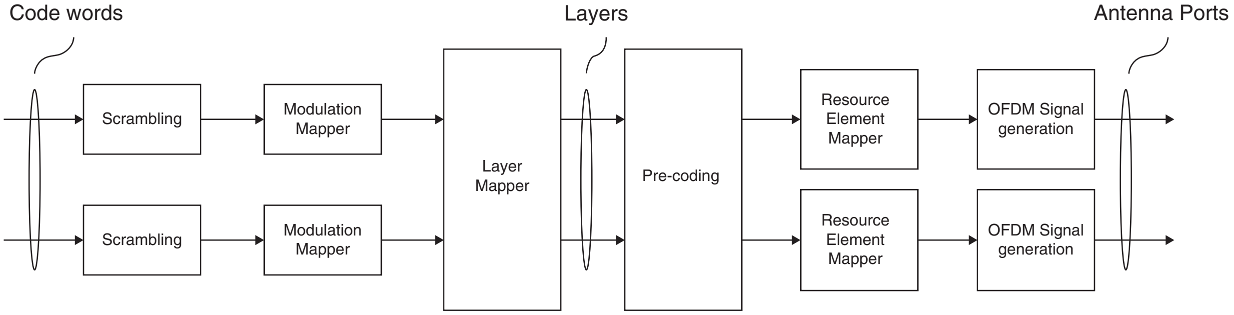


Figure 1.29 Downlink physical layer processing.

phase shift of the signal on each layer. *Resource element mapping* transforms the complex-valued symbols to the allocated resources. For each of the antenna ports used for transmission of the physical channel, the block of complex-valued symbols is mapped in sequence to *resource elements*. At this stage, the resource grids, which allocate the required physical resource blocks, are ready for transmission. The final physical layer processing stage is the actual *OFDM signal generation*. This generates the time-domain signals for each antenna. This is a signal processing procedure.

1.10.1 Main Definitions for MIMO

A MIMO antenna port, codeword, layer, and channel rank are illustrated in Figure 1.30 and we will define them below.

Antenna port

- Antennas are logical ports used for transmission. They have no one-to-one relationship with physical antennas.
- Signals on an antenna port can be transmitted over one or more physical antennas.
- Different antenna ports are used to transmit different reference signals.

Codeword

- Codewords are data blocks formed after channel coding. Different codewords represent different data blocks.
- By transmitting different data blocks, MIMO implements spatial multiplexing.
- To reduce the overhead on CQI and ACK/NACK reporting, LTE supports a maximum of two codewords. In transmit diversity, the number of codewords is one.
  - When there is only one antenna at the transmit or receive end, the number of codewords can only be one.
- When there are two or more antennas at both transmit and receive ends, the number of codewords depends on the radio channel conditions and the UE category. Dual-codeword transmission is mainly used in scenarios with high SINR, low channel correlation, and a UE category of 2 or above.

Layer

- The number of codewords may be different from the number of transmit antenna ports. Therefore, codewords need to be mapped to transmit antenna ports. This is implemented through layer mapping and pre-coding.
- In transmit diversity, the number of layers is equal to the number of antenna ports for transmitting cell-specific reference signals.
- In spatial multiplexing, the number of layers is equal to the number of independent data blocks.
- Downlink 2 × 2 MIMO and 4 × 2 MIMO support a maximum of two layers, and downlink 4 × 4 MIMO supports a maximum of four layers.

Channel rank

- The rank of transmit diversity is 1, and the rank of spatial multiplexing is equal to the number of layers.
- Downlink 2 × 2 MIMO and 4 × 2 MIMO support ranks 1 or 2, and downlink 4 × 4 MIMO supports ranks 1, 2, 3, or 4.

The DL or UL codewords are generated prior to insertion into the scrambler by applying the following steps:

Transport-block CRC (Cyclic Redundancy Check) attachment.
Code-block segmentation and code-block CRC attachment.
Turbo coding.
Rate matching to handle any requested coding rates.
Code-block concatenation to generate codewords.

1.10.2 Scrambling

In LTE downlink processing, the codeword bits generated as the outputs of the channel coding operation are scrambled using different scrambling sequences. The initial stage of the physical layer processing is scrambling.

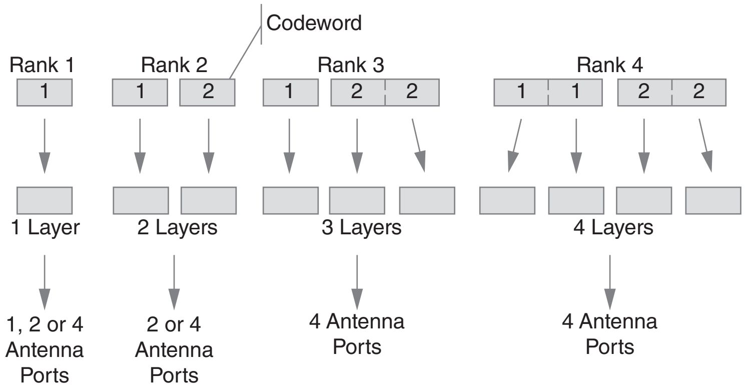


Figure 1.30 MIMO rank, codeword, layer, and antenna port.

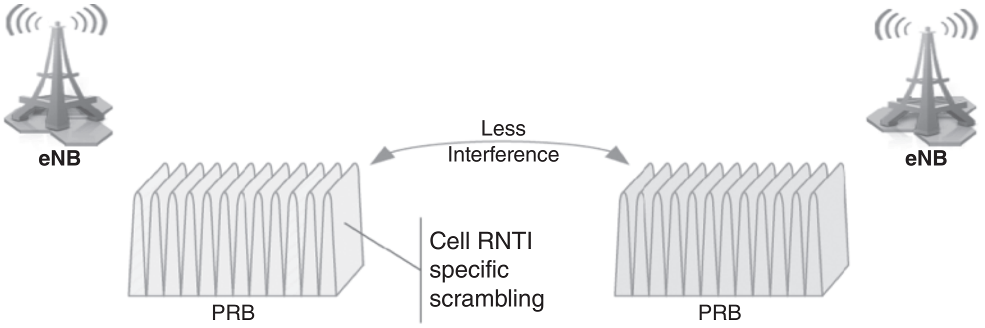


Figure 1.31 Scrambling operation.

This stage is applied to the signal in order to provide interference rejection properties. Scrambling effectively randomizes interfering signals using a pseudo-random scrambling process. Different scrambling sequences are used in neighboring cells to ensure that the interference is randomized and that transmissions from different cells are separated prior to decoding. In order to achieve this, data bits are scrambled with a sequence that is unique to each cell by initializing the sequence generators in the cell based on the PHY cell identity. Different channels are transmitted with different associated RNTIs (Radio Network Temporary Identifiers) obtained for each procedure: paging, system information blocks, data information, RACH, SPS, etc. Different RNTI assignments for each cell scramble the channels with a sequence that is unique to each cell (RNTIs are described in the next section). The scrambling improves the interference by scrambling the user data information with a scrambling code based on the physical cell ID and RNTI. Figure 1.31 highlights the scrambling operation.

1.10.3 Higher-order Modulation

For the downlink, up to 3GPP Release 11, only 64QAM was used. Later, 256QAM was introduced by 3GPP. UE Categories 11, 12, and 13 utilize 256QAM to achieve higher downlink throughput. 64QAM is used in the UL as the maximum modulation technique. The modulation stage converts the scrambled bits into complex-valued modulated symbols using one of: BPSK, QPSK, 16QAM, 64QAM, or 256QAM. Table 1.19 presents different modulation schemes.

The layer-mapping stage effectively maps the complex-valued modulated symbols onto one or several transmission layers. It splits the data into a number of layers that are configured depending on the transmission mode of the MIMO used. There are several options for layer mapping:

Single antenna mapping: For transmission on a single antenna port.

Table 1.19 Modulation schemes.

Modulation	Bits per Symbol	Typical Channel Usage in LTE
BPSK	1	Uplink or downlink control channels
QPSK	2	Uplink or downlink control and data channels
16QAM	4	Uplink and downlink data channels
64QAM	6	Uplink and downlink data channels
256QAM	8	Uplink and downlink data channels (introduced in LTE-A)

Spatial multiplexing: Mapping multiple codewords onto multiple antennas to improve the data throughput of the channel.

Transmit diversity: There is only one codeword and the number of layers is equal to the number of antenna ports used for transmission of the physical channel.

1.11 LTE Channels and Procedures

The LTE air interface provides connectivity between the user equipment and the eNB. It is split into a control plane and a user plane. Among the two types of control plane signaling, the first is provided by the access stratum and carries signaling between the UE and the eNB. The second carries non-access stratum signaling messages between the UE and the MME, which are piggybacked onto an RRC message. The user plane delivers the IP packets to and from the EPC, S-GW, and PDN-GW.

The structure of the lower-layer protocols for the control and user planes in the AS is the same. Both planes utilize the protocols of PDCP (Packet Data Convergence Protocol), RLC (Radio Link Control), and MAC (Medium Access Control) as well as the PHY (Physical Layer) for the transmission of the signaling and data packets.

The NAS is the layer above the AS layers. There are also two planes in the NAS: the higher-layer signaling related to the control plane and the IP data packets of the user plane. NAS signaling exists in two protocol layers, the EMM and the ESM. The NAS user plane is IP-based. The IP data packets pass directly into the PDCP layer for processing and transmission to or from the user.

The concept of "channels" is not new. Both GSM and UMTS define various channel categories; however, LTE terminology is closer to UMTS. There are three main categories of channels in addition to the radio bearer configured by the RRC and NAS, described in detail in the previous section. Figure 1.32 illustrates the LTE channel mapping of protocol layers.

Three layers of channels are defined in the downlink, as follows:

Logical channels: The interface between the MAC and the RLC provides the logical channels.

Control logical channels – The various forms of these channels include:

BCCH (Broadcast Control Channel) – A downlink channel used to send SI (System Information) messages from the eNB. These are defined by the RRC.

PCCH (Paging Control Channel) – A downlink channel used by the eNB to send paging information.

CCCH (Common Control Channel) – Used to establish an RRC (Radio Resource Control) connection, SRB. The SRB is also used for re-establishment procedures after any call drop. SRB0 maps to the CCCH. These are for both uplink and downlink.

DCCH (Dedicated Control Channel) – Provides a bidirectional channel for signaling. Two DCCHs are activated. One is used for SRB1 carrying RRC messages, as well as high-priority NAS signaling. The other is used for SRB2 carrying low-priority NAS signaling piggybacked onto RRC messages. Prior to its establishment, low-priority signaling is sent on SRB1.

Traffic logical channels:

DTCH (Dedicated Traffic Channel) – Used to carry DRB (Dedicated Radio Bearer) IP packets. The DTCH is configured for uplink and downlink.

Transport channels: In UMTS, transport channels (TrCh) were split between common and dedicated channels. However, LTE has moved away from dedicated channels in favor of common/shared channels.

BCH (Broadcast Channel) – A fixed-format channel which occurs once per frame and carries the MIB (Master Information Block). Note that the majority of system information messages are carried on the DL-SCH.

PCH (Paging Channel) – Used to carry the PCCH, i.e. paging messages.

DL-SCH (Downlink-Shared Channel) – This is the main downlink channel for data and signaling. It supports dynamic scheduling as well as dynamic link adaptation. In addition, it supports HARQ operation to improve performance. As previously mentioned, it also facilitates the system information messages.

RACH (Random Access Channel) – Carries limited information and is used in conjunction with physical channels and preambles to provide contention resolution procedures.

UL-SCH (Uplink-Shared Channel) – Similar to the DL-SCH, this channel supports dynamic scheduling (eNB controlled) and dynamic link adaptation

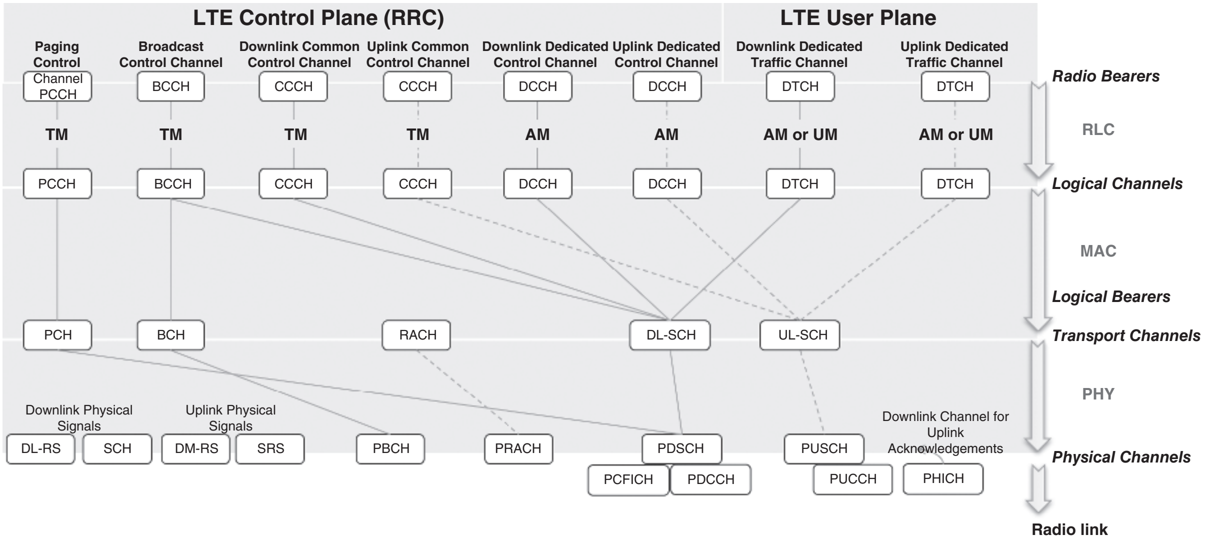


Figure 1.32 LTE channel mapping of protocol layers.

by varying the modulation and coding. In addition, it supports HARQ operation to improve the link performance.

Physical channels: The physical layer facilitates transportation of MAC TrCh as well as providing scheduling, formatting, and control indicators. The TB coming from the MAC layer is mapped onto the corresponding PHY channel to be sent over the air. The TB size is tied to the channel quality feedback from the UE such as CQI and RI. CRC (Cyclic Redundancy Check) bits are added to the TB. The purpose of the CRC is to detect errors which may have occurred when the data were being sent. The UE uses the CRC bits to detect errors on the PDSCH for HARQ retransmissions. The physical layer performs other functions on the TB such as channel coding and rate matching to ensure reliable transmission of the TB over the air.

1.11.1 LTE Physical Layer Channels

The LTE PHY layer, referred to as L1, provides a new channel structure. The main functions provided by the PHY layer in LTE are described below:

- Services with higher layers
  - Error detection on the transport channel and indication to higher layers.
  - FEC encoding/decoding of the transport channel.
  - Hybrid ARQ soft-combining.
  - Rate matching of the coded transport channel to physical channels.
  - Mapping of the coded transport channel onto physical channels.
- Power control
  - Power weighting of physical channels.
- Radio link
  - Modulation and demodulation of physical channels.
  - Frequency and time synchronization.
  - Radio characteristic measurements and indication to higher layers.
  - RF signal processing.
- Multiple Input, Multiple Output (MIMO)
  - MIMO antenna processing.
  - Transmit diversity (Tx diversity).
  - Beamforming.

The main L1 physical layer channels in the DL and UL are summarized in Figure 1.33, and other channels are summarized in Table 1.20.

1.11.2 Downlink Synchronization Channels

The SCH comprises the PSS (Primary Synchronization Signal) and the SSS (Secondary Synchronization Signal). Together they enable the UE to identify the Physical Cell Identity (PCI) and then synchronize any further transmissions. There are 504 unique PCIs, divided into 168 cell identity groups, each containing three cell identities (sectors). Once a PCI is identified and both slot and frame synchronization have been done through the PSS and SSS, the UE acquires the strongest cell measured during this cell search stage, known as the acquisition stage. The same PCI should be avoided within the same site and as neighbors in order to avoid interference and degradation of the system performance. The PCI, PSS, and SSS are illustrated in Tables 1.21 and 1.22.

In UMTS, the cells are identified by primary scrambling codes (a total of 512 PSCs). During the eNB planning and deployment, the PCI and PSC planning of cells in adjacent clusters is an important topic to avoid any mismatch given the limited number of PCI/PSCs. A mismatch in PCI within two nearby cells can typically lead to system acquisition failures, low throughput, or, eventually, call drops.

1.11.3 Downlink Reference Signals

LTE utilizes different RSs (Reference Signals) to facilitate coherent demodulation, channel estimation, channel quality measurements, and timing synchronization. There are three possible reference signals used on the downlink, as demonstrated in Table 1.23.

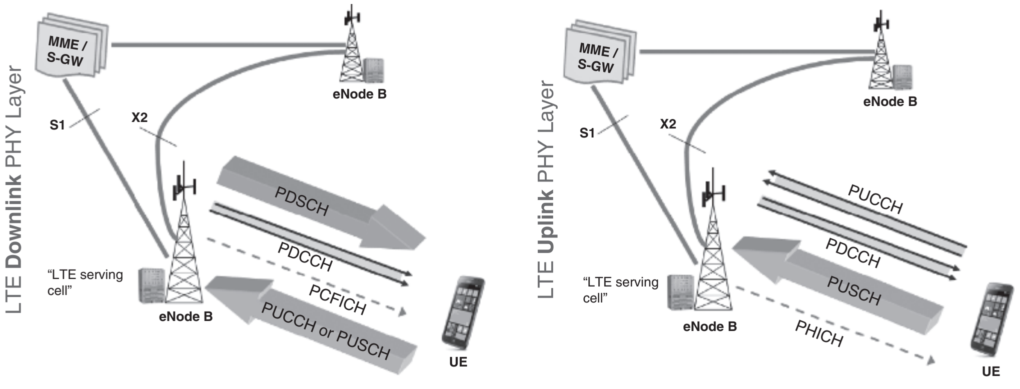


Figure 1.33 Main LTE physical channels in the DL and UL.

Table 1.20 LTE physical layer channels.

Physical Layer Channel	Direction	Main Functions	Similar Channels in UMTS
PBCH Physical Broadcast Channel	DL	• Carries RRC broadcast messages such as SIBs or MIB. • Carries SFN (System Frame Number) used for timing.	PCCPCH
SCH Synchronization Channel	DL	Used to identify the cell ID, frame and slot timing.	SCH
PCFICH Physical Control Format Indicator Channel	DL	Informs the UE of the number of OFDM symbols used for the PDCCHs. UMTS does not have an equivalent channel.	None
PHICH Physical HARQ Indicator Channel	DL	Informs the UE of the acknowledgment response (ACK/NACK) for packets in the uplink.	HS-DPCCH
DL-RS Downlink Reference Signal	DL	Used for cell signal quality estimation.	CPICH
DM-RS Demodulation Reference Signal	UL	Channel estimation for uplink coherent demodulation/detection of the uplink control and data channels.	DPCCH
SRS Sounding Reference Signal	UL	Used to provide uplink channel quality estimation feedback to uplink scheduler for channel-dependent scheduling at the eNB.	None
PRACH Physical Random Access Channel	UL	Carries the RACH preambles.	PRACH

Table 1.21 Physical cell identity.

	Physical Cell Identity (PCI)		
SSS	PSS = 0	PSS = 1	PSS = 2
0	0	1	2
1	3	4	5
2	6	7	8
3	9	10	11
....			
165	495	496	497
166	498	499	500
167	501	502	503

Table 1.22 PSS and SSS.

Information	Usage
Primary synchronization signal (PSS)	Provides downlink subframe timing for the device and unique cell ID (0, 1, or 2).
Secondary synchronization signal (SSS)	Provides downlink frame timing for the device and unique cell ID group (total of 168).
Resource grid (for LTE-FDD)	Time: Sent in subframes 0 and 5 of every frame. Freq: Occupies the middle bandwidth with 72 Res.

The cell-specific reference signals are arranged in time and frequency. The spacing in *time* between the reference signals is important for channel estimation and relates to the maximum Doppler spread supported. The spacing in the *frequency domain* relates to the expected coherent bandwidth and delay spread of the channel. For example, it uses one symbol in every third subcarrier (in the 12 subcarriers), resulting in four REs per RB. The *position* of the reference signals in time–frequency is dependent on the value of the Physical Cell ID (PCI). The location

Table 1.23 Downlink reference signals.

Information	Usage
Cell-specific RS (non-MBSFN)	Facilitates coherent demodulation, channel estimation, channel quality measurements.
MBSFN RS	Reference signal for MBSFN.
UE-specific RS	Typically used for beamforming. Therefore, single-antenna port transmission on the PDSCH and transmitted on antenna port 5.

of the reference signals is offset based on the PCI (Physical Cell ID mod 6). This means that there are six possible frequency shifts of RSs.

Other reference signals include Positioning Reference Signals (PRSs) and CSI (Channel State Information) reference signals (CSI-RSs). Positioning reference signals are used for the OTDOA (Observed Time Difference of Arrival) feature in LTE. The positioning reference signals have been introduced to facilitate the determination of the position of the UE – referred to as a UE-assisted positioning technique. CSI-RSs were introduced in LTE Release 10. They perform a complementary function to the DM-RS in LTE Transmission Mode 9. They can also support the Coordinated Multi-Point (CoMP) feature. The overhead of DL-RS in terms of resource elements per resource block can cause suboptimal performance when more antenna ports are added. Hence, LTE-A introduces the Channel State Information (CSI) concept. In principle, decoupling the RS for channel state information and RS for demodulation generates a new downlink reference signal known as a CSI-RS. A CSI-RS is transmitted on each physical antenna port with less overhead. It is used for measurement purposes. CSI-RSs are used with Release 10 Transmission Mode 9. Mode 9 supports both SU-MIMO and MU-MIMO with seamless switching between both.

LTE operates with multiple transmit antennas for MIMO or transmit diversity. The reference signals are defined with different patterns for multiple antenna ports. The RS pattern corresponding to a given antenna port enables the device to derive a channel estimation. The reference signals for normal CP are illustrated in Figure 1.34 and the RS overhead is calculated in Table 1.24.

RSRP and RSRQ are derived from the power level of DL-RS signals. Assume the shortest measurement bandwidth of 6 RBs (i.e. 72 REs) transmitting with 43 dBm (i.e. total downlink Tx power per cell). This means that the RSRP is 1/72 of the total power. Assuming all REs are going through a similar path loss of –100 dB, then the RSRP can be derived as follows:

$$\mathrm{RSRP} = 43 - 100 - 10 * \log(72) = -75.6\ \mathrm{dBm} \tag{1.3}$$

RSRQ is the ratio between the RSRP and the RSSI, depending on the measurement bandwidth, i.e. resource blocks. Consider an ideal interference and noise-free cell where reference signals and subcarriers carrying data are of equal power over one RB (i.e. 12 REs). Then, over the 100 RBs in a 20 MHz system, for one OFDM symbol with R0, then RSRQ is estimated as inter-cell interference, which, in practice, would decrease the results. Inter-cell interference would appear as a wideband RSSI increment impacting the denominator in the RSRQ calculations.

$$\begin{aligned}\mathrm{RSRQ} &= 10 * \log((100 * 1\mathrm{RE}) \big/ (100 * 12\mathrm{RE}))\\ &= -10.79\ \mathrm{dB}\end{aligned} \tag{1.4}$$

1.11.4 Physical Broadcast Channel (PBCH)

Once the device has decoded the PSS and SSS it is able to:

Decode cell-specific reference signals (since their location is based on the physical cell ID).
Perform channel estimation procedures for cell selection on the searched PCI.
Decode the PBCH which carries the MIB (Master Information Block).

Based on the MIB, the UE is able to decode the PCFICH. This identifies the number of OFDM symbols assigned to the downlink control region in the subframe.

The PBCH is used to schedule the MIB while other SIBs (System Information Blocks) are sent using the PDSCH. The MIB repeats every 40 ms and uses a 40 ms TTI. It carries system configuration parameters:

The downlink bandwidth (6, 15, 25, 50, 75, or 100) resource blocks.
PHICH configuration parameter and cyclic prefix information.
SFN (System Frame Number) that enables the UE to know the subframe number for synchronization of all PHY channels transmitted.

The frame structure of the LTE downlink along with the location of the SSS, PSS, and PBCH are illustrated in Figure 1.35. Table 1.25 provides the locations of the PBCH.

1.11.5 Physical Hybrid ARQ Indicator Channel (PHICH)

The PHICH carries HARQ (Hybrid ARQ) ACK/NAKs for every uplink data transmission. It is transmitted in PHICH groups. A PHICH group consists of up

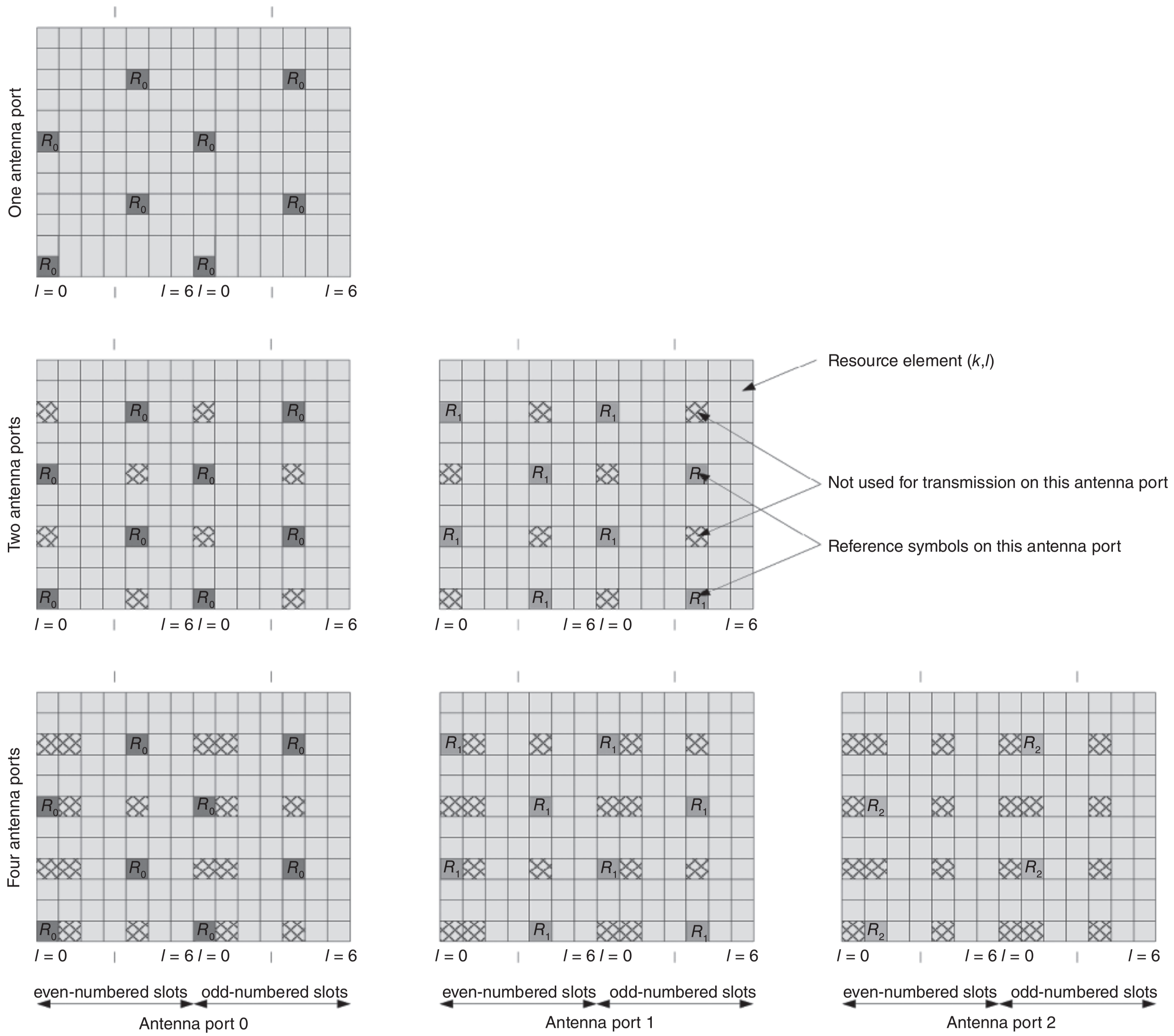


Figure 1.34 Reference signals for normal CP.

Table 1.24 Reference Signals total overhead for normal CP.

Antenna Configuration	Total Overhead (Normal CP)
1 Transmit antenna	Total REs in a subframe = 12 subcarriers × 7 OFDMA symbols (normal CP) × 2 slots = 168 Total DL-RS REs in subframe = 4 symbols + 4 subcarriers = 8 for R_0 **Overhead = 8 / 168 = 4.76 %**
2 Transmit antennas	$8 \times R_0 + 8 \times R_1 = 16$ for two antennas **Overhead = 16 / 168 = 9.52 %**
4 Transmit antennas	$8 \times R_0 + 8 \times R_1 + 4 \times R_1 + 4 \times R_1 = 24$ for four antennas **Overhead = 24 / 168 = 14.29 %**

Table 1.25 Locations of the PBCH channel.

Information	Usage
Time-domain location	Located in four symbols of second slot only (symbols 0, 1, 2, and 3).
Resource grid (for LTE-FDD)	Time: Sent in subframe 0 in every frame. Freq: Occupies the middle bandwidth with 72 REs.

Table 1.26 PHICH information.

Information	Usage
Configuration	N_g is equal to 1/6, 1/2, 1, or 2 and depends on whether "Normal" or "Extended" PHICH mode is being used.
Resource grid (for LTE-FDD)	Time (normal CP): Sent in first OFDM symbol of a subframe. Time (extended CP): Sent in the first three subframes. Freq: Each PHICH group consists of 3 REGs (i.e. 3*4 REs) in one frame (i.e. $N_g = 1$ in 10 MHz would generate 7 groups with a total of $7 * 3 * 4 = 84$ REs)

to eight ACK/NACK processes and requires three REGs for transmission. Each PHICH within the same PHICH group is separated through different orthogonal sequences. The amount of PHICH resources (N_g) is signaled on the PBCH as part of the MIB. Table 1.26 provides PHICH-relevant information. A PHICH can be defined as follows:

$$\#\ \text{of PHICH groups} = \begin{cases} \lceil N_g * (\#\ \text{RBs}/8) \rceil & \text{for normal CP} \\ 2 * \lceil N_g * (\#\ \text{RBs}/8) \rceil & \text{for extended CP} \end{cases} \tag{1.5}$$

Different REGs belonging to a PHICH group may be transmitted on different symbols. PHICH allocation is critical when it comes to system capacity, as will be shown later. An example of the number of PHICH symbols in a frame for normal CP at different N_g is shown in Table 1.27.

1.11.6 Physical Control Format Indicator Channel (PCFICH)

The PCFICH is used to inform the UE of the number of OFDM symbols used for the PDCCH in a subframe.

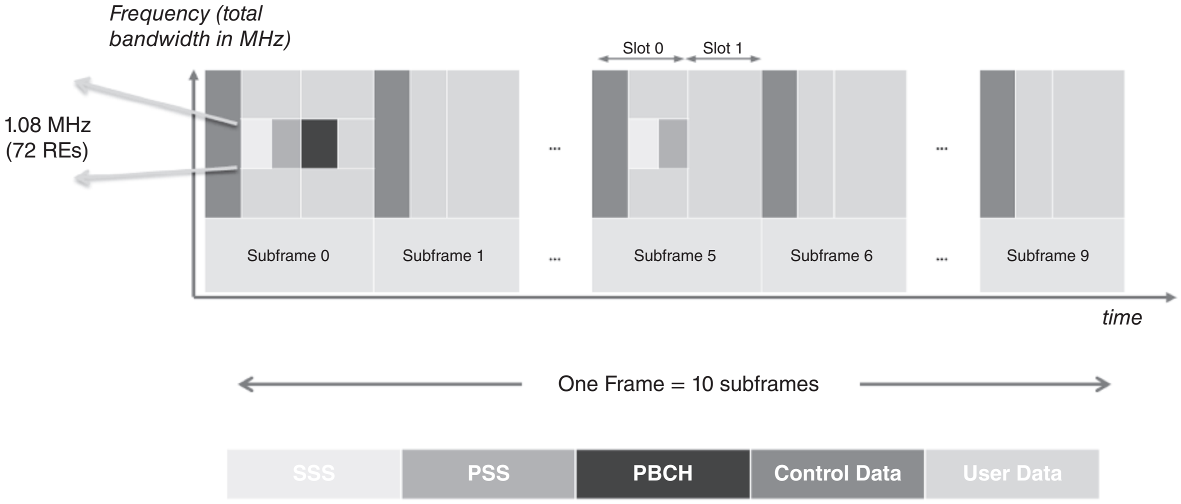


Figure 1.35 Frame structure for the LTE downlink.

Table 1.27 Example of number of PHICH symbols in a frame (normal CP).

N_g	Example of Number of PHICH Symbols in a Frame (Normal CP)	
	10 MHz bandwidth (total overhead)	**20 MHz bandwidth (total overhead)**
1/6	240 (0.29%)	360 (0.21%)
1/2	480 (0.57%)	840 (0.5%)
1	840 (1%)	1560 (0.93%)
2	1560 (1.86%)	3000 (1.79%)

Since the PDCCH time domain allocation (depending on capacity) is not fixed, this channel indicates how the UE is scheduled. It indicates the UE CFI (Control Format Indicator), which determines the number of OFDM symbols assigned to the PDCCH in a subframe. Specifically, it defines the number of OFDM symbols that the DCI occupies in a subframe. PCFICH-relevant information is defined in Table 1.28. Table 1.29 provides the number of OFDM symbols assigned for the PDCCH in a subframe for different CFI values.

1.11.7 Physical Downlink Control Channel (PDCCH)

The PDCCH carries scheduling assignments and other control information. It is the main channel used to schedule the UE for user data, signaling, paging, system information blocks, and Random Access (RACH) responses.

Table 1.28 PCFICH information.

Information	Usage
Frequency-domain location	The location of these varies depending on the system bandwidth and cell ID.
Resource grid (for LTE-FDD)	Time: Sent in first OFDM symbol in every subframe. Freq: Requires four REGs, i.e. 16 resource elements, which are distributed over the channel bandwidth.

Table 1.29 Number of OFDM symbols assigned for the PDCCH in a subframe.

CFI Value	Number of OFDM Symbols Assigned to PDCCH in a Subframe	
	System bandwidth > 10 RBs	**System bandwidth ≤ 10 RBs**
1	1	2
2	2	3
3	3	4

In the *frequency domain*, the PDCCH is transmitted on an aggregation of one or several consecutive CCEs (Control Channel Elements). One CCE corresponds to nine REGs (36 REs). In the *time domain*, the PDCCH occupies one to four symbols per subframe. The PCFICH is used to inform the UE of the PDCCH control region.

The PDCCH supports multiple formats (called *aggregation levels*), which vary depending on the information sent in the channel, as follows:

PDCCH Format 0 → This consists of one CCE (9 REGs).
PDCCH Format 1 → This consists of two CCEs (18 REGs).
PDCCH Format 2 → This consists of four CCEs (36 REGs).
PDCCH Format 3 → This consists of eight CCEs (72 REGs).

The information sent over the PDCCH is sent as an indicator called a Downlink Control Indicator (DCI). Each DCI conveys control and/or scheduling information to the UE. Once the UE knows the DCI, it knows how to use the data channel (PDSCH). The size of the DCI format depends on its function as well as the system bandwidth. The different DCI values and a relevant description for each value are provided in Table 1.30.

The eNB first encodes the PDCCH message by scrambling the CRC bits with the configured RNTI(s). For each DCI and based on the purpose of the PDSCH transmission, different RNTI configurations are used by the eNB. On the UE side, multiple RNTIs can be associated with one PDCCH decoding, and hence, multiple CRC checks are performed to retrieve the PDSCH data associated with the purpose of the transmission. Different RNTI format values and their usage are provided in Table 1.31.

The common search space corresponds to CCEs 0–15 at two levels:

4-CCE: CCEs 0–3, 4–7, 8–11, 12–15
8-CCE: CCEs 0–7, 8–15

These are monitored by all UEs in the cell and can be used for any PDCCH signaling. In addition, a UE must monitor one UE-specific search space at each of the aggregation levels 1, 2, 4, and 8. This may overlap with the common control search space. The location of the UE-specific search space is based on the C-RNTI, as illustrated in Table 1.32.

Putting together the explanations of DCI and RNTI thus far, we can now derive the number of PDCCH decoding hypotheses. For the *user-specific search*, a maximum of two payload sizes can be available for decoding, with the combination of aggregation level decoding candidates creating a search space up to $[2 \text{ payloads} * (6+6+2+2 \text{ PDCCH candidates}) = 32]$. On the *common search* side, any RNTI combination can only use up to two payload sizes, and

Table 1.30 Different DCI values.

DCI Format	Description
0	PUSCH resource assignment/Aperiodic CQI/RI request.
1	PDSCH resources with no spatial multiplexing. Scheduling of one PDSCH codeword.
1A	Compact scheduling of one PDSCH codeword and random access procedure initiated by a PDCCH order.
1B	PDSCH with one codeword transmission and closed-loop SU-MIMO.
1C	Special purpose (paging, random access, system information). Very compact scheduling of one PDSCH codeword.
1D	Compact scheduling of one PDSCH codeword in MU-MIMO.
2	PDSCH with two-codeword transmission and closed-loop spatial multiplexing in SU-MIMO.
2A	PDSCH with two-codeword transmission and open-loop spatial multiplexing in SU-MIMO.
3	Transmission of TPC (Transmit Power Control) commands for PUCCH and PUSCH with 2-bit power adjustments.
3A	Transmission of TPC (Transmit Power Control) commands for PUCCH and PUSCH with 1-bit power adjustments.

Table 1.31 Different RNTI format values and their usage.

RNTI Format		Usage
SI-RNTI	System Information-Radio Network Temporary Identifier	Used when System Information Blocks (SIBs) are carried on DL-SCH.
P-RNTI	Paging-Radio Network Temporary Identifier	Used when a paging message is carried on DL-SCH.
RA-RNTI	Random Access-Radio Network Temporary Identifier	Used when a random access response is carried on DL-SCH.
C-RNTI	Cell-Radio Network Temporary Identifier	Uniquely used for identifying an RRC connection and user plane scheduling on DL-SCH.
TC-RNTI	Temporary Cell-Radio Network Temporary Identifier	Used for the random access procedure.
TPC-PUCCH-RNTI	Transmit Power Control for PUCCH-Radio Network Temporary Identifier	Used for the uplink power control of PUCCH.
TPC-PUSCH-RNTI	Transmit Power Control for PUSCH-Radio Network Temporary Identifier	Used for the uplink power control of PUSCH.

Table 1.32 The location of the UE-specific search space.

Downlink or Uplink	Common		UE-Specific		
Downlink	SI-RNTI, P-RNTI, RA-RNTI	C-RNTI, TC-RNTI	TC-RNTI	C-RNTI	MIMO transmission mode [a]
	DCI 1A, 1C	DCI 1A	DCI 1A, 1	DCI 1A, 1	1
				DCI 1A, 1	2
				DCI 1A, 2A	3
				DCI 1A, 2	4
				DCI 1A, 1D	5
				DCI 1A, 1B	6
				DCI 1A, 1	7
Uplink	C-RNTI, TC-RNTI	TPC-PUCCH-RNTI TPC-PUSCH-RNTI	C-RNTI		
	DCI 0	DCI 3, 3A	DCI 0		

[a] MIMO transmission modes are discussed in the following sections.

with the combination of aggregation level decoding candidates, the common search space can be up to $[2\ \text{payloads} * (4 + 2\ \text{PDCCH candidates}) = 12]$. As a result, there is a total of up to *44 PDCCH decoding hypotheses* exercised for each subframe for the entire control region. Unlike HSDPA, where H-RNTI is configured by the RRC, LTE's RNTIs are mostly derived from the MAC layer based on computed or pre-configured values.

1.11.8 Physical Downlink Shared Channel (PDSCH)

After decoding the PDCCH, it is now easy to read the PDSCH. The PDSCH is used for various transport channels, such as paging, user data (i.e. VoLTE or PS data traffic), and signaling messages. The PDSCH will utilize the remaining available resource blocks in a cell after assigning the control regions. The PDSCH is shared among users, and the eNB scheduler decides how much bandwidth is given to the PDSCH. The PDSCH is scheduled based on MIMO modulation and can be sent from different carriers if carrier aggregation is enabled, based on UE-reported channel conditions (channel quality indicators and rank indicators).

1.12 Uplink Physical Channels

1.12.1 Uplink Reference Signals

There are two types of RSs in the uplink of the LTE. The first type is Demodulation Reference Signals (DM-RSs), which are used to enable coherent signal demodulation at the eNodeB side, similar to the UE-specific reference signals in the DL. These signals are time multiplexed with uplink data and are transmitted on the fourth or third SC-FDMA symbol of an uplink slot for normal or extended CP, respectively, using the same bandwidth as the data.

The second type is the Sounding Reference Signal (SRS), which is used to allow channel-dependent (i.e. frequency-selective) uplink scheduling. The DM-RSs cannot be used for this purpose since they are assigned over the assigned bandwidth to a UE. The SRS is introduced as a wider-band reference signal typically transmitted in the last SC-FDMA symbol of a 1 ms subframe. User data transmission is not allowed in this block, which results in about a 7% reduction in uplink capacity. The SRS is an optional feature and is highly configurable to control overhead – it can be turned off in a cell. Users with different transmission bandwidth share this sounding channel in the frequency domain.

LTE utilizes different RSs (reference signals) on the uplink to facilitate coherent demodulation at the eNodeB and channel estimation for channel-dependent scheduling by the eNodeB. There are two possible reference signals used on the uplink, as shown in Table 1.33 and Figure 1.36.

The SRS provides the eNB with uplink channel quality information which can be used for scheduling. The UE sends an SRS in different parts of the allocated bandwidth where no uplink data transmission is available. Two modes for transmitting an SRS are supported, as follows:

Wideband mode: The SRS occupies the bandwidth required. This could, however, lead to poor channel quality estimates.

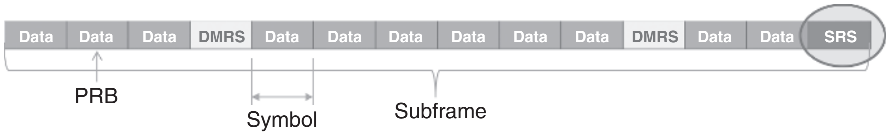
Frequency hopping mode: Sends multiple SRS signals using a narrowband transmission. This will, over time, cover the same bandwidth.

The configuration of the sounding signal (bandwidth, duration, and periodicity) is signaled to the UE by higher layers (RRC). The SRS is transmitted in the last symbol of the subframe. Since the SRS can be sent when the UE has no current PUSCH or PUCCH assignment, mechanisms must exist to stop the UE interfering with other users' PUSCHs. This is done by making sure all UEs know when the SRSs are transmitted, such that the last symbol of the subframe where an SRS is transmitted is not used by any UEs for their PUSCH. The SRS may need to interact with ACK/NACK, CQI, or SR information. If interacting with ACK/NACK, the SRS may be dropped or the ACK/NACK punctured. When interacting with CQI and SR information, the SRS is dropped.

Table 1.33 Uplink Reference Signal.

Information	Usage
DM-RS (Demodulation Reference Signal)	Associated with transmission of PUSCH or PUCCH and used by the eNodeB for coherent signal demodulation.
SRS (Sounding Reference Signal)	Not associated with transmission of PUSCH or PUCCH. This channel is power controlled and used by eNodeB for uplink channel quality information which can be used for scheduling (i.e. UL SINR estimation).

Figure 1.36 LTE subframe with SRS and DM-RS signals.



The advantages of SRS usage can be summarized as follows:

- The LTE carrier typically occupies much wider spectrum.
  - The RF channel response in different frequency portions of the carrier bandwidth can be noticeably different.
  - This channel frequency selectivity is particularly pronounced in stationary or slow-mobility cases.
- SRS transmissions help the eNB to analyze the real-time UL channel frequency selectivity and allow data transmissions to be allocated in the frequency portion that has the best channel response.
  - RF spectrum efficiency is hence improved, especially under multi-user traffic conditions.

The disadvantages of SRS are:

- The reservation of the SRS resource leads to 1/12 loss of UL PUSCH symbols.
- The reduction of PUSCH resource leads to ∼10% average UL throughput loss.
- A reduction in the UL peak throughput.
  - With 16QAM, up to MCS-22 may be supported with certain SRS configurations, while MCS-24 may be supported without SRS configuration.
  - Higher SRS bandwidth would reduce resources available for PUSCH.
  - This can cause ∼ 16% peak throughput reduction (single user).

1.12.2 Physical Random Access Channel (PRACH)

The random access procedure is used in various scenarios, including initial access, handover, and call re-establishment. It is used primarily in times when the UE needs to initiate a connection with a cell to perform open-loop power control. The PRACH channel is used for the uplink to transmit preambles with certain power that is adjusted based on the path loss and number of retransmissions needed for each preamble. To minimize the collision of preambles between users, LTE defined both contention-based and contention-free RACH procedures.

1.12.3 Physical Uplink Control Channel (PUCCH)

The PUCCH carries information needed by the eNodeB to schedule the UE on the uplink and downlink. The information sent on the PUCCH is in the form of UCI (Uplink Control Information), including:

- ACK/NAKs in response to downlink transmission.
- DL channel conditions represented by CQI (Channel Quality Indicator) reports.
- MIMO feedback such as PMI (Pre-coding Matrix Indicator) and RI (Rank Indicator).
- UL scheduling information such as SRs (Scheduling Requests).

The PUCCH is transmitted on a reserved frequency region. This is configured by the higher layer and is shown in Figure 1.37.

Similar to the downlink PDCCH, the uplink PUCCH supports multiple formats. Each format, defined as an *Uplink Control Indicator (UCI)*, is used for a certain type of operation, as shown in Table 1.34.

1.12.4 Physical Uplink Shared Channel (PUSCH)

If a UE has data or signaling to be sent on the uplink, the UE requests a grant from the network and receives it on the PDCCH. The PUSCH is used for various transport channels, such as user data (i.e. VoLTE or PS data traffic) and signaling messages. Like the downlink, the uplink also has resource elements reserved for reference signals and control, and the remaining portion of the grid is used for the PUSCH. The UE is not allowed to transmit the PUCCH and PUSCH in the same subframe, thus multiplexing of different control/data information in one PUSCH is possible.

Figure 1.37 PUCCH control regions.

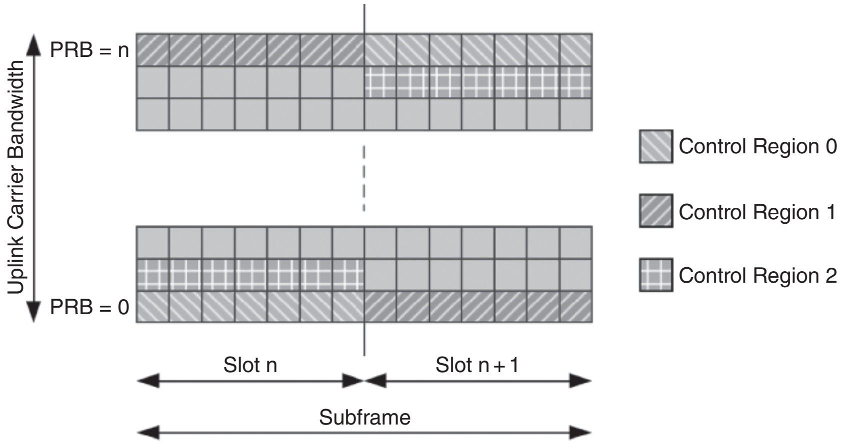


Table 1.34 PUCCH formats.

UCI Format	Description
1	Scheduling request (SR)
1a	ACK/NACK ACK/NACK + SR With 1 bit per subframe
1b	ACK/NACK ACK/NACK + SR With 2 bits per subframe
2	CQI/PMI or RI (CQI/PMI or RI) + ACK/NACK (extended CP only)
2a	(CQI/PMI or RI) + ACK/NACK (normal CP only)
2b	(CQI/PMI or RI) + ACK/NACK (normal CP only)

Figure 1.38 illustrates a combination of control signals and user data on the PUSCH. In this example, three additional types of signaling are added:

ACK/NACK – These are part of the HARQ process and are located next to the RS. This ensures that they benefit from the best possible channel estimation. The information is punctured to make way for the ACK/NACK information.

CQI/PMI – The CQI (Channel Quality Indicator) and PMI (Pre-coding Matrix Indicator) can also be multiplexed onto the PUSCH. These are rate matched with the UL-SCH. The mapping of these is sequential on one subcarrier before continuing on the next.

RI (Rank Indicator) – These are placed next to the ACK/NACK.

Various rules on the mapping and coding of control information exist. In addition, it is possible to send control information on the PUSCH without data, i.e. not the UL-SCH.

1.13 Physical Layer Procedures

The network scheduler used for the uplink and downlink is the main differentiator in terms of the performance of one infra-vendor over another. Hence, each vendor tends to utilize different mechanisms when assigning the data for a user or group of users. There are many policies to ensure fair scheduling among users, taking into account the available resources. The most common schedulers are Round Robin (RR) and Proportional Fair

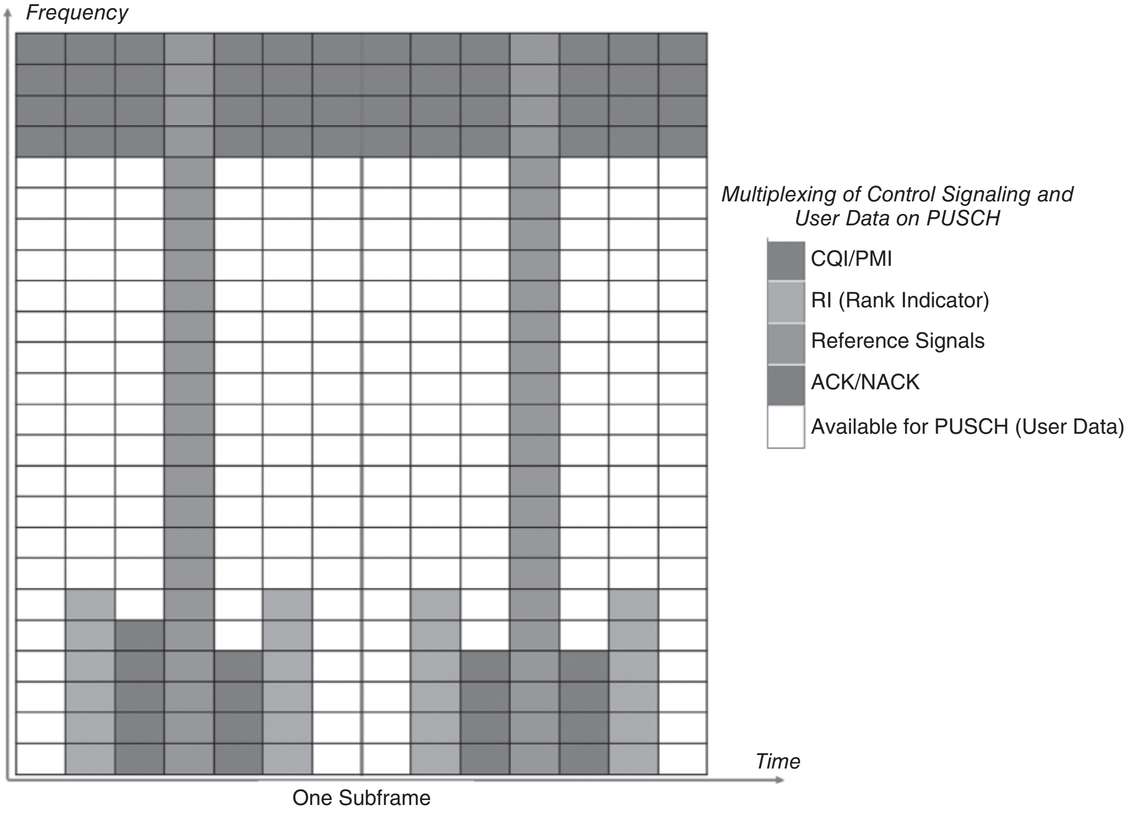


Figure 1.38 A combination of control signals and user data on the PUSCH.

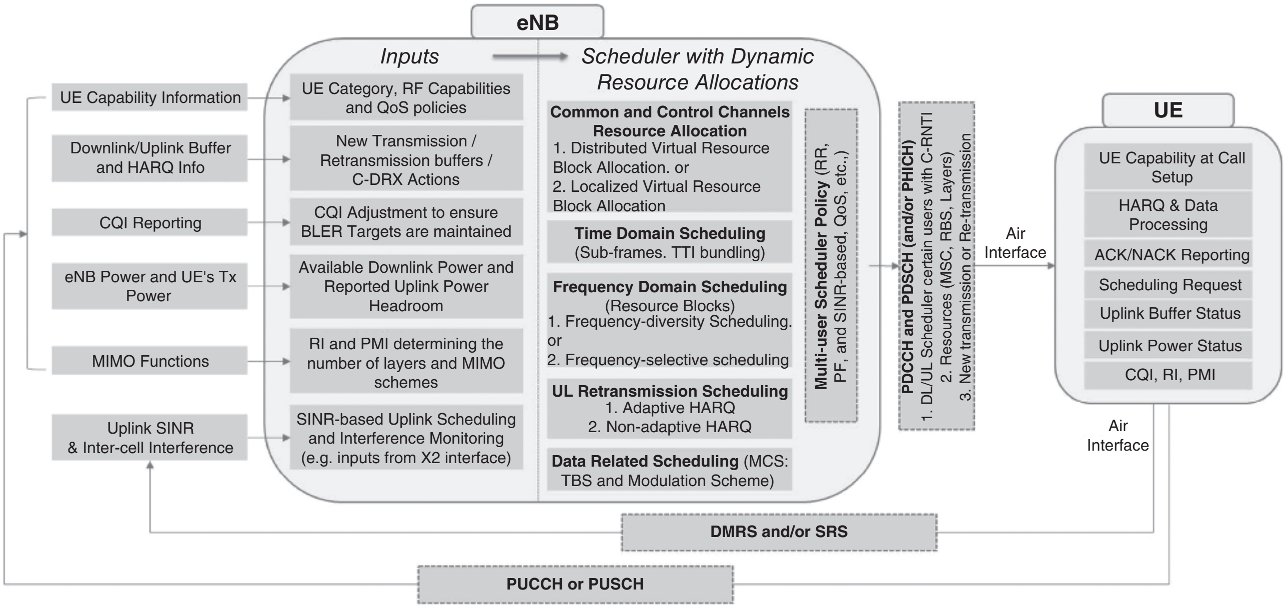


Figure 1.39 Basic uplink and downlink scheduling implementations.

(PF). Round robin typically ensures both time/frequency domain scheduling and allocation in sequential patterns. RR typically aims to ensure user fairness with limited inputs to the algorithm in terms of considering the CQI reported by different UEs. Hence, the main disadvantage is that RR may lead to lower system capacity with more unutilized resources, while fairness is guaranteed at best levels. On the other hand, proportional fair typically aims to make a tradeoff between system capacity and user fairness. This is achieved by taking the overall data available for the UE in the buffer proportionally to the actual channel quality (i.e. CQI). There are other ways of scheduling depending on the available cell power and QoS-aware schedulers. However, in most cases, the inputs to the scheduler for each user remain the same regardless of vendor implementations and scheduler policies. Figure 1.39 illustrates basic uplink and downlink scheduling implementations.

1.13.1 CQI (Channel Quality Indicator)

The CQI provides an indication of the downlink channel quality and effectively identifies an optimal modulation and coding scheme for the eNB to use. The CQI has a direct relation to:

DL channel conditions: A high CQI indicates good UE conditions and a low CQI indicates bad UE conditions.
Cell loading: As the CQI is derived from the PDSCH SINR.

The CQI mainly allows the cell to decide on the modulation technique to use, and this is periodically reported based on higher-layer (RRC) configuration. The period can be, for example, 5 ms, 20 ms, etc.Based on the reported CQI, the eNB scheduler decides on the Modulation and Coding Scheme (MCS) to be assigned to the user. MCS indices of 0 to 31 are allowed according to the 3GPP standard, as shown in Table 1.35. 3GPP Release 12 introduced 256QAM, as shown in Table 1.36, which is the update of Table 1.35.

LTE defines multiple types of CQI. *Wideband CQI* relates to the entire system bandwidth. In contrast, *sub-band CQI* relates to a value per sub-band. This is defined and configured by the higher layers and relates

Table 1.35 CQI versus MCS and modulation.

CQI Index	MCS Range	Modulation
1	0–9	QPSK
2		QPSK
3		QPSK
4		QPSK
5		QPSK
6	10–16	QPSK
7		16QAM
8		16QAM
9		16QAM
10	17–28 *(MCS 29, 30, and 31 are special MCSs used for retransmissions)*	64QAM
11		64QAM
12		64QAM
13		64QAM
14		64QAM
15		64QAM

Table 1.36 CQI versus MCS and modulation for 256QAM.

CQI Index	MCS Range	Modulation
0	0–4	QPSK
1		QPSK
2		QPSK
3		QPSK
4	5–10	16QAM
5		16QAM
6		16QAM
7	11–19	64QAM
8		64QAM
9		64QAM
10		64QAM
11		64QAM
12	20–27	256QAM
13		256QAM
14		256QAM
15		256QAM

to the number of resource blocks. One CQI per codeword is reported for MIMO spatial multiplexing and depends on MIMO transmission modes. Also, depending on the scheduling mode, *periodic* and *aperiodic CQI* reporting can be used. In "Frequency non-selective" and "Frequency-selective" mode, the PUCCH is used to carry periodic CQI reports. For "Frequency-selective" mode, the PUSCH is used to carry aperiodic CQI reports.

1.13.2 DL Scheduling

The DL scheduling implementation follows the following steps:

Determining MCS:
- The eNB selects an MCS based on the reported CQI as follows:
  - If frequency-diverse scheduling is used, the eNB selects an MCS based on the wideband CQI reported by the UE.
  - If frequency-selective scheduling is used, the eNB selects an MCS based on the sub-band CQIs reported by the UE.
- The eNB determines whether to adjust the CQI reported by the UE based on the setting of the CQI adjustment algorithm and parameters:
  - If this algorithm is turned on, the eNB adjusts the CQI reported by the UE and selects an MCS based on the adjusted CQI.
  - If this algorithm is turned off, the eNB does not adjust the CQI reported by the UE and selects an MCS based on the reported CQI.
- The eNB maps the CQI reported by the UE to the Transport Block Size Index (ITBS) and then maps the ITBS to the IMCS.
  - The IMCS is the MCS used to schedule the UE.

Determining the number of RBs:
- The amount of data to be scheduled in a TTI determines the number of RBs to be scheduled for UEs. Before determining the user data to be scheduled, the scheduler estimates the RLC overhead and MAC header overhead. This enables the scheduler to allocate scheduling resources as precisely as possible, maximizing the resource utilization efficiency.
- The scheduler then obtains the amount of data to be scheduled and the IMCS, and estimates the number of RBs to schedule based on 3GPP 36.213. Based on the remaining power of the cell, the scheduler determines the number of RBs to schedule for the UE. The scheduler selects the positions of the RBs to be scheduled based on the scheduling mode: frequency-diverse scheduling or frequency-selective scheduling.

There are two types of DL scheduling that are related to CQI, and these are defined as follows:

Frequency-diverse scheduling (FDS)
- Does not consider the differences in the frequency-domain channel quality for UEs.
- The eNodeB calculates the scheduling priorities based on the *wideband CQIs* reported by UEs.
- Based on the priority calculation results, the eNodeB allocates DL resources to the UEs from a low frequency band to a high frequency band.

Frequency-selective scheduling (FSS)
- Considers the differences in the frequency-domain channel quality for UEs.
- The eNodeB calculates the scheduling priorities based on *sub-band CQIs* reported by UEs.
- The UEs are scheduled to the sub-bands with the optimal channel quality.

1.13.3 UL Scheduling

Data-related inputs from a UE to the eNodeB are as follows:

SR/BSR (UL)
- A Scheduling Request (SR) is a 1-bit message sent by a UE to the eNodeB to request UL resources for data transmission.
- A Buffer Status Report (BSR) is sent by a UE to the eNodeB to show the data amount in the UL buffer of the UE.

The procedure for triggering UL scheduling is as follows:

Before transmitting data, a UE sends the eNodeB a scheduling request (SR) on the PUCCH to request UL resources for data transmission.

Upon receiving the SR, the eNodeB schedules the UE.

The UE transmits MAC protocol data units (PDUs), including the Buffer Status Report (BSR), using the UL resources allocated by the eNodeB.

If the BSR received at the eNodeB is greater than zero, the eNodeB continues scheduling the SR UE and data transmission on the SR UE proceeds.

The UL scheduler determines the RB resources required for the user based on the buffer status reported by UEs, the QoS requirements, the power headroom of the UE, and the maximum number of RBs supported by the cell.

The processes of determining MCSs for the UL and the positions of RBs to be allocated are both based on the UL SINR measured by the eNodeB on the SRS channel (no CQI for UL), and hence SRS becomes important.

1.13.4 Multiple Input, Multiple Output (MIMO)

MIMO builds on Single Input, Multiple Output (SIMO), also called Receive Diversity (RxD), as well as Multiple Input, Single Output (MISO), also called Transmit Diversity (TxD). Both of these techniques seek to boost SNR in order to compensate for signal degradation. As a signal passes from Tx to Rx, it gradually weakens, while interference from other RF signals also reduces the SNR. In addition, in dense urban environments, the RF signal frequently encounters objects which alter its path or degrade the signal. Multiple-antenna systems can compensate for some of the loss of SNR due to multi-path conditions by combining signals that have different fading characteristics, as the path from each antenna will be slightly different.

However, SIMO and MISO systems may not be fully suitable for the high-speed data rates promised in 3GPP's next-generation cellular systems. Therefore, the full version of MIMO can achieve benefits in terms of both an increase in SNR and throughput gains. MIMO in 3GPP exploits several concepts such as spatial multiplexing, transmit diversity, beamforming, and multi-user MIMO. All these techniques fall into two main MIMO categories: open loop and closed loop.

Therefore, the MIMO system utilizes the space and time diversity in a rich multi-path environment and creates multiple parallel data transmission pipes on which data can be carried, as shown in Figure 1.40. We can summarize the MIMO operation as follows:

The data pipes are realized with proper digital signal processing by combining signals on the NxM paths.

A transmission pipe does not correspond to an antenna transmission chain or any one particular signal path.

The rank of the MIMO system is limited by the number of transmitting or receiving antennas, whichever is lower.

Codewords, layers, antenna ports, and pre-coding are described in Section 1.10.1.

In MIMO 2 × 2 systems, the Rank 2 multiplexing gain of increasing the throughput is mainly achieved with good channel conditions experiencing little interference in the rich, multi-path environment. With good channel conditions, the data streams are transmitted simultaneously where the total transmission power is shared among multiple data streams. Hence, the total SNR is also shared among multiple data streams, resulting in a lower SNR on each individual data stream. If the total SNR is low, the SNR on each individual stream will be small and the throughput on each data stream will suffer. This indicates that the spatial multiplexing gain for MIMO is mostly achieved in the high-SNR region, where good throughput can be achieved on each of the independent data streams.

In open-loop spatial multiplexing operations, the network receives minimal information from the UE: a Rank Indicator (RI) and a Channel Quality Indicator (CQI). The RI indicates the number of streams (the term "stream" is used for now, but in later subsections it will be changed to "layers") that can be supported under

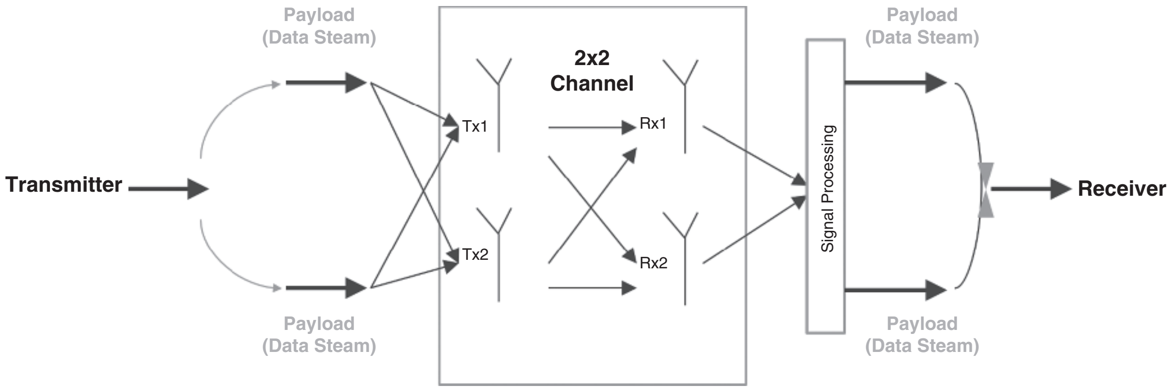


Figure 1.40 MIMO 2 × 2 operation.

the current channel conditions and modulation scheme. The CQI indicates the channel conditions under the current transmission scheme, roughly indicative of the corresponding SNR. Hence, only one CQI is reported by the UE, which is the spatial average of all the streams. The network scheduler then uses the CQI to select the corresponding modulation and coding scheme for the channel conditions. The network adjusts its transmission scheme and resources for the UE to match the reported CQI and RI with an acceptable block error rate.

On the other hand, at a cell edge or in other low-SNR or poor multi-path conditions, instead of increasing the data rate or capacity, MIMO is used to exploit diversity and increase the robustness of data transmission. In transmit diversity mode, MIMO functions much like a MISO system. Each antenna transmits essentially the same stream of data, so the receiver gets replicas of the same signal. This increases the SNR at the receiver side and thus the robustness of data transmission, especially in fading scenarios. Typically, additional antenna-specific coding is applied to the signals before transmission to increase the diversity effect and to minimize co-channel interference. The UE receives the signals from both Tx at both Rx and reconstructs a single data stream from all multi-path signals.

The most popular open-loop transmit diversity scheme is space/time coding, where a code known to the receiver is applied at the transmitter. Of the many types of space/time codes, the most popular are orthogonal space/time block codes (OSTBCs) or Alamouti codes. This type of code has become the most popular transmit diversity scheme, with its ease of implementation and linearity at both the transmitter and the receiver.

Dual-layer beamforming combines beamforming with 2 × 2 MIMO spatial multiplexing capabilities and appears in more advanced 3GPP versions (starting in Release 9, as shown in the next section) for both MU-MIMO and SU-MIMO. These beamforming techniques require the deployment of beamforming antenna arrays as well as special configurations of the network and UEs. The four types of MIMO in LTE are summarized in Figure 1.41.

A *codeword* represents an output from the channel coder. With multiple-layer transmissions, data arrive from higher-level processes in one or more codewords. In Release 8/9, one codeword is used for Rank 1 transmission, and two codewords for Rank 2/3/4 transmissions. Each codeword is then mapped onto one or more *layers*. The number of layers depends on the number of transmit antenna ports and the channel rank report by the UE (RI). There is a fixed mapping scheme of codewords to layers depending on the transmission mode used. Each layer is then mapped onto one or more antennas using a *pre-coding matrix*. In Release 8/9, there are a maximum of four antenna ports which potentially form up to four layers. Pre-coding is used to support spatial multiplexing. When the UE detects a similar SNR from both Tx, the pre-coding matrix will map each layer onto a single antenna. However, when one Tx has a high SNR and another has a low SNR, the pre-coding matrix will divide the layers between the Tx antennas in an effort to equalize the SNR between the layers. In Release 10, a non-codebook pre-coding with seamless switching between SU-MIMO and MU-MIMO with up to Rank 8 is defined. The MIMO transmission modes are provided in Table 1.37.

MIMO 2 × 2 is commonly used with TM3 (open-loop (OL) spatial multiplexing) or TM4 (closed-loop (CL) spatial multiplexing). Table 1.38 provides a comparison between TM3 and TM4. CL-MIMO is better suited for

Open Loop MIMO	Closed Loop MIMO	Multi-User MIMO	Beamforming
• Supports Transmit Diversity and Open-loop Spatial Multiplexing • The use for either one of these two mechanisms depends on the channel conditions and rank • In rank-2 channel, single codeword is sent and TxD gains are achieved • In rank-1 channel, two codewords are sent and Spatial multiplexing gains are achieved with higher throughput • No Pre-coding Matrix Indicator (PMI) reported	• Similar to Open loop, closed loop also supports Transmit Diversity and Closed-loop Spatial Multiplexing • UE provides an RI as well as a Precoding Matrix Indicator (PMI), which determines the optimum precoding for the current channel conditions • PMI can cause higher overhead on Uplink, but better channel estimation generally	• While SU-MIMO (Single User –MIMO) increases the data rate of one user, MU-MIMO allows increasing the overall system capacity	• Similar to the Rank-1 Spatial Multiplexing (i.e. Closed Loop MIMO), the beamforming gain is realized because both antenna paths carry the same information in low SNR or in less multipath conditions • Beamforming and Spatial Multiplexing have conflicting antenna configuration requirements • Beamforming requires antenna to be correlated with same polarization. While Spatial Multiplexing requires transmit antennas to be de-correlated with cross-polarization

Figure 1.41 MIMO types in LTE.

Table 1.37 MIMO DL TxM mode.

Downlink Transmission Mode	PDSCH Transmission On	UE Feedback	3GPP Release
Mode 1	Single antenna port (SISO, SIMO)	CQI	Release 8
Mode 2	Transmit diversity	CQI	
Mode 3	Open-loop (OL) spatial multiplexing	CQI, RI	
Mode 4	Closed-loop (CL) spatial multiplexing	CQI, RI, PMI	
Mode 5	MU-MIMO (Rank-1 to the UE)	CQI, PMI	
Mode 6	CL, with Rank 1 spatial multiplexing (pre-coding)	CQI, PMI	
Mode 7	Beamforming with single antenna port (non-codebook based)	CQI	
Mode 8	Dual-layer beamforming	CQI, RI, PMI	Release 9
Mode 9	Non-codebook pre-coding with seamless switching between SU-MIMO and MU-MIMO up to Rank 8	CQI, RI, PMI	Release 10

Table 1.38 Comparison between TM3 and TM4.

Transmission Mode 3			Transmission Mode 4		
# of Antenna Ports	2		**# of Antenna Ports**	2	
PDCCH DCI Format	2A Pre-coding information not sent		**PDCCH DCI Format**	2 Pre-coding information decides on the # of layers	
# Codewords	**# Layers**	**MIMO Technique**	**# Codewords**	**# Layers**	**MIMO Technique**
One codeword when UE reports RI = 1 and no PMI (fixed pre-coding)	2 layers	Transmit diversity	One codeword when UE reports RI = 1 with unreliable PMI	2 layers	Transmit diversity
Two codewords when UE reports RI = 2 and no PMI (fixed pre-coding)	2 layers	OL spatial multiplexing	Two codewords when UE reports RI = 2 with reliable PMI (3 pre-coding choices)	2 layers	Rank 2 CL spatial multiplexing
			One codeword when UE reports RI = 1 with reliable PMI (4 pre-coding choices)	1 layer	Rank 1 CL spatial multiplexing

low-speed scenarios when the PMI feedback is accurate, while OL-MIMO provides robustness in high-speed scenarios when the feedback may be less accurate. The advantage of CL-MIMO over OL-MIMO is limited due to the small number of PMI choices for 2 × 2 configurations in the current LTE standard. The adaptive mode selection between modes 2, 3, 4, and 6 requires the eNB to reconfigure the mode through RRC messages, which can produce increasing signaling load and additional delay in adapting to the best RF conditions suitable for the selected mode.

1.13.5 Uplink Power Control

Uplink power control reduces interference and enables it to be managed/optimized by the eNB. Downlink power control is achieved by varying the MCS and changing MIMO techniques adaptively based on the RF conditions and cell load. The PUSCH, PUCCH, and SRS are all channels that use closed-loop power control. Open-loop power control is used for the PRACH to determine the initial and ramping up power of the preambles.

The following factors impact UL power control:

System bandwidth and the maximum allowed power (by the eNB or the UE power class).
PUSCH/PUCCH/SRS channel configurations.
Downlink path loss estimate calculated in the UE.
TPC (Transmit Power Control) sent by the eNodeB to increase or decrease the power.
Other higher-layer parameters configured by the eNodeB based on the network configurations.

Table 1.39 LTE DL quality KPIs.

KPI	Definition
Serving cell RSRP, RSRQ, RSSI, SINR, CQI, path loss, uplink transmit power	Reflect RF and channel conditions observed by the UE.
Rank 2 request by UE	Distribution of the UE's samples requesting Rank 2 MIMO (two codewords).
Rank 2 served by eNB	Distribution of the eNB's samples requesting Rank 2 MIMO (two codewords).
Physical layer throughput	Throughput at PHY including all new transmissions and retransmissions.
MAC layer throughput	Throughput at MAC including only new transmissions and excluding MAC headers.
Upper layer throughput	Throughput at RLC, PDCP, and application layers.
Scheduling rate in time domain	PDCCH scheduling rate in the time domain (samples of TTIs for how frequently the UE is receiving PDCCH with C-RNTI for data scheduling) for either uplink or downlink.
Normalized physical throughput	PHY layer throughput/scheduling rate
BLER on all transmissions	Distributions of BLER on all transmissions over all packets with C-RNTI (PDSCH on downlink and PUSCH on uplink).
Number of RBs scheduled	Distribution of the samples of resource blocks assigned by the eNB scheduler for uplink or downlink.
MCS	Modulation scheme assigned by the eNB for uplink or downlink.

1.13.6 Techniques for Data Retransmission on the UL

Two techniques are defined, as follows:

UL Non-adaptive HARQ

The RB positions and MCS for retransmissions are *identical* to those for the initial transmission.

If the RB positions conflict with positions of the PRACH and PUCCH resources, the retransmission is suspended, affecting UL throughput.

The eNodeB uses the PHICH channel for ACK/NACK.

UL Adaptive HARQ

If data to be retransmitted are allocated resources that conflict with other UL resources, the eNodeB adaptively adjusts the number of RBs, their positions, and the MCS for retransmission.

This way, UL resources are scheduled in a timely manner to reduce UL transmission delay and increase UL throughput.

With adaptive HARQ retransmission, the eNodeB uses PDCCH scheduling to act as NACK for the UE, as the retransmission will have different resource from the retransmitted data.

Therefore, adaptive retransmission utilizes the special MCS of {29 "QPSK", 30 "16QAM", 31 "64QAM"}.

During the assessment of downlink and uplink throughput performance, several quality and system KPIs become important in order to benchmark the performance or troubleshoot certain issues raised during field testing. Table 1.39 lists several of these quality KPIs. Different tools can be used to collect these KPIs from either the UE or the network tracing point of view.

All layers above the physical layer are discussed in the following sections, so turn to those for an overview of the overheads in each one.

When multiple users are present, they share either the time or frequency domain scheduling, which reduces the peak throughput. BLER is always expected to be at 10% to improve the cell capacity. MCS typically depends on the CQI and channel conditions. MIMO TM3 above assumes near-cell conditions where Rank 2 is reported and two codewords are used for scheduling. An example to estimate the DL TP for Category 4 terminals is shown in Figure 1.42 and the factors impacting the DL TP are summarized in Table 1.40. Figure 1.43 and Table 1.41 illustrate the same for an LTE-A Category 6 terminal with carrier aggregation.

1.14 RRC Layer and Mobility Procedures

The LTE air interface provides connectivity between the user equipment and the eNB. It is split into a control plane and a user plane. Among the two types of control

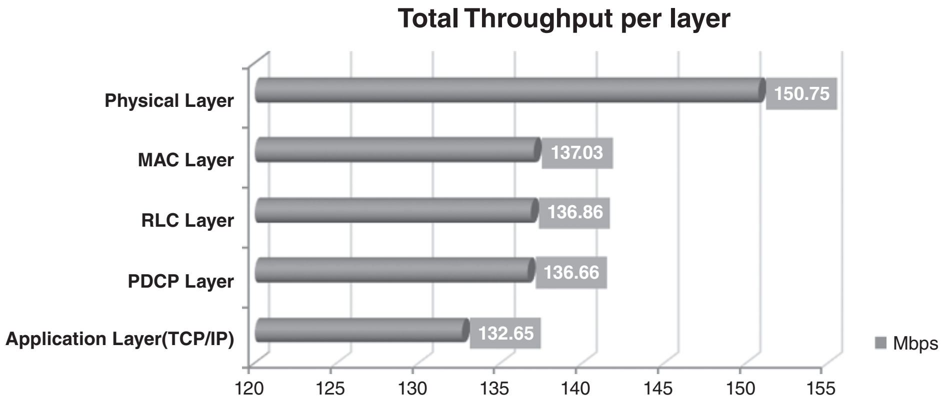


Figure 1.42 DL peak TP at differing layers for Category 4 terminals.

Table 1.40 DL peak TP factors for Category 4 terminals.

All Factors Impacting DL Peak Throughput	
LTE bandwidth (MHz)	20
UE category	4
2 × 2 MIMO transmission mode	3
Maximum MCS – DL	28
Maximum resource blocks	100
DL PHY layer PDSCH BLER (%)	10
DL PDCCH time domain scheduling rate (%)	100

plane signaling, the first is provided by the access stratum and carries signaling between the UE and the eNB. The second carries non-access stratum signaling messages between the UE and the MME, which are piggybacked onto an RRC message. The user plane delivers the IP packets to and from the EPC, S-GW, and PDN-GW.

The structure of the lower-layer protocols for the control and user planes in AS is the same. Both planes utilize the protocols of PDCP (Packet Data Convergence Protocol), RLC (Radio Link Control), and MAC (Medium Access Control) as well as the PHY (Physical Layer) for the transmission of signaling and data packets. The NAS is the layer above the AS layers. There are also two planes in the NAS: the higher-layer signaling related to the control plane and the IP data packets of the user plane. NAS signaling exists in two protocol layers, the EMM and the ESM. The NAS user plane is IP-based. The IP data packets pass directly into the PDCP layer for processing and transmission to or from the user.

Table 1.41 DL peak TP factors for a Category 6 terminal.

All Factors Impacting DL Peak Throughput		
	Carrier 1	**Carrier 2**
LTE bandwidth (MHz)	20	20
UE category	6	N/A
MIMO transmission mode	3	3
Maximum MCS – DL	28	28
Maximum resource blocks	100	100
DL PHY layer PDSCH BLER (%)	10	10
DL PDCCH time domain scheduling rate (%)	100	100

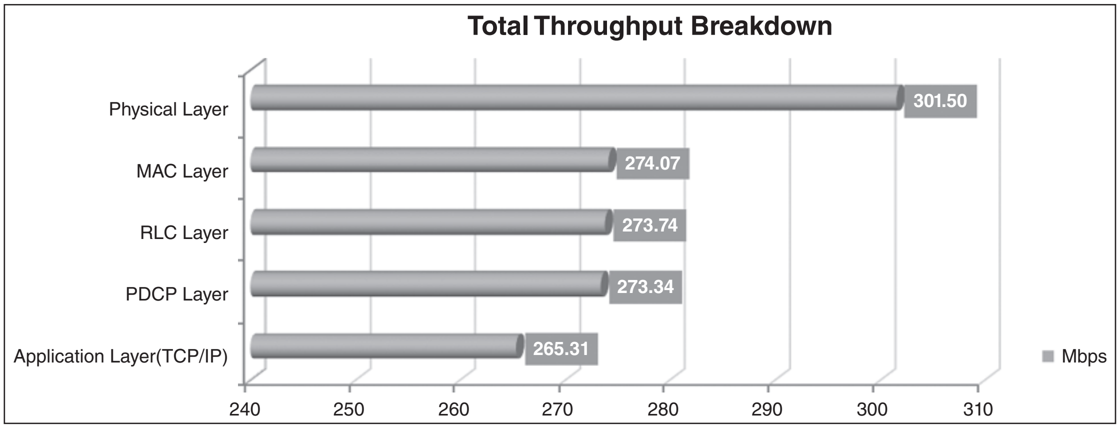


Figure 1.43 DL peak TP at differing layers for a Category 6 terminal.

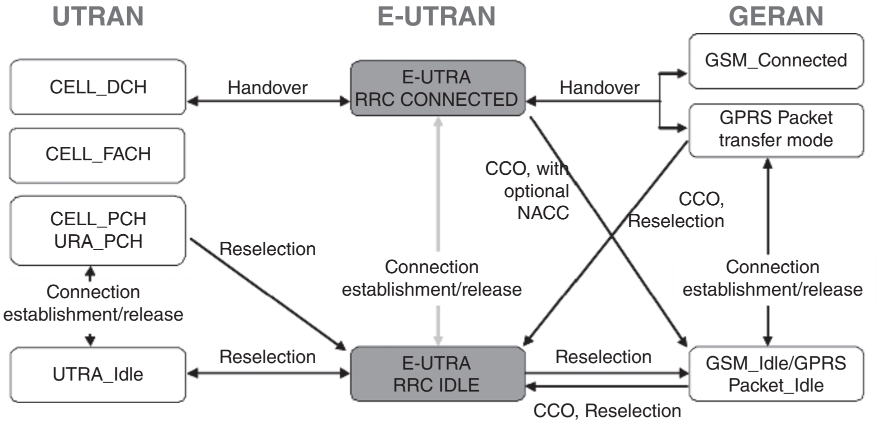
The RRC constitutes the main air interface protocol for the control plane signaling messages. The RRC functions are similar to those in UMTS. Each signaling message the UE sends to the EPS, and vice versa, comprises a set of system parameters. In order for the messages to be transferred between the UE and the eNB, the RRC layer uses the services of PDCP, RLC, MAC, and PHY. During the course of this mapping, the packets are directed on a Signaling Radio Bearer (SRB). The RRC handles all the signaling between the UE and the E-UTRAN. Additionally, the core network NAS signaling is carried by a dedicated RRC message (piggybacked). When carrying NAS signaling, the RRC does not alter the information but instead provides the delivery mechanism.

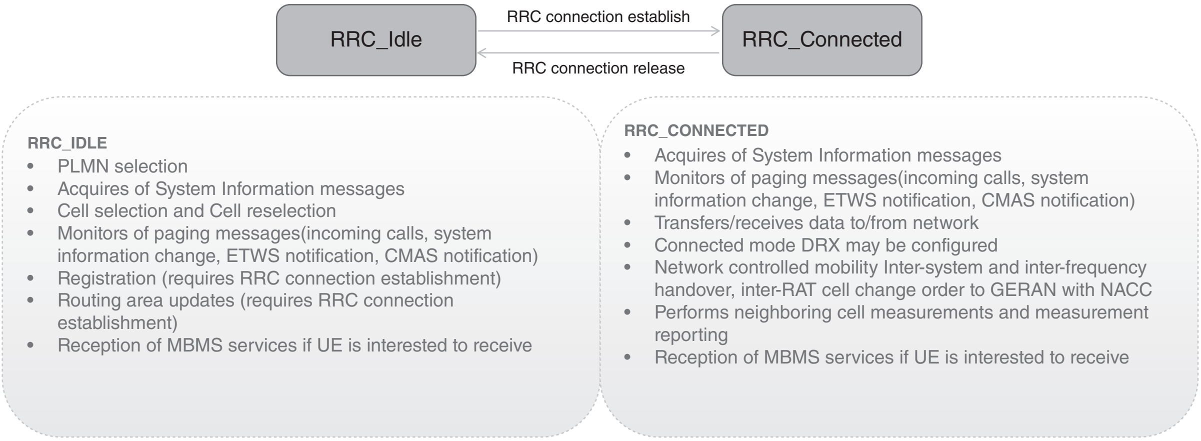
The state transitions including inter-RAT are demonstrated in Figure 1.44. Since CELL_FACH in UTRAN is considered a very short period, a direct transition from UTRAN CELL_FACH to E-UTRAN RRC state is not supported. The main states for the RRC layer are provided in Figure 1.45. The upper layers can define specific DRX in RRC Idle mode, then the UE will monitor the paging DRX cycle depending on the shortest of the UE-specific DRX values, if allocated by the upper layers, and a default DRX value broadcast in the system information.

The RRC constitutes the main air interface protocol for the control plane signaling messages. In general, signaling messages are needed to regulate the UE's behavior in order to comply with the network procedures. Each signaling message the UE sends to the EPS, or vice versa, comprises a set of system parameters. For example, the eNB needs to communicate the parameters related to mobility procedures as and when the UE needs to hand over from one cell to another. These parameters will be sent to the UE in a specific RRC message.

The RRC handles all the signaling between the UE and the E-UTRAN. Additionally, the core network NAS signaling is also carried by a dedicated RRC message. When carrying NAS signaling, the RRC does not alter the information but instead provides the delivery mechanism. SRB1 is used for RRC messages as well as for NAS messages prior to the establishment of SRB2. After SRB2 has been established, the NAS message will transfer: a UL NAS message will always transfer to SRB2; a DL NAS message will transfer to SRB2 or be piggybacked on an RRC Connection Reconfiguration message (depending

Figure 1.44 State transitions LTE, 3G, 2G.





RRC_IDLE

- PLMN selection
- Acquires of System Information messages
- Cell selection and Cell reselection
- Monitors of paging messages(incoming calls, system information change, ETWS notification, CMAS notification)
- Registration (requires RRC connection establishment)
- Routing area updates (requires RRC connection establishment)
- Reception of MBMS services if UE is interested to receive

RRC_CONNECTED

- Acquires of System Information messages
- Monitors of paging messages(incoming calls, system information change, ETWS notification, CMAS notification)
- Transfers/receives data to/from network
- Connected mode DRX may be configured
- Network controlled mobility Inter-system and inter-frequency handover, inter-RAT cell change order to GERAN with NACC
- Performs neighboring cell measurements and measurement reporting
- Reception of MBMS services if UE is interested to receive

Figure 1.45 Comparison between RRC Idle and RRC Connected.

Table 1.42 Signaling bearers (SRBs) and data bearers (DRBs).

Direction	Function	SRB0	SRB1	SRB2	DRB
General	Transfer NAS message	No	Yes	Yes	No
	High priority	Yes	Yes	No	No
Downlink	PDCP	N/A	Yes	Yes	Yes
	RLC	TM	AM	AM	AM/UM
	Logical channel	CCCH	DCCH	DCCH	DTCH
	Transport channel	DL-SCH	DL-SCH	DL-SCH	DL-SCH
	Physical channel	PDSCH	PDSCH	PDSCH	PDSCH
Uplink	PDCP	N/A	Yes	Yes	Yes
	RLC	TM	AM	AM	AM/UM
	Logical channel	CCCH	DCCH	DCCH	DCCH
	Transport channel	UL-SCH	UL-SCH	UL-SCH	UL-SCH
	Physical channel	PUSCH	PUSCH	PUSCH	PUSCH

on the NW). SRB2 and DRBs are only configured after security activation. An initial UL NAS message is piggybacked on an RRC Connection Setup Complete message. The relevant signaling bearers (SRBs) and data bearers (DRBs) are provided in Table 1.42.

SRB1 is used for RRC messages (which may include a piggybacked NAS message) or NAS messages prior to the establishment of SRB2 (DCCH). In the downlink, piggybacking of NAS messages is used only for one dependent (i.e. with joint success/ failure) procedure: bearer establishment/modification/ release. In the uplink, NAS message piggybacking is used only for transferring the initial NAS message during connection setup. The RRC constitutes the main air interface protocol for the control plane signaling messages. In general, signaling messages are needed to regulate the UE's behavior in order to comply with the network procedures. Each signaling message the UE sends to the EPS, or vice versa, comprises a set of system parameters. For example, the eNB needs to communicate the parameters related to mobility procedures as and when the UE needs to hand over from one cell to another. These parameters will be sent to the UE in a specific RRC message. The RRC handles all the signaling between the UE and the E-UTRAN. Additionally, the core network NAS signaling is carried by a dedicated RRC message. When carrying NAS signaling, the RRC does not alter the information but instead provides the delivery mechanism.

After the UE decodes the required SIBs successfully, it camps on the selected cell. But to verify measured cell levels, the UE performs a procedure known as *cell selection*. The criteria for this process are based on the UE's downlink measurements and threshold values configured in the SIBs. Cell selection is needed to ensure that a UE that passes the acquisition stage (UE-dependent implementation) can only camp on the cell within a coverage threshold conveyed in the SIBs. A cell measured with levels lower than the threshold is not suitable for selection and the UE may then try another LTE acquisition or another PLMN search on other technologies. The main System Information Blocks (SIBs) are summarized in Table 1.43.

The PBCH carries the master information block. The MIB repeats every 40 ms and uses a 40 ms TTI in subframe 0 of each radio frame. It carries system configuration parameters:

The downlink bandwidth: 6, 15, 25, 50, 75, or 100 resource blocks.

PHICH configuration parameter and cyclic prefix information.

SFN (System Frame Number): The SFN is used by the UE to know the subframe number for synchronization of all PHY channels transmitted.

SIBs are carried in system information (SI) messages which are then transmitted on the DL-SCH based on various system parameters. Other than SIB1, the UE uses the SI-RNTI to decode the SIBs carried on the PDSCH. SIB1 is broadcast with 80 ms periodicity in subframe 5 of every radio frame. Scheduling of all other SIBs is specified in SIB1, except for SIB2 which is always contained in the first SI. System information transmission is illustrated in Figure 1.46. SIB1 has a fixed broadcast period (80 ms). SIB1 configures the periodicity and windows of other SIBs. The UE knows which one is the new one by means of the SI-windows. Scheduling of system information is demonstrated in Figure 1.47.

The scheduling of SI may be summarized as follows:

Determine the entry order number, *n*, of the considered SI configured by *schedulingInfoList* in SIB1.

Table 1.43 Main system information blocks.

Main LTE SIBs	Common Information Broadcast	Equivalent SIB in UMTS
MIB	Dl bandwidth, PHICH configuration parameter and cyclic prefix information. SFN (System Frame Number).	N/A
SIB1	PLMN list, tracking area code, intra-frequency reselection, closed subscriber group, frequency band indicator, SI periodicity and mapping information.	MIB and SIB 1/2
SIB2	RACH information, reference signals information, paging channel information, uplink PHY channel information, access timers and constants.	SIB 1/5/7
SIB3	Cell reselection information.	SIB 3/4
SIB4	Neighboring cell related information only for intra-frequency cell reselection. It includes cells with specific reselection parameters and blacklisted cells.	SIB 11/12
SIB5	Contains information relevant only for inter-frequency cell reselection.	SIB 11/12
SIB6	Contains information relevant only for inter-RAT cell reselection to UTRAN.	SIB 19 for UTRAN to E-UTRAN cell reselection
SIB7	Contains information relevant only for inter-RAT cell reselection to GERAN.	SIB 3/11/12
SIB8	Contains information relevant only for inter-RAT cell reselection to CDMA 2000.	SIB 3/11/12
SIB9	Contains home eNB identifier (HNBID).	SIB 20
SIB10	Contains an ETWS primary notification.	N/A
SIB11	Contains an ETWS secondary notification.	N/A
SIB12	Contains a CMAS warning notification.	N/A
SIB13	Contains MBMS-related information.	N/A

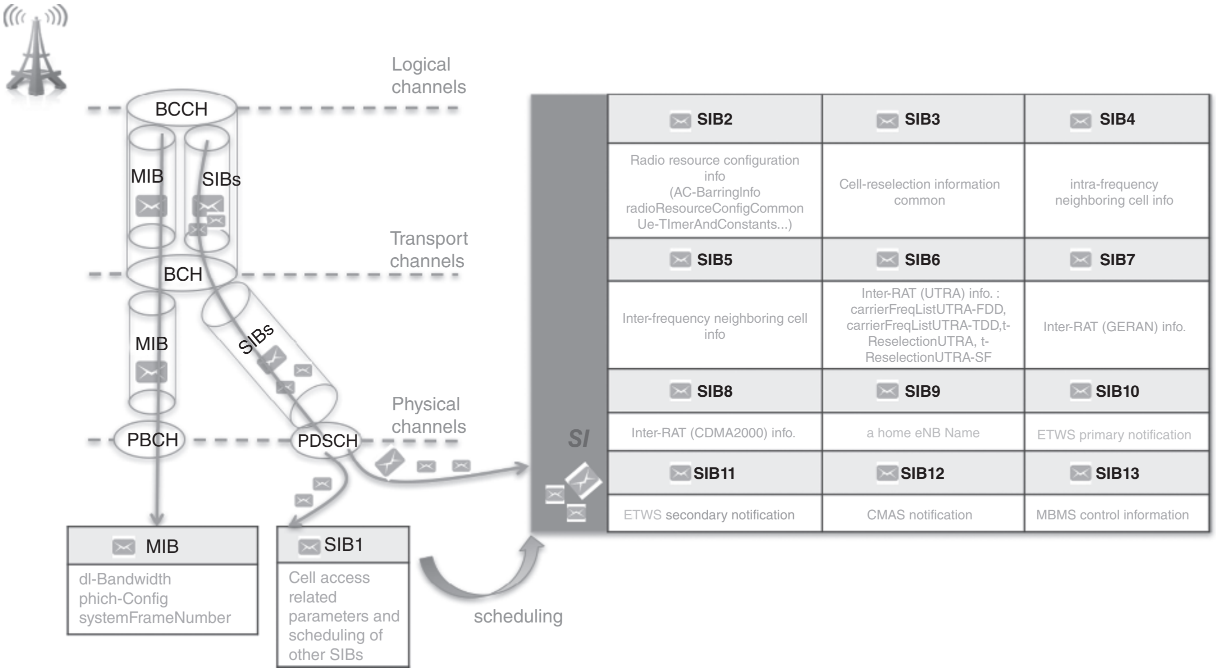


Figure 1.46 System information (SI) transmission.

Determine the integer value $x = (n - 1) * (si\text{-}WindowLength)$.
The start SI-window of the considered SI is:
Radio frame: SFN mod $(si\text{-}Periodicity) = \mathrm{FLOOR}(x/10)$.
Subframe: x mod 10.
Duration of SI-window: *si-WindowLength.*

Based on the SI message order and periodicity, this will make sure that different SI messages never overlap.

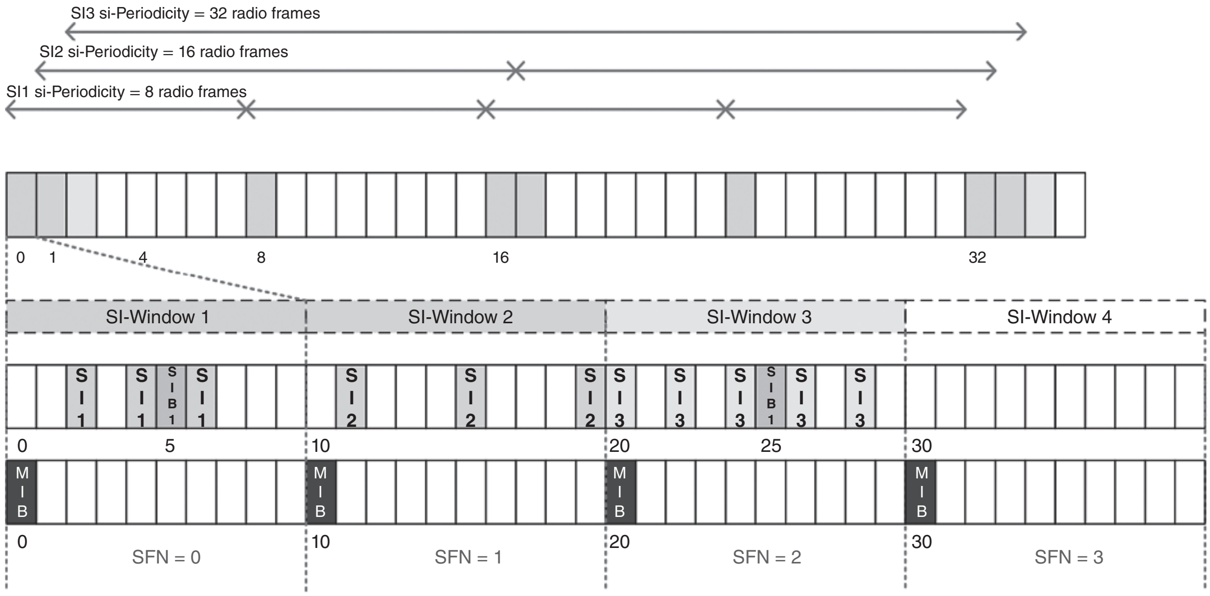


Figure 1.47 Scheduling of system information (SI).

MIB and SIB1 use fixed schedules as follows:

MIB:

First transmission: Subframe #0, SFN mod 4 = 0.
Repetitions: Subframe #0, all other radio frames.
Periodicity 40 ms.

SIB1:

First transmission: Subframe #5, SFN mod 8 = 0.
Repetitions: Subframe #5, all other radio frames for SFN mod 2 = 0.
Periodicity 80 ms.

The *system information acquisition* procedure applies to UEs in RRC Idle and UEs in RRC Connected. The system information acquisition procedure applies upon:

Selecting (for example, upon power on) and reselecting a cell.
After handover completion.
After entering E-UTRA from another RAT.
Return from out of coverage.
Receiving a notification that the system information has changed.
Receiving an indication about the presence of an ETWS notification.
Receiving an indication about the presence of a CMAS notification.
Receiving a request from CDMA2000 upper layers.
Exceeding the maximum valid duration (3 hours).

1.14.1 Paging

The UE will wake up for monitor paging every discontinuous reception (DRX) in Idle mode. When DRX is used, the UE needs only to monitor one PO per DRX cycle. A Paging Occasion (PO), as demonstrated in Figure 1.48, is a subframe where the NW may transmit a paging message. (P-RNTI transmitted on the PDCCH). A Paging Frame (PF) is one radio frame which may contain one or multiple paging occasion(s). The PO index in one PF is based on the UE identity (IMSI/IMEI), the DRX cycle length, and cell-specific parameter (nB).

Using DRX will reduce power consumption.

The PF is given by the following equation:

$$\text{SFN } mod \text{ T} = (\text{T div N}) * (\text{UE\_ID mod N}) \tag{1.6}$$

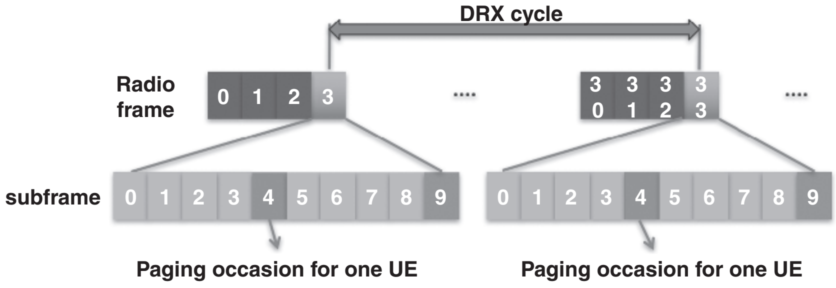


Figure 1.48 Paging occasion with DRX enabled.

Index i_s points to the PO from the subframe pattern and is derived from the following calculation:

$$\text{i\_s} = \text{floor}(\text{UE\_ID}/\text{N}) \ \text{mod} \ \text{Ns} \tag{1.7}$$

T is the DRX cycle of the UE and is determined by the shortest of the UE-specific DRX values, if allocated by the upper layers, and a default DRX value broadcast in SIB2. If a UE-specific DRX is not configured by the upper layers, the default value is applied.

The cell-specific parameter, nB, may take the following values:

$$\text{nB}: \ 4\text{T}, \ 2\text{T}, \ \text{T}, \ \text{T}/2, \ \text{T}/4, \ \text{T}/8, \ \text{T}/16, \ \text{T}/32 \tag{1.8}$$

This parameter indicates the number of paging occasions in T.

The value N in the above equation is given by:

$$\text{N}: \ \min(\text{T}, \ \text{nB}) \tag{1.9}$$

It indicates the number of paging frames within T[1T,1/32T].

The value Ns is given by:

$$\text{Ns}: \ \max(1, \text{nB}/\text{T}) \tag{1.10}$$

It indicates the number of paging subframes used for paging within a paging frame [1, 2, 4].

The parameter UE_ID is:

$$\text{UE\_ID: IMSI } mod \ 1024. \tag{1.11}$$

IMSI is given as a sequence of integer digits (0…9).

The network may initiate paging for EPS services using IMSI with the CN domain indicator set to "PS" if the S-TMSI is not available due to a network failure; the UE will locally detach and re-attach.

Paging informs the UE of system information changes, ETWS notifications, and CMAS notifications in RRC Idle and RRC Connected, as well as transmitting paging information to a UE in RRC Idle. A UE may initiate RRC connection establishment if paging information is provided to the upper layers. The paging message procedure is illustrated in Figure 1.49.

Upon receiving a *Paging* message, if the *ue-Identity* included in the *PagingRecord* matches one of the UE identities allocated by the upper layers for the UE in RRC Idle mode, the UE needs to forward the *ue-Identity* and the *cn-Domain* to the upper layers. The upper layers will make a decision as to whether to respond to this paging or not; if yes, while in RRC Idle mode, an RRC connection also needs to be established. The paging record UE ID will be S-TMSI/IMSI with CS/PS domain.

1.14.2 Initial Security Activation

The initial security activation (illustrated in Figure 1.50) is used to activate AS security, which includes integrity protection of the SRB and ciphering of the SRB and DRBs. SRB2 and DRB can be established after security has been activated. A UE can accept a handover message

Figure 1.49 Paging message procedure.

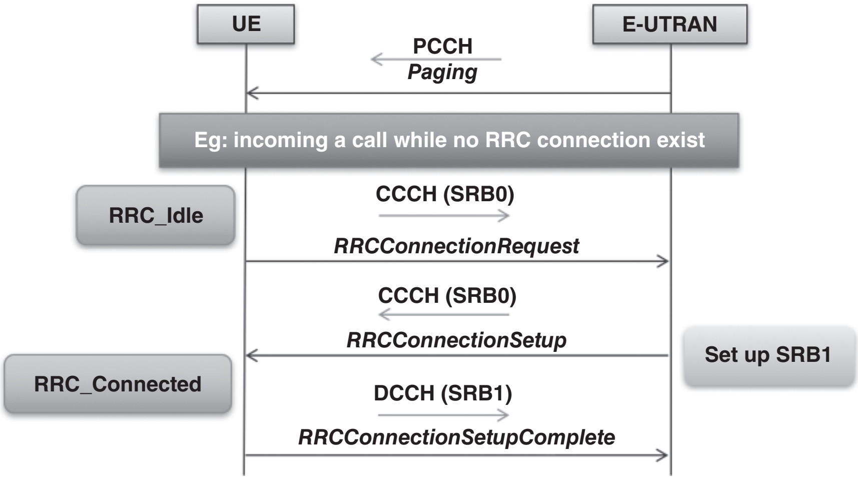
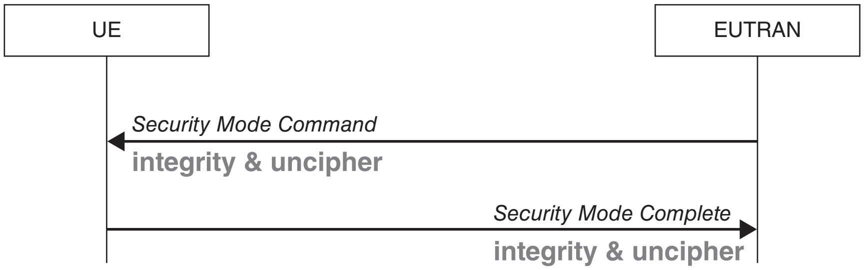


Figure 1.50 Initial security activation.



when security has been activated. The AS applies three different security keys derived from the KeNB key, as follows:

Integrity protection of RRC signaling (KRRCint)
Ciphering of RRC signaling (KRRCenc)
Ciphering of user data (KUPenc)

Integrity protection starts from *SecurityModeComplete,* while ciphering starts after the completion of *SecurityModeComplete.* Neither integrity protection nor ciphering applies for SRB0. The integrity and ciphering algorithms can only be changed upon handover. The "NULL" integrity protection algorithm (eia0) is used only for the UE in limited service mode. When the "NULL" integrity protection algorithm is used, the "NULL" ciphering algorithm is also used.

1.14.3 RRC Connection Reconfiguration

The RRC connection reconfiguration procedure (illustrated in Figure 1.51) has several functions:

Modifying an RRC connection, for example, to establish/modify/release RBs.
Performing handover (including a change in integrity and ciphering algorithms).
Set up/modify/release measurements.
May transfer NAS-dedicated information from the E-UTRAN to the UE.

During handover, if the target cell cannot inherit settings from the source cell, the NW can invoke the *full* configuration option to let the UE release and initialize with a newly configured radio configuration. Full configuration can be used to release and initialize the radio configuration if the configuration cannot continue during handover.

1.14.4 RRC Connection Release

The purpose of this procedure (illustrated in Figure 1.52) is to release the RRC connection, which includes the release of the established radio bearers as well as all radio resources. Only the E-UTRAN can initiate the RRC connection release procedure for a UE. The UE may release the RRC connection locally if requested by the upper layers. Access to the current cell may be barred for 300 s as a result of this procedure. The UE may have failed an authentication check, for example, see TS24.301. In the NAS procedure, most local RRC connection release scenarios will not cause the current cell to be barred. RRC release scenarios are outlined in Table 1.44.

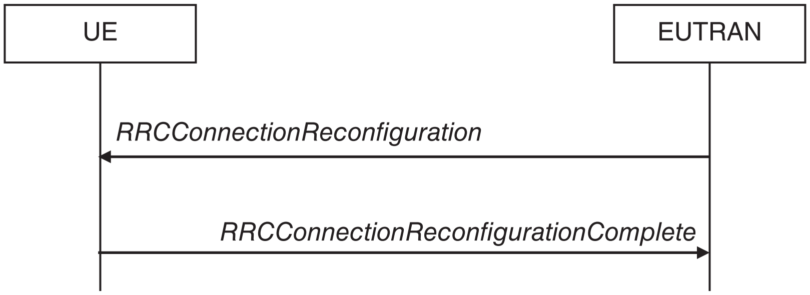


Figure 1.51 RRC connection reconfiguration.

Figure 1.52 RRC connection release.

Table 1.44 RCC release scenarios.

Possible Release Scenario	UE Behavior
With redirectedCarrierInfo IE	UE shall attempt to camp on a suitable cell according to redirectedCarrierInfo.
With idleModeMobilityControlInfo IE	Dedicated priority contained in idleModeMobilityControlInfo should take precedence over the SIB before T320 expires.
Cause: loadBalancingTAUrequired	UE will make tracking area updates.
Cause: Other	UE just moves to RRC Idle and attempts to select a suitable cell. No other specific procedure.

T320 starts upon receiving *t320* or upon cell (re)selection to E-UTRAN from another RAT with validity time configured for dedicated priorities (in which case, the remaining validity time is applied). T320 stops upon entering RRC Connected, when PLMN selection is performed on request by the NAS, or upon cell (re)selection to another RAT (in which case, the timer is carried on to the other RAT). At T320 expiration, the cell reselection priority information provided by dedicated signaling is discarded.

1.14.5 DL Information Transfer

The purpose of the DL information transfer procedure (as illustrated in Figure 1.53) from the E-UTRAN to a UE in RRC Connected mode is to transfer the following:

A NAS message
(Tunneled) non-3GPP dedicated information.

This can be transferred in SRB1 only if SRB2 has not been established yet. Otherwise, even if SRB2 is suspended, the E-UTRAN does not send this message until SRB2 is resumed. Sometimes a downlink NAS message may be piggybacked onto an RRC Connection Reconfiguration message instead of this message when there is one dependent (i.e. with joint success/failure) procedure, even if SRB2 has already been established.

1.14.6 UL Information Transfer

The purpose of the UL information transfer procedure (as illustrated in Figure 1.54) from the UE to the E-UTRAN in RRC Connected mode is to transfer:

A NAS message
(Tunneled) non-3GPP dedicated information.

During the RRC connection establishment, the NAS information is piggybacked onto the RRC Connection Setup Complete message instead of this message.

The information will be transferred in SRB1 if SRB2 has not been established; otherwise, it will always transfer in SRB2.

1.14.7 UE Capability Transfer

The purpose of the UE capability transfer procedure (as illustrated in Figure 1.55) is to transfer UE radio access capability information from the UE to the E-UTRAN. Based on the capability of the UE, the NW can make decisions about handover, measurement, and so on.

It is important to know that the RRC Connection Setup Complete does not carry any UE capability, and the network can query the capability of a specific RAT in a ue-CapabilityRequest; also, a change in E-UTRAN radio access capabilities will trigger TAU with IE "UE radio capability information update needed".

1.14.8 UE Information

The purpose of the UE information procedure (as illustrated in Figure 1.56) from the E-UTRAN is to request the UE to report information about:

The random access procedure:
  The number of preambles sent by the MAC for the last successfully completed RA procedure.
  Whether contention has been detected by the MAC for at least one of the transmitted preambles for the last successfully completed RA procedure.
Measurement information when a Radio Link Failure (RLF) occurred:
  The measurement result of the last serving cell.
  The measurement result of neighboring cells with decreasing order based on triggerQuantity (LTE) or quantityConfig (other RAT).

If the UE faces a radio link failure, the UE will report Rlf-Info_Available in the RRC Connection Reestablishment Complete message after RRC connection

Figure 1.53 DL information transfer.

Figure 1.54 UL information transfer.

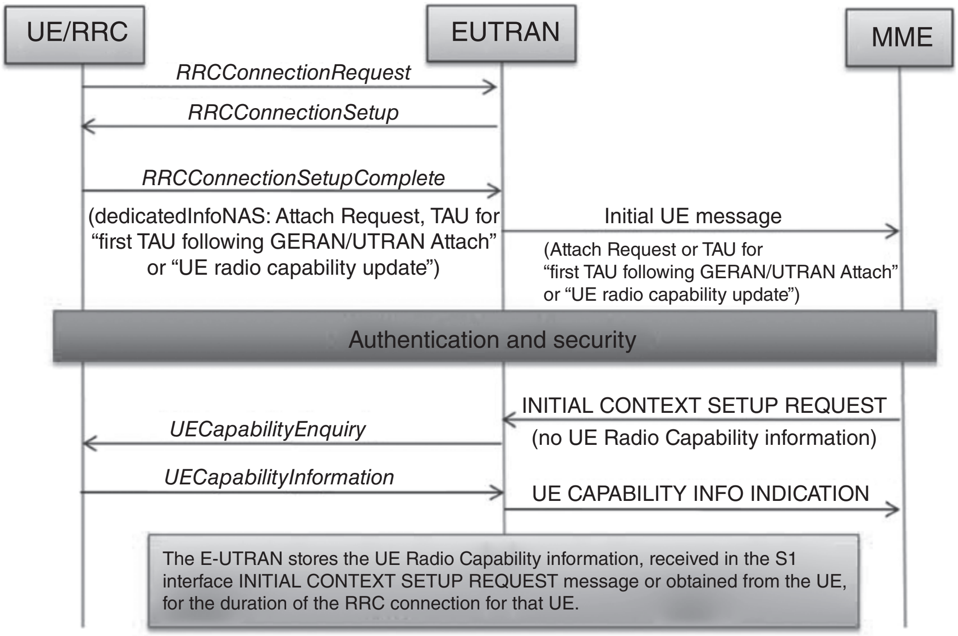


Figure 1.55 UE capability transfer.

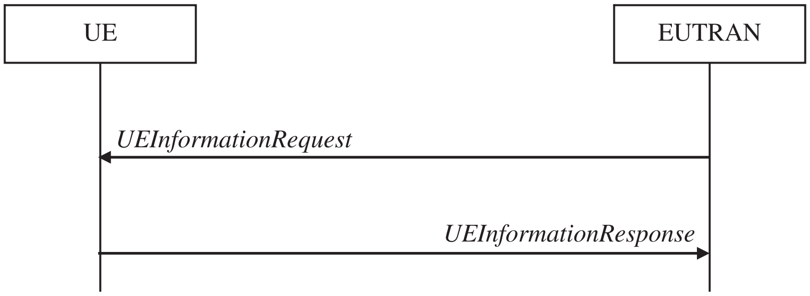


Figure 1.56 UE information.

re-establishment. Then, the network will retrieve the RLF information via UE information. The network can also retrieve an RA-related report via rach-ReportReq or a radio link failure report via Rlf-ReportReq, or both, by indicating the relevant IE in UE information.

1.15 LTE Idle Mode Mobility Procedures

1.15.1 General Mobility Procedure

The procedure for general LTE mobility is illustrated in Figure 1.57.

1.15.2 Public Land Mobile Network (PLMN) Selection

Public Land Mobile Network (PLMN) selection can be completed using either manual mode or automatic mode. The NAS will request the AS to select a cell belonging to this PLMN and then the AS will try to search the cell with the following procedure:

Initial cell selection
Stored information cell selection.

Elementary files within the USIM can support PLMN selection. These files can specify the PLMN search order, forbidden PLMNs, higher-priority PLMN timers, and previously used cell information.

Manual mode will also include PLMNs in the "forbidden PLMNs" list. The UE should use one of the following two cell selection procedures:

Initial cell selection: This procedure requires no prior knowledge of which RF channels are E-UTRA carriers. The UE will 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 is selected.

Stored information cell selection: This procedure requires stored information on carrier frequencies and, optionally, also information on cell parameters

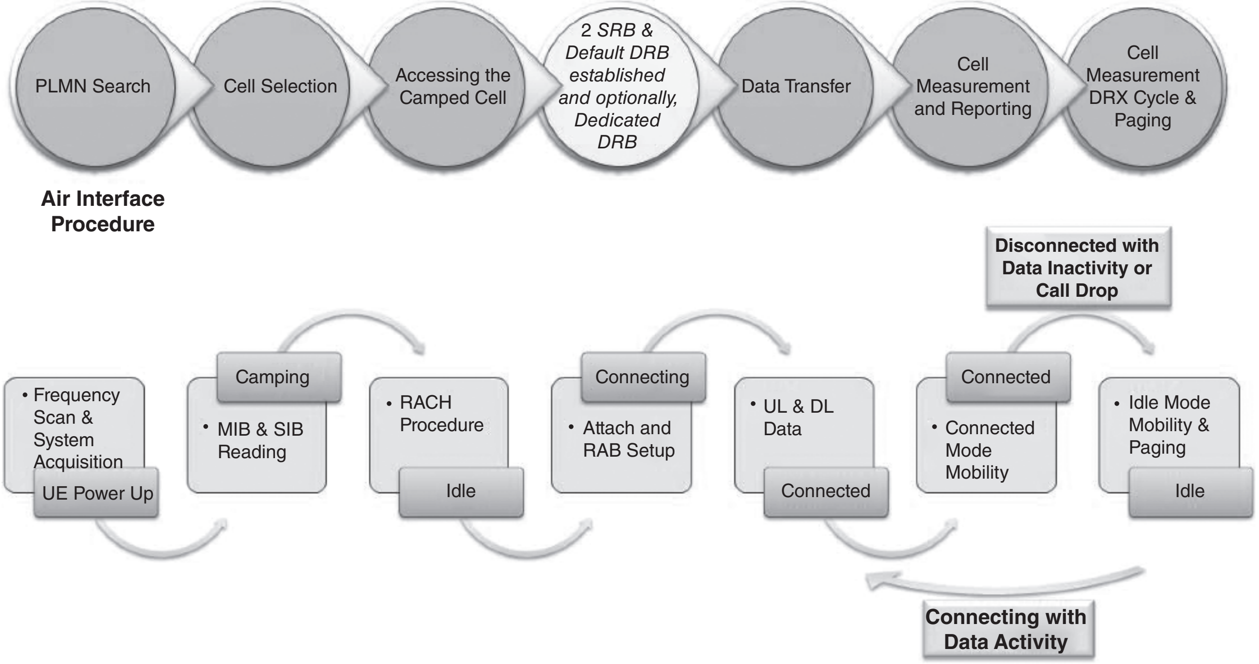


Figure 1.57 LTE mobility procedure.

from previously received measurement control information elements or from previously detected cells. Once the UE has found a suitable cell, the UE will select it. If no suitable cell is found, the initial cell selection procedure is started. The periodic attempts will only be performed in automatic mode when the MS is roaming and not while the MS is attached for emergency bearer services or has a PDN connection for emergency bearer services.

1.15.3 PLMN Selection Order

The PLMN selection order is classified into two modes: automatic mode and manual mode.

There are five PLMN selection orders from 1 to 5; each of them has its own characteristics, as described in Table 1.45.

The equivalent HPLMN list is as follows. To allow provision for multiple HPLMN codes, PLMN codes that are present within this list shall replace the HPLMN code derived from the IMSI for PLMN selection purposes. This list is stored on the USIM and is known as the *EHPLMN list*. The EHPLMN list may also contain the HPLMN code derived from the IMSI. If the HPLMN code derived from the IMSI is not present in the EHPLMN list, then it will be treated as a visited PLMN for PLMN selection purposes. HPLMN/EPLMN determination is carried out as follows: Either the

Table 1.45 PLMN selection order characteristics.

Order	PLMN Type	From
1	HPLMN/EHPLMN	Elementary file in USIM (EFIMSI and EFEHPLMN)
2	User-controlled PLMN selector with access technology (in priority order)	Elementary file in USIM (EFPLMNwACT)
3	Operator-controlled PLMN selector with access technology (in priority order)	Elementary file in USIM (EFOPLMNwACT)
4	PLMN/access technology combinations with received high-quality signal (in random order)	AS measured
5	PLMN/access technology combinations (in order of decreasing signal quality (RSRP))	AS measured

HPLMN (if the EHPLMN list is not present or is empty) or the highest priority EHPLMN that is available (if the EHPLMN list is present).

1.15.3.1 High Quality Criterion

For an E-UTRAN cell, the measured RSRP value should be greater than or equal to –110 dBm. The UE needs to read related SIBs such as MIB and SIB1 to obtain the PLMN ID of the cell and the related S-criteria , as well as SIB2. For more details, refer back to the RRC SIB description.

1.15.4 Service Type and Cell Categories

Different service types have different cell categories, as described in Table 1.46. The levels of services defined for a UE are as follows:

Limited service (emergency calls, ETWS, and CMAS on an acceptable cell).
Normal service (for public use on a suitable cell).
Operator service (for operators only on a reserved cell).

1.15.4.1 Acceptable Cell, Exception

If a UE has an ongoing emergency call, all acceptable cells of that PLMN are treated as suitable for cell reselection for the duration of the emergency call.

1.15.4.2 Suitable Cell, Exception

A cell that belongs to an RA that is forbidden for regional provision service is suitable but provides only limited service.

Access classes are applicable, as follows:

Classes 0–9, for home and visited PLMNs.
Classes 11 and 15, for the home PLMN only if the EHPLMN list is not present, or any EHPLMN.
Classes 12, 13, and 14, for home PLMN and visited PLMNs of the home country only. For this purpose, the home country is defined as the country of the MCC part of the IMSI.

1.15.5 Cell Selection – S-criteria

In LTE, cell selection criteria can be calculated from the equations below:

$$S_{rxlev} > 0 \text{ AND } S_{qual} > 0 \tag{1.12}$$

$$S_{rxlev} = Q_{rxlevmeas} - (Q_{rxlevmin} + Q_{rxlevminoffset}) - P_{compensation} \tag{1.13}$$

$$S_{qual} = Q_{qualmeas} - (Q_{qualmin} + Q_{qualminoffset}) \tag{1.14}$$

Descriptions and sources for each term are given in Table 1.47.

The values $Q_{rxlevminoffset}$ and $Q_{qualminoffset}$ are only signaled when a cell is evaluated for cell selection as a result of a periodic search for a higher priority PLMN while camped normally in a VPLMN. The combination of $Q_{rxlevminoffset}$ and $Q_{qualminoffset}$ is an offset to avoid a ping-pong effect in a higher priority PLMN search.

1.15.6 Camping on a Suitable Cell

When a UE is camping on a suitable cell, the UE performs the following tasks:

Register on the PLMN (done by the NAS).

Table 1.46 Service type vs cell categories.

Service Type	Cell Categories
Limited service	Acceptable cell The cell is not barred The cell selection criteria are fulfilled
Normal service	Suitable cell The cell is not barred The cell selection criteria are fulfilled In SPLMN or RPLMN or EPLMN Not in “forbidden tracking areas for roaming” For a CSG cell, the CSG ID broadcast by the cell is present in the CSG white list associated with the PLMN for which the above condition is satisfied
Operator service	Reserved cell (SIB1 -> cellReservedForOperatorUse) A cell on which camping is not allowed, except for particular UE
X	Barred cell (SIB1 → cellBarred) A cell a UE is not allowed to camp on

Table 1.47 Parameter descriptions for cell selection criteria.

Parameter	Description	Source
S_{rxlev}	Cell selection Rx level value (dB)	Based on S-criteria calculation
S_{qual}	Cell selection quality value (dB)	Based on S-criteria calculation
$Q_{rxlevmeas}$	Measured cell Rx level value (RSRP)	Based on L1 measurement
$Q_{qualmeas}$	Measured cell quality value (RSRQ)	Based on L1 measurement
$Q_{rxlevmin}$	Minimum required Rx level in the cell (dBm)	q-RxLevMin in SIB1
$Q_{qualmin}$	Minimum required quality level in the cell (dB)	q-QualMin in SIB1
$Q_{rxlevminoffset}$	Offset to the signaled $Q_{rxlevmin}$ taken into account in the S_{rxlev} evaluation as a result of a periodic search for a higher priority PLMN while camped normally in a VPLMN	q-RxLevMinOffset in SIB1
$Q_{qualminoffset}$	Offset to the signaled $Q_{qualmin}$ taken into account in the S_{qual} evaluation as a result of a periodic search for a higher priority PLMN while camped normally in a VPLMN	q-QualMinOffset in SIB1
$P_{compensation}$	$\max(P_{EMAX} - P_{PowerClass}, 0)$ (dB)	Based on $P_{PowerClass}$ and P_{EMAX}
P_{EMAX}	Maximum Tx power level a UE may use when transmitting on the uplink in the cell (dBm)	P-Max in SIB1
$P_{PowerClass}$	Maximum RF output power of the UE (dBm) according to the UE power class	For example, 23 dBm (Power class 3)

Select and monitor the indicated paging channels of the cell in the registered routing area.
Monitor relevant system information.
Perform measurements necessary for the cell reselection evaluation procedure:
  Using UE internal triggers; evaluate the cell selection criterion, S, for the serving cell at least every DRX cycle.
  When information on the BCCH used for the cell reselection evaluation procedure has been modified.
Execute the cell reselection evaluation process.
  Reselection can be intra-frequency, inter-frequency, or inter-rat cells.

Camping on a cell in Idle mode has several purposes:

It enables the UE to receive system information from the PLMN.
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.
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.
It enables the UE to receive ETWS and CMAS notifications.
It enables the UE to receive MBMS services.

Registration on the PLMN is performed by the Attach procedure of the EMM.

1.15.7 Cell Reselection in Idle Mode

The cell reselection evaluation process in Idle mode involves the following:

Handling reselection priorities
  Knowing the priorities of different E-UTRAN frequencies or inter-RAT frequencies.
Measurement rules for cell reselection
  Knowing which kind of measurements should be performed, for example: intra-frequency, inter-frequency, inter-RAT.
Mobility states of a UE
  If the UE is in a high- or medium-mobility state, the UE applies the speed-dependent scaling rules.
Cell reselection criteria
  E-UTRAN inter-frequency and inter-RAT cell reselection criteria:
    Choose the highest priority frequency among those fulfilling the cell reselection criteria.
  Intra-frequency and equal priority inter-frequency cell reselection criteria:
    Choose the best-ranked cell in the selected frequency.

1.15.8 Handling Reselection Priorities

Handling reselection priorities is illustrated in Figure 1.58.

If priorities are provided in dedicated signaling, the UE ignores all the priorities provided in the system information. Otherwise, the UE needs to use the priorities provided in the system information.

The UE only performs cell reselection evaluation for E-UTRAN frequencies and inter-RAT frequencies that are given in the system information and for which the UE has a priority provided.

In the system information, an E-UTRAN frequency or inter-RAT frequency may be listed without providing a priority (i.e. the field Cell_Reselection_Priority is absent for that frequency). If the UE is inthe camped on any cell state, the UE shall only apply the priorities provided by the system information from the current cell, and the UE preserves priorities provided by dedicated signaling unless specified otherwise. When the UE is in the camped normally state, it has only dedicated priorities other than for the current frequency, so the UE shall consider the current frequency to be the lowest priority frequency (i.e. lower than the eight network-configured values). While the UE is camped on a suitable CSG cell, the UE shall always consider the current frequency to be the highest priority frequency (i.e. higher than the eight values configured in the network), irrespective of any other priority value allocated to this frequency.

1.15.9 Measurement Rules for Cell Reselection

The measurement rules for cell reselection are illustrated in Figure 1.59.

If Sintrasearch is not sent, intra-frequency measurement is always performed.

If Snonintrasearch is not sent, equal or lower priority inter-frequency and inter-RAT measurements are always performed.

1.15.10 Speed-dependent Scaling of Reselection Parameters

As shown in Figure 1.60, speed-dependent scaling for reselection parameters is the process used to reselect to other cells quickly in order to avoid out-of-service periods during high/medium-speed movement. The UE shall not count consecutive reselections between the same two cells in the mobility state detection criteria if the same cell is reselected just after one other reselection. Connected-mode speed-dependent scaling will count handovers instead of cell reselections.

The criteria defining medium- and high-mobility states are as follows:**Medium-mobility state criteria:** If the number of cell reselections during time period T_{CRmax} exceeds N_{CR_M} but does not exceed N_{CR_H}.

High-mobility state criteria: If the number of cell reselections during time period T_{CRmax} exceeds N_{CR_H}.

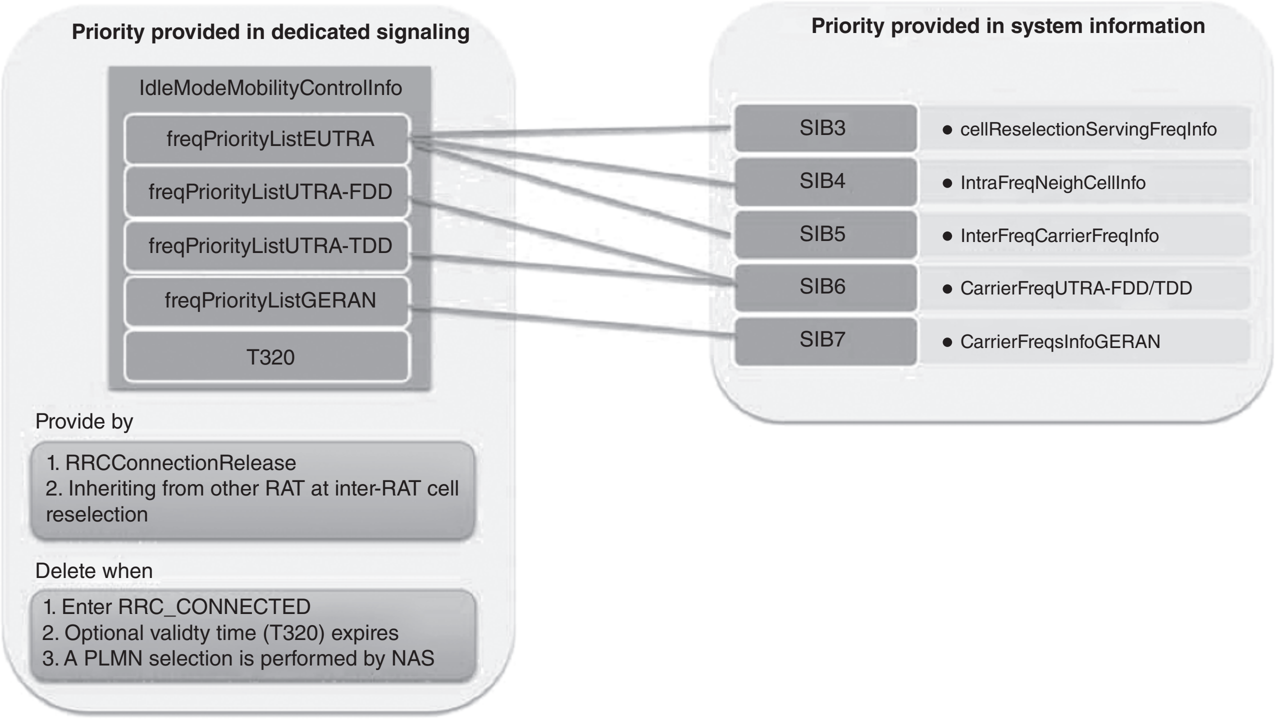


Figure 1.58 Handling reselection priorities.

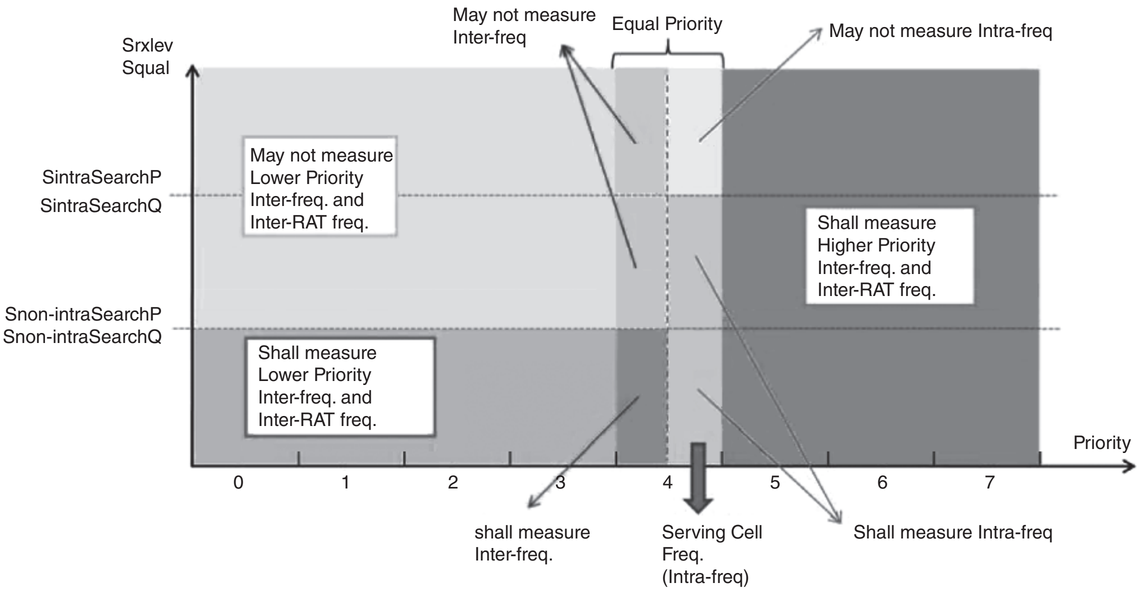


Figure 1.59 Measurement rules for cell reselection.

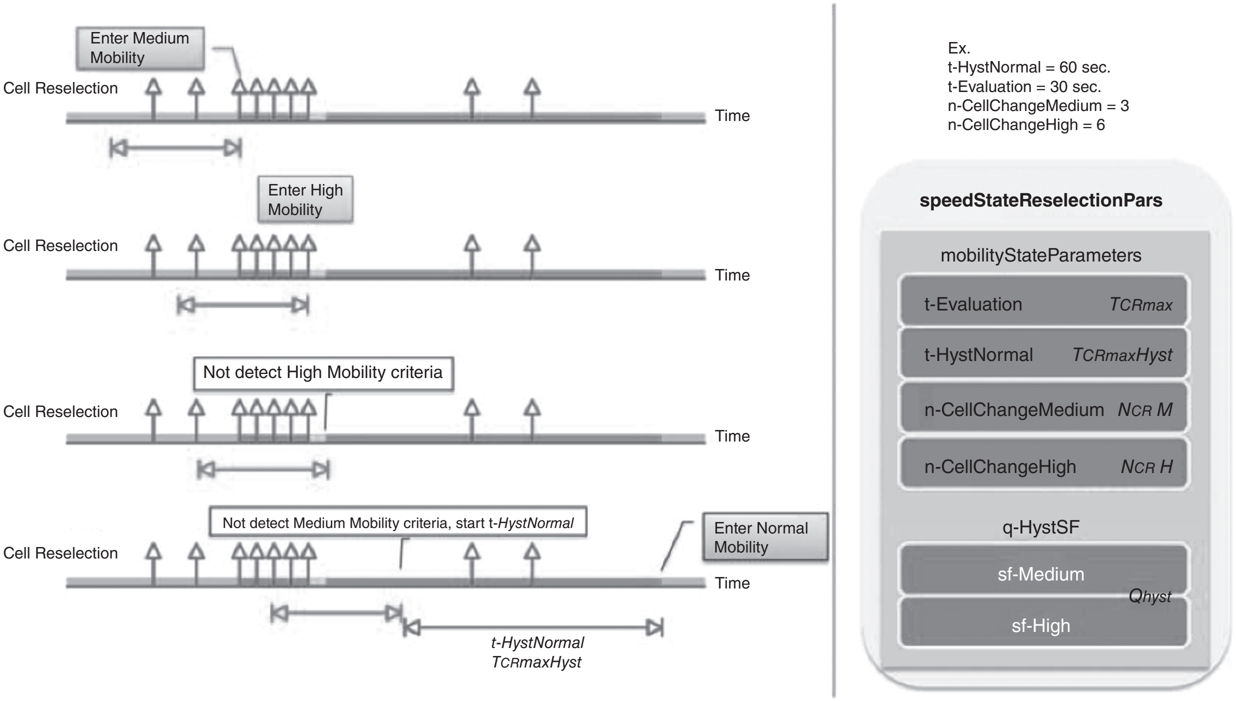


Figure 1.60 Speed-dependent scaling of reselection parameters.

If the criteria for either a medium- or high-mobility state are not detected during time period $T_{CRmaxHyst}$, then a normal-mobility state has been entered.

If a high-mobility state is detected:

Add the sf-High of “Speed dependent ScalingFactor for Qhyst” to Qhyst if sent in the system information.

For E-UTRAN cells, multiply $T_{reselectionEUTRA}$ by the sf-High of “Speed dependent ScalingFactor for TreselectionEUTRA” if sent in the system information.

For UTRAN cells, multiply $T_{reselectionUTRA}$ by the sf-High of “Speed dependent ScalingFactor for TreselectionUTRA” if sent in the system information.

For GERAN cells, multiply $T_{reselectionGERA}$ by the sf-High of “Speed dependent ScalingFactor for TreselectionGERA state” if sent in the system information.

If a medium-mobility state is detected:

Add the sf-Medium of “Speed dependent ScalingFactor for Qhyst for medium mobility state” to Qhyst if sent in the system information.

For E-UTRAN cells, multiply $T_{reselectionEUTRA}$ by the sf-Medium of “Speed dependent ScalingFactor for TreselectionEUTRA” if sent in the system information.

For UTRAN cells, multiply $T_{reselectionUTRA}$ by the sf-Medium of “Speed dependent ScalingFactor for TreselectionUTRA” if sent in the system Information.

For GERAN cells, multiply $T_{reselectionGERA}$ by the sf-Medium of “Speed dependent ScalingFactor for TreselectionGERA” if sent in the system information.

1.15.11 LTE Intra-frequency Cell Reselection

Figure 1.61 illustrates an example of LTE intra-frequency reselection parameters based on ranking due to equal priority:

Intra-frequency cell measurement criteria: $S_{rxlev} < S_{IntraSearchP}$ or $S_{Qual} > S_{IntraSearchQ}$.

Ranking based on RSRP.

The UE initially camps on the LTE F1 cell (first frequency) with physical cell ID 1. The only other neighbor defined is the F1 (same frequency) cell with physical cell ID 12. Before point 1, the serving cell fulfills $S_{rxlev} > S_{IntraSearchP}$ and $S_{qual} > S_{IntraSearchQ}$, here, the UE may choose not to perform intra-frequency measurements. At point 1, $S_{rxlev} < S_{IntraSearchP}$ (if $S_{rxlev} < S_{IntraSearchP}$ or $S_{qual} > S_{IntraSearchQ}$) and thus the UE begins the search for an intra-frequency neighbor. The PCI = 12 cell is ranked the highest at point 2 due to its received level ($Q_{hyst} + Q_{offset}$) being better than the serving F1 cell. The UE reselects to the PCI = 12 cell when the timer expires (set at two seconds – at point 3 in this example).

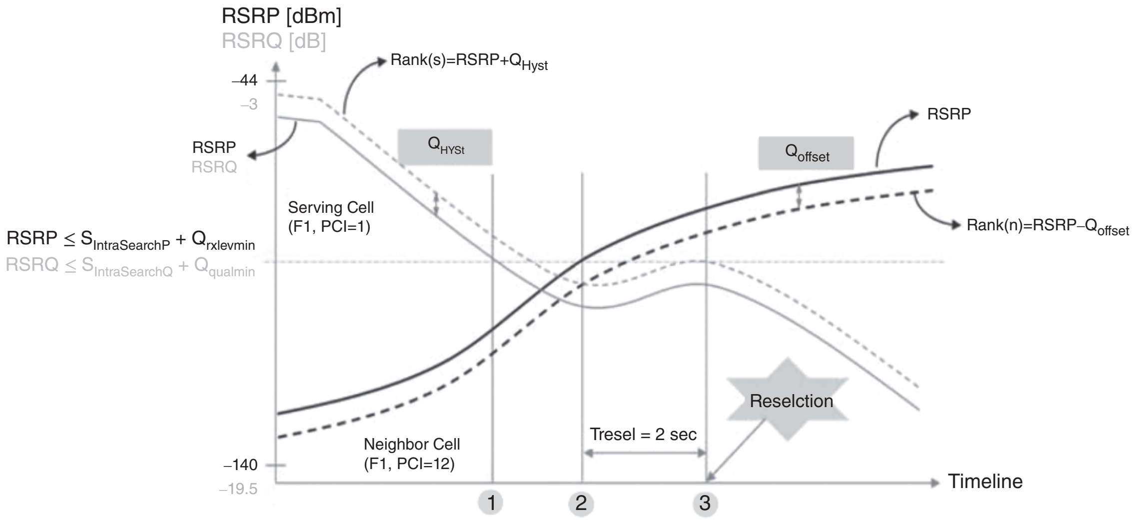


Figure 1.61 LTE intra-frequency cell reselection.

1.15.12 LTE Inter-frequency Cell Reselection Rules

Inter-frequency reselection is based on absolute priorities. The UE tries to camp on the highest priority frequency available while the priorities are provided in LTE SIB5 and are valid for all UEs in the serving cell. The specific priorities per UE can be signaled in the RRC Connection Release message, and this is known as dedicated priority.

Only the frequencies listed in SIB5 are considered for inter-frequency reselection. This list can contain a maximum of eight frequencies which the UE may be allowed to monitor within the E-UTRAN. The parameters provided in SIB3 are also considered for ranking evaluations.

For inter-frequency neighboring cells, it is possible to indicate the cell-specific offset to be considered during reselection. These parameters are common to all cells on a different frequency. Blacklists can be provided to prevent the UE from reselecting to specific intra- and inter-frequencies. Cell reselection can also be speed-dependent.

1.15.13 LTE Inter-frequency Cell Reselection with Equal Priority

Figure 1.62 illustrates an example of LTE inter-frequency reselection parameters for equal priority:

Inter-frequency cell measurement criteria: $S_{rxlev} < S_{nonIntraSearchP}$ or $S_{qual} < S_{nonIntraSearchQ}$.

Ranking based on RSRP.

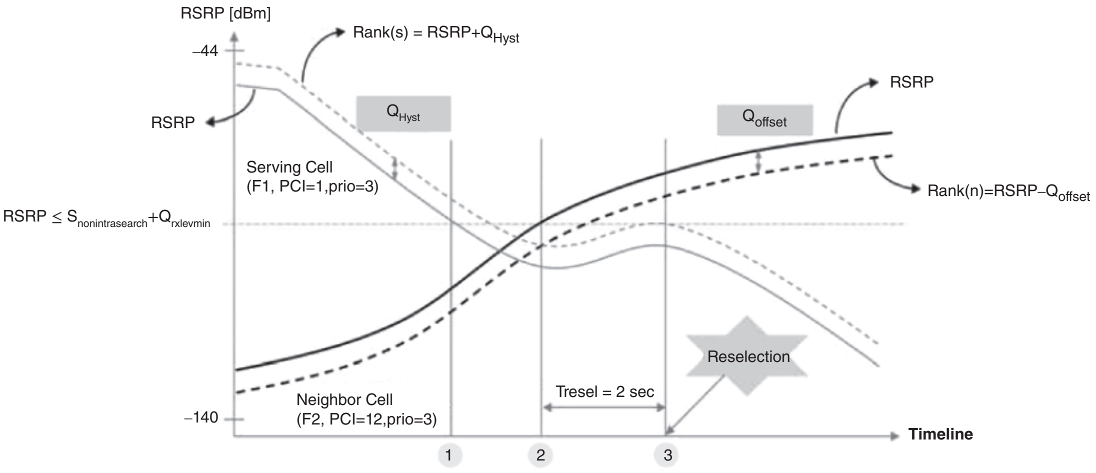


Figure 1.62 LTE inter-frequency cell reselection with equal priority.

The UE initially camps on the LTE F1 cell (first frequency) with physical cell ID 1. The only other neighbor defined is the F2 (second frequency) cell with physical cell ID 12. The priorities of the two frequencies F1 and F2 are defined as the same. At point 1, $S_{\text{Servingcell}} < S_{\text{nonIntraSearch}}$ and thus the UE begins the search for an inter-frequency neighbor. The F2 cell is ranked the highest at point 2 due to the fact that its received level ($Q_{\text{hyst}} + Q_{\text{offset}}$) is better than the serving F1 cell. The UE reselects to the F2 cell when the timer expires (set at two seconds – at point 3 in this example).

The fact that $S_{\text{nonIntraSearch}}$ is common between LTE inter-frequency measurements and inter-RAT requires additional planning. One of the ways to handle this situation is by treating sites within core LTE coverage – inter-frequency in particular – differently from edge LTE sites. Setting "$S_{\text{nonIntraSearch}}$" and "LTE SIB3 Q_{rxlevmin}" on a per-cell basis avoids situations where the UE is performing concurrent inter-RAT and inter-frequency measurements. This per-cell setting also helps in performing inter-frequency LTE reselection before inter-RAT, which allows the UE to remain on LTE coverage longer. In addition, "$Q_{\text{offsetFreq}}$" can be introduced on the inter-frequency LTE layer to treat intra- and inter-frequency cell reselection differently for equal priority inter-frequency reselection. This offset is especially important if no changes to "$S_{\text{nonIntraSearch}}$" and "LTE SIB3 Q_{rxlevmin}" are made on the serving LTE cell. It can be concluded that inter-frequency with equal priority cell reselection is similar to that for intra-frequency.

1.15.14 LTE Inter-frequency Cell Reselection with Low Priority

Figure 1.63 illustrates an example of LTE inter-frequency reselection parameters based on low priority, where the inter-frequency cell measurement criteria are:

$S_{\text{rxlev}} < S_{\text{nonIntraSearchP}}$ or $S_{\text{qual}} < S_{\text{nonIntraSearchQ}}$

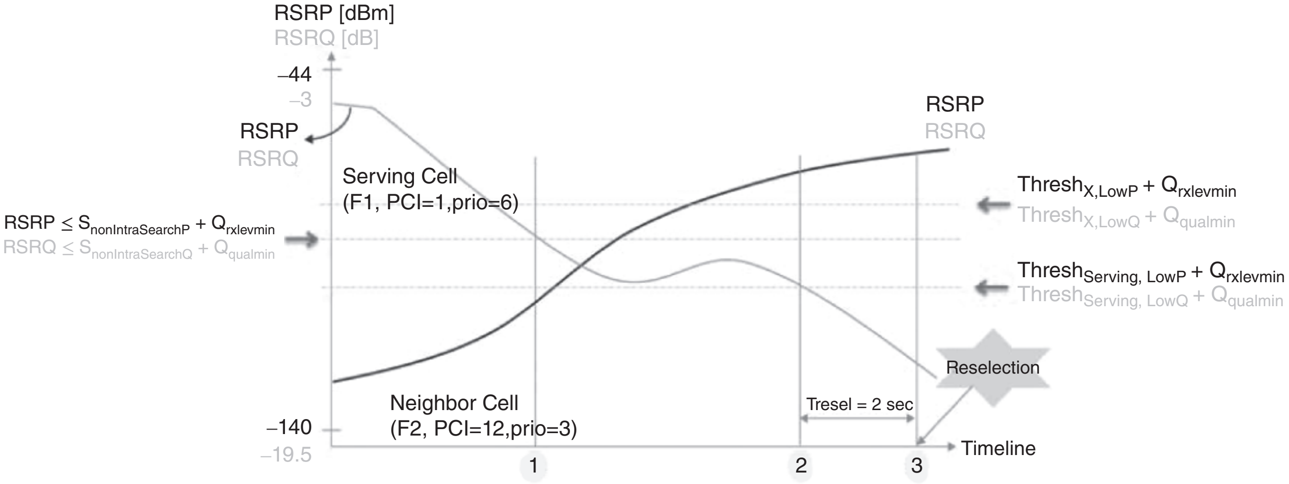


Figure 1.63 LTE inter-frequency cell reselection with low priority.

Table 1.48 Serving and neighboring cell threshold definitions.

Parameter	Serving Cell	Neighboring Cell
threshServingLowQ provided in SIB3	$S_{qual} < Thresh_{Serving,\ LowQ}$	$S_{qual} > Thresh_{X,\ LowQ}$
threshServingLowQ not provided in SIB3	$S_{rxlev} < Thresh_{Serving,\ LowP}$	$S_{rxlev} > Thresh_{X,\ LowP}$

The UE initially camps on the LTE F1 cell (first frequency) with physical cell ID 1 with high priority (such as priority 6). The only other neighbor defined is the F2 (different frequency) cell with physical cell ID 12 with a lower priority than the serving cell (such as priority 3). Before point 1, the serving cell fulfills $S_{rxlev} > S_{nonIntraSearchP}$ and $S_{qual} > S_{nonIntraSearchQ}$, so the UE may choose not to perform inter-frequency measurements. At point 1, $S_{rxlev} < S_{nonIntraSearchP}$ or $S_{qual} < S_{nonIntraSearchQ}$ and thus the UE begins the search for an inter-frequency neighbor. The quality of the serving cell is lower than a threshold ($S_{qual} < Thresh_{Serving,\ LowQ}$ or $S_{rxlev} < Thresh_{Serving,\ LowP}$), meanwhile, the quality of the neighboring inter-frequency cell is better than a threshold ($S_{qual} > Thresh_{X,\ LowQ}$ or $S_{rxlev} > Thresh_{X,\ LowP}$) at point 2 to meet the lower priority cell reselection criteria. The UE reselects to the PCI = 12 cell when the timer expires (set at two seconds – at point 3 in this example). Descriptions of threshold parameters for serving and neighboring cells are given in Table 1.48.

1.15.15 LTE Inter-frequency Cell Reselection with High Priority

Figure 1.64 illustrates an example of LTE inter-frequency reselection parameters based on high priority. The UE initially camps on the LTE F1 cell (first frequency) with physical cell ID 1 with lower priority (such as priority 3).

Table 1.49 Neighboring cell threshold definitions.

Parameter	Neighboring Cell
threshServingLowQ provided in SIB3	$S_{qual} > Thresh_{X,\ HighQ}$
threshServingLowQ not provided in SIB3	$S_{rxlev} > Thresh_{X,\ HighP}$

The only other neighbor defined is the F2 (different frequency) cell with physical cell ID 12 with a higher priority than the serving cell (such as priority 6). Before point 1, the UE always performs high-priority measurements. At point 1, the quality of the neighboring inter-frequency cell is better than a threshold ($S_{qual} > Thresh_{X,\ HighQ}$ or $S_{rxlev} > Thresh_{X,\ HighP}$ or $S_{qual} > Thresh_{X,\ HighQ}$). The UE reselects to the PCI = 12 cell when the timer expires (set at two seconds – at point 2 in this example).

Descriptions of the threshold parameters for neighboring cells are given in Table 1.49.

1.16 LTE Connected Mode Mobility Procedures

1.16.1 Measurement Parameters

The Connected mode measurement objects, reporting configurations, quantity configurations including

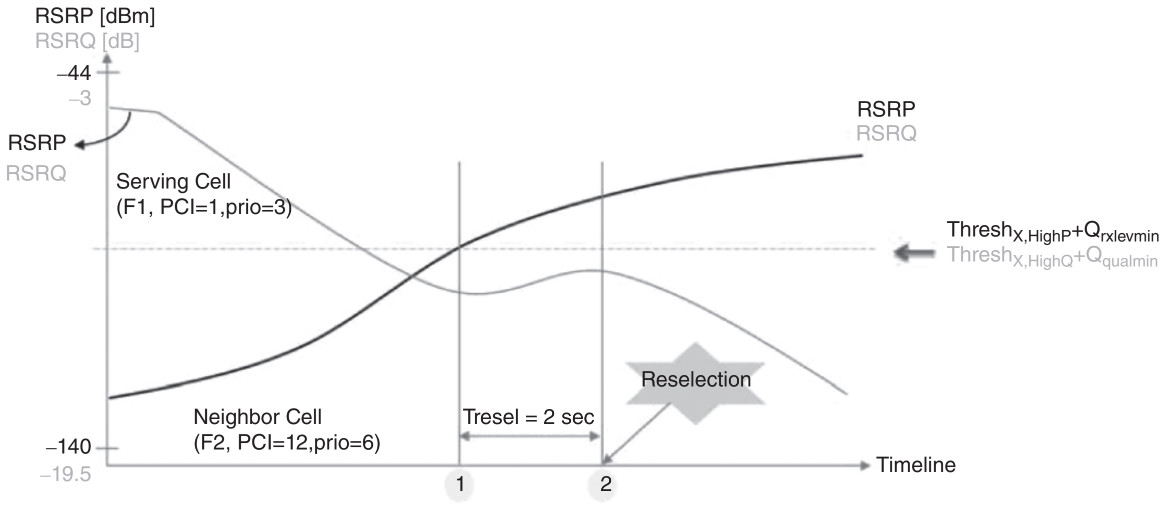


Figure 1.64 LTE inter-frequency cell reselection with high priority.

different RATs (E-UTRAN, UTRAN, GERAN), and measurement gaps are all illustrated in Figure 1.65. The measurement parameters consist of set up/modify/release via the RRC Connection Reconfiguration message in RRC Connected mode, while intra-frequency measurements are the measurements at the downlink carrier frequency of the serving cell and inter-frequency measurements are the measurements at frequencies that differ from the downlink carrier frequency of the serving cell. The network must configure *measObject* for the serving frequencies (earfcn) during measurement setup.

1.16.2 Measurement Procedure in RRC_Connected Mode

LTE events are shown in detail in Table 1.50.

The eNodeB executes the handover based on the UE measurements. The eNB's RRC layer requests the UE to measure intra-frequency cells, inter-frequency cells, or inter-RAT cells belonging to another 3GPP or non-3GPP system. The reporting by the UE is controlled by the eNB through periodic or event-based measurements. The list of events configured by the eNB's RRC layer is summarized in Table 1.50.

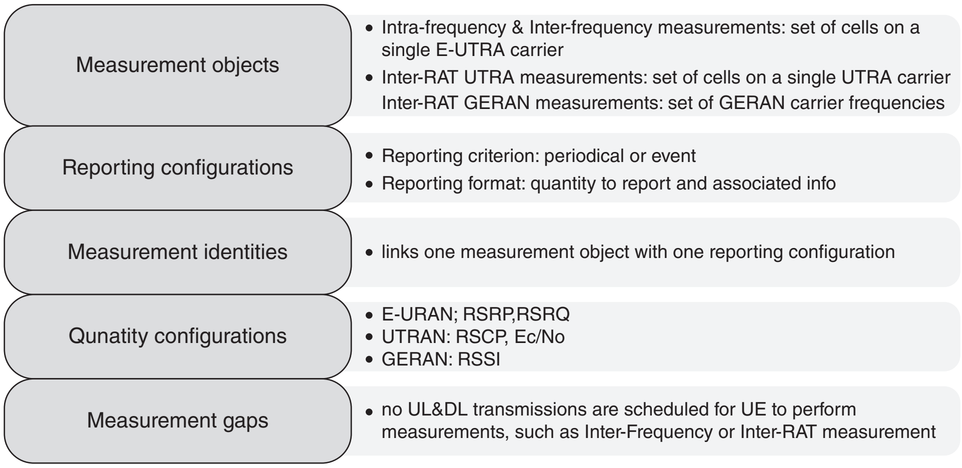


Figure 1.65 Measurement parameters.

Table 1.50 Serving and neighboring cell threshold definitions.

Handover Event	Definition
A1	Serving cell becomes better than a threshold. UE measurements can be based on RSRP and/or RSRQ.
A2	Serving cell becomes worse than a threshold. UE measurements can be based on RSRP and/or RSRQ.
A3	Neighboring cell offset becomes better than the serving cell. UE measurements can be based on RSRP and/or RSRQ.
A4	Neighboring cell becomes better than a threshold. UE measurements can be based on RSRP and/or RSRQ.
A5	Serving cell becomes worse than threshold 1 and neighboring cell becomes better than threshold 2. UE measurements can be based on RSRP and/or RSRQ.
B1	Inter-RAT neighbor becomes better than a threshold. UE measurements can be based on other RAT measurement values (i.e. WCDMA CPICH RSCP and/or Ec/No).
B2	Serving cell becomes worse than threshold 1 and inter-RAT neighbor becomes better than threshold 2. UE measurements can be based on LTE and other RAT measurements.

RSRP (Reference Signal Received Power): Calculated as the linear average over the power from the first antenna port, indicated as R0. Within the measurement cycle (or bandwidth), RSRP is estimated over all REs where R0 is transmitted. If the UE can reliably detect that R1 is available, it may use R1 in addition to R0 to determine the RSRP in each transmission symbol over the measurement cycle.
RSRQ (Reference Signal Received Quality): The ratio between the RSRP and the RSSI, depending on the measurement bandwidth, i.e. resource blocks.

In UMTS, the same concept of event-based measurement applies. However, because UMTS supports handover between multiple cells, the events have different definition scope: for example, event 1A is used to add a cell into the active set, and event 1B is used to remove a cell from the active set.

Assume the shortest measurement bandwidth of 6 RBs (i.e. 72 REs) transmitting with 43 dBm (i.e. total downlink Tx power per cell). This means that the RSRP is 1/72 of the total power. Assuming all REs are going through a similar path loss of –100 dB, the RSRP can be derived as follows:

$$\text{RSRP} = 43 - 100 - 10 * \log(72) = -75.6\ \text{dBm}. \tag{1.15}$$

RSRQ is the ratio between the RSRP and the RSSI, depending on the measurement bandwidth, i.e. the resource blocks. Consider an ideal interference and noise-free cell where reference signals and subcarriers carrying data are of equal power over one RB (i.e. 12 REs). Then, over the 100 RBs in a 20 MHz system, for one OFDM symbol with R0, RSRQ is estimated as inter-cell interference, which, in practice, would decrease the results. Inter-cell interference would appear as a wideband RSSI increment impacting the denominator in the RSRQ calculation.

$$\begin{aligned}\text{RSRQ} &= 10 * \log\ \left((100 * 1\text{RE})\big/(100 * 12\text{RE})\right)\\ &= -10.79\ \text{dB}\end{aligned} \tag{1.16}$$

1.16.3 DRB Establishment During Initial Attach

DRB establishment during initial attach is illustrated in the signaling flow in Figure 1.66. During the initial attach, the network will assign a default EPS bearer and related DRB.

The NAS requests the registration procedure and it then requires the AS to establish the RRC connection. The PRACH procedure in the MAC and L1 is needed before the RRC connection can be established.

In Step 7, SRB2, DRB, and the default EPS bearer can be set up at the same time after security has been activated:

The link between the EPS bearer and the DRB is via eps-BearerIdentity and drb-Identity.

The NW will also indicate QoS-related parameters in the ESM message.

A dedicated EPS bearer is optional during this procedure, and if included it will be contained in another dedicatedInfoNASList.

A measurement-related configuration can be set up during this procedure or later.

It will also contain dedicated radio resource configuration.

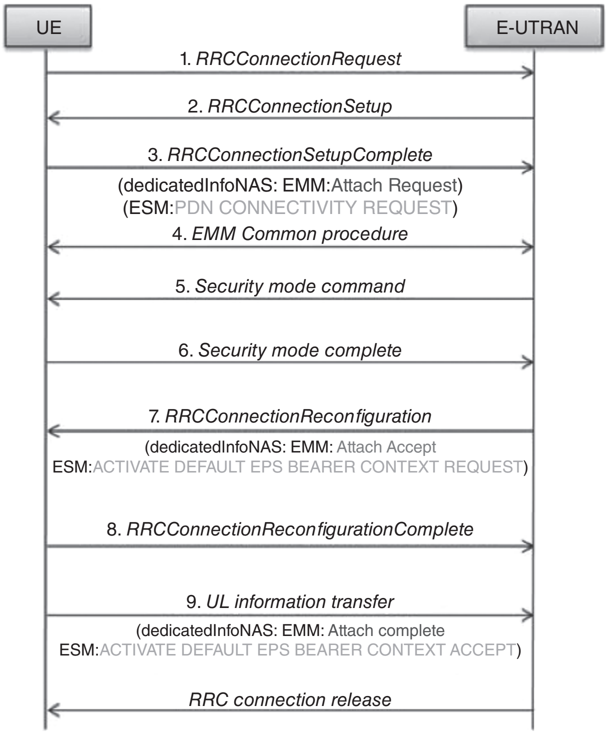


Figure 1.66 DRB establishment during initial attach.

After the related DRBs have been established, the UE can send and receive user data with the corresponding DRB and EPS bearer. The number of DRBs that a UE of Categories 1–5 can support is eight.

1.16.4 DRB Establishment After Initial Attach

DRB establishment after initial attach is illustrated in the signaling flow shown in Figure 1.67. During the initial attach and due to the application package not always being continuous (the NW will release the RRC connection due to the inactivity of a user), then, upon receipt of the application package or paging for an MT package, the UE will trigger the establishment of the DRB.

In Step 6, SRB2 and DRB can be set up after security has been activated:

The link between the EPS bearer and the DRB is via eps-BearerIdentity and drb-Identity.

A measurement-related configuration can be set up during this procedure or later.

It will also contain dedicated radio resource configuration.

1.16.5 Connected Mode Mobility

In RRC Connected mode, the network controls UE mobility and decides when the UE should move to another cell, which may be on another frequency or

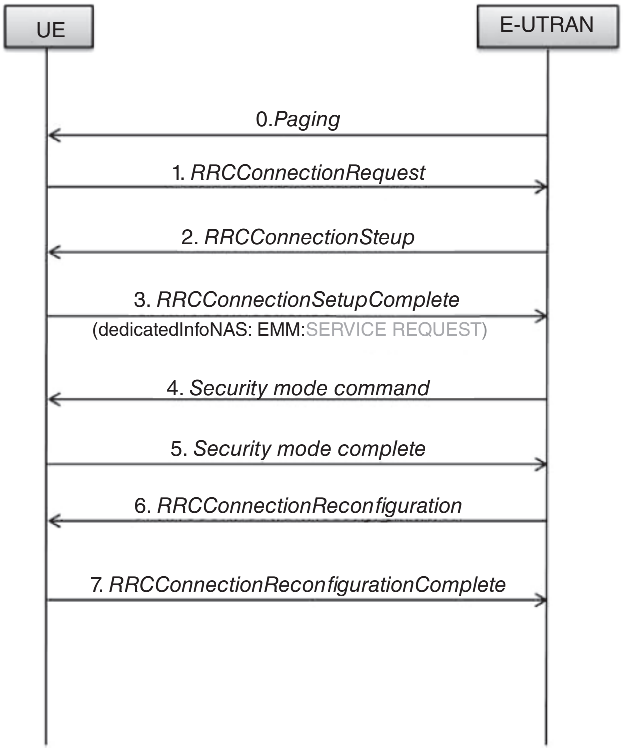


Figure 1.67 DRB establishment after initial attach.

RAT. The network triggers a handover procedure as a result of, for example, radio conditions or loading. This may be based on a measurement report from the UE or it may be a blind handover.

The handover type may be:

An intra-frequency handover
An inter-frequency handover
An inter-RAT handover to UTRAN, GERAN, CDMA2000, or a cell change order to GERAN.

Compared with UMTS, which can have several active set cells, LTE only has one serving cell, so every handover is a hard handover instead of a soft handover.

1.16.6 LTE Intra-frequency Handover

An LTE cell change always involves a hard handover. LTE introduces handovers that can be supported through S1 or X2 interfaces, as follows:

In an S1-type handover, the source and target eNBs communicate via the MME through the S1 interface to exchange handover-related signaling messages.
X2-based handovers are the most commonly used handovers because they involve fewer delays, and the eNBs communicate directly.
X2 is a logical interface that needs to be set up between neighboring cells.
If an X2 handover fails, typically the handover is re-tried over the S1 interface.

The messages between the UE and the source/target eNB are transmitted on the RRC layer of the control plane. For LTE's X2-based handover, when the UE sends a measurement report message over the RRC layer, the source eNB sends a handover request to the target eNB including a list of the bearers to be transferred, and whether downlink data forwarding is being proposed. Then, the source eNB sends an RRC Connection Reconfiguration message to the UE over the RRC layer. At the same time, the downlink packets received at the source eNB from the S-GW are forwarded to the target eNB. Then, the UE synchronizes with the target eNB using the RA procedure, after which, the UE sends an RRC Connection Reconfiguration Complete message over the newly established RRC with the target eNB. The UE then starts collecting the SIBs from the target eNB carrying the required information about the cell parameters. The target eNB sends a UE Context Release message to the source eNB confirming the successful handover and enabling source eNB resources to be released. Finally, the data start flowing directly from the new serving eNB to the UE.

1.16.7 Delay Assessment During Handover

Delay assessment during handover is illustrated in Figure 1.68. Refer to [1] for more details on handover delay and total interruption times.

1.16.8 Event A3 Measurement Report Triggering

An A3 measurement report is used to compare the serving cell with an E-UTRAN neighboring cell. It can be used by the NW for intra-LTE handover.

Figure 1.69 illustrates an example of A3 measurement reporting. The NW has already configured the intra/inter-frequency neighboring cell with an A3 measurement event. At point 1, the UE satisfies the A3 measurement entering condition until time to trigger (TTT) seconds. The UE will trigger and send the A3 measurement report at point 2 (TTT = 320 ms in this example). An A3 measurement report can be configured by the eNB to trigger A3 measurement reports when the leaving condition for this event is met. At point 3, the UE satisfies the A3 measurement leaving condition until time to trigger (TTT) seconds. The UE will trigger and send the A3 measurement report at point 4 (TTT = 320 ms in this example). The details of A3 measurement are available at TS36.331 section 5.5.4.4 EventA3 (Neighbor becomes offset better than serving).

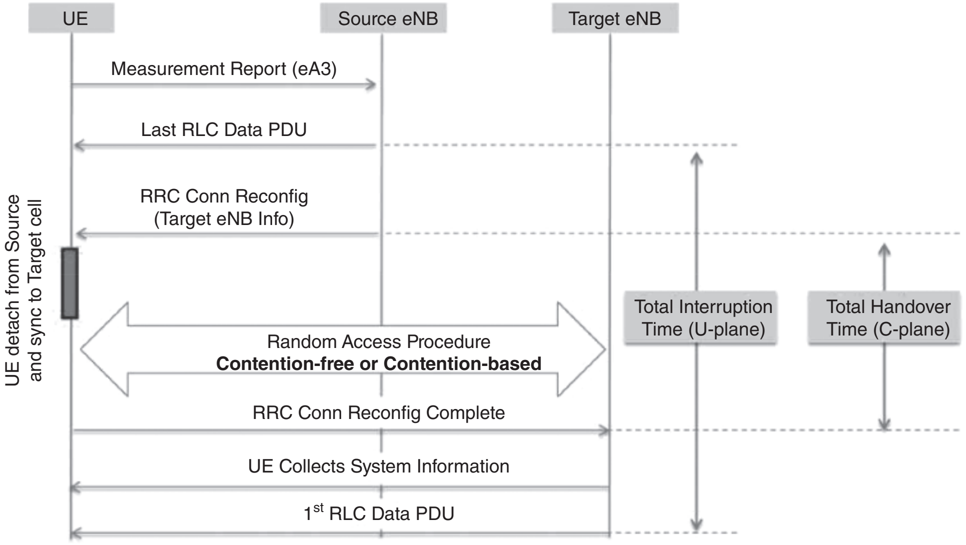


Figure 1.68 Delay assessment during handover.

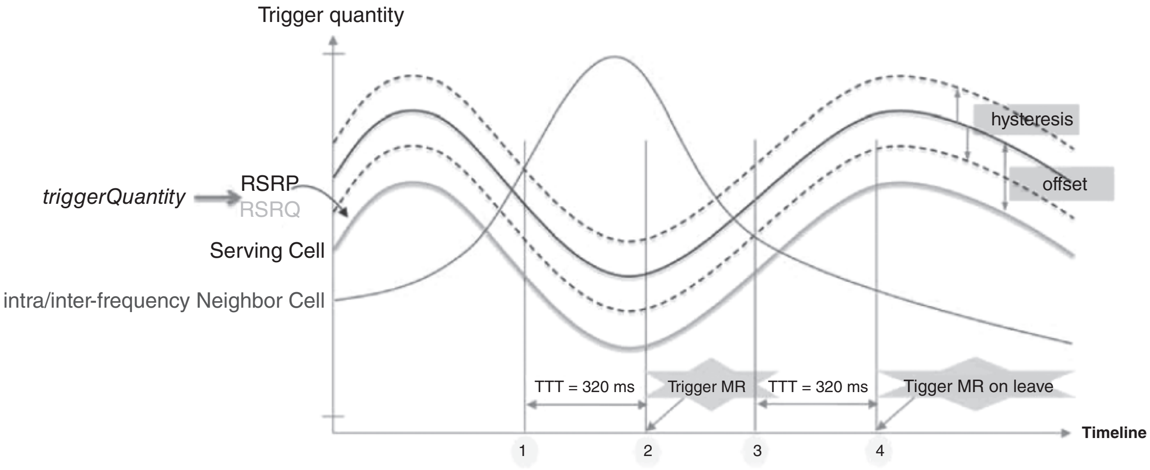


Figure 1.69 Event A3 measurement report triggering.

1.16.9 Intra-frequency Handover Call Flow

The intra-frequency handover call flow is illustrated in Figure 1.70. Refer to [1] for more details on intra-frequency handover.

In Step 2, handover can only occur after security has been activated. In Step 3, the NW configures the measurement of the neighboring cell (intra-frequency and/or inter-frequency) and in Step 9, the target eNB generates an RRC Connection Reconfiguration message including the mobilityControlInformation to perform the handover. This is sent by the source eNB to the UE and it contains the necessary parameters (i.e. new C-RNTI, target eNB security algorithm identifiers, and optionally dedicated RACH preamble, target eNB SIBs, etc.) for handover. Meanwhile, the UE will start the T304 safeguard for the handover execution phase.

In Steps 11 and 12, the random access procedure can be contention-free or contention-based depending on the RA configuration in Step 9. After a successful RA procedure, T304 will be stopped.

1.16.10 Intra-frequency Parameter Tradeoffs

Intra-frequency parameter tradeoffs are described in Table 1.51.

The main areas to consider while optimizing event A3 are:

Reducing pilot pollution areas that can impact SINR and therefore the throughput.
Reducing the amount of handover ping-pongs.
Reducing call drops.
Data interruption time during handover.

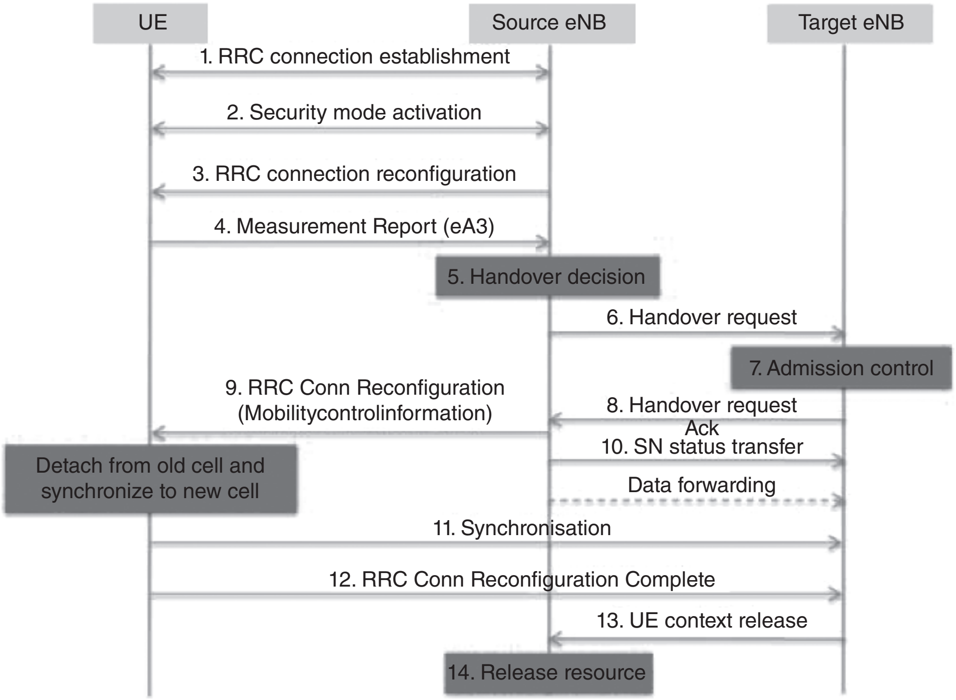


Figure 1.70 Intra-frequency handover call flow.

Table 1.51 Intra-frequency parameter tradeoffs.

Parameter	Example of Settings	Discussion
a3-Triggerquantity	RSRP	RSRP is more robust than RSRQ for handovers, especially in unloaded conditions. RSRQ can be used as an additional A3 trigger.
a3-Hysteresis	4 (2 dB)	Small values can cause cases of going out of triggering conditions earlier and TTT reset.
a3-offset	6 (3 dB)	Low values would cause more handovers and possible ping-pong effects, causing data interruption.
a3-timeToTrigger	240 ms	Higher values delay handover.
a3-ReportAmount	Infinity	If the handover is not triggered (due to eNB issues/failures), it is better to keep reporting event A3.
a3-ReportInterval	240 ms	Re-trigger of event A3 when the handover command is not sent.
filterCoefficient	8 to 11	If this value is set too low, measurement reports could be triggered by rapid, temporary, or short-term fluctuations in RSRP.

The impact of these phenomena is low SINR while the RSRP of the serving cell is good, especially around handover regions where a sharp fall in SINR is observed:

Impacting overall throughput performance where RLF occurs mainly due to SIB read failure or RACH failure (both are DL-related failures).

Fixing RF pilot pollution and cell overshooting can be a first step to improving the serving cell SINR and overall CQI and throughput.

1.16.11 Radio Link Failures and Re-establishment

Radio link failure can be caused by:

Normal radio link failure, for example, due to poor quality:

No N311 consecutive “in-sync” indications from the lower layers before T310 expires.

An RA problem being indicated from the MAC while T300, T301, T304, and T311 are not running.

For example, RA fails when the UL synchronization status is “non-synchronized” or there are no PUCCH resources for SR available.

Reaching the maximum number of retransmissions in the RLC layer.

Intra-LTE handover failure (T304 expiry).

Mobility from E-UTRA failure (inter-RAT handover failure).

An integrity check failure indication from the PDCP.

RRC connection reconfiguration failure (inability to comply with the configuration).

While RRC connection re-establishment can be made for the following reasons:

The UE triggers an RRC connection re-establishment procedure to resume SRB1 operation and the reactivation of security.

  Only when AS security has not been activated. Otherwise, the UE will move directly to RRC Idle.

During a radio link failure, the UE will start T311 to find a suitable cell to recover the connection. If it cannot find a cell after the expiry of T311, the UE will move directly to Idle mode. If the UE can find a suitable cell, it will trigger the re-establishment procedure and start T301 to guard the re-establishment. If T301 expires, the UE will also move to Idle mode and the re-establishment also fails, as illustrated in Figure 1.71.

There are several reasons leading to LTE call drops. They vary from PHY layer issues all the way to RRC-related problems. Some of these factors are handover failures, RACH failures, RLC unrecoverable errors, or misconfigured RRC parameters. In LTE, any of these air interface failures leads to a loss of the radio link between the UE and the eNB, and this is known as Radio Link Failure (RLF). RLF does not necessarily cause a call drop, as there are methods to restore the connection through a re-establishment procedure. If this procedure subsequently fails, the call drops and a new RRC connection is then required. Figure 1.71 illustrates the factors involved in RLF and call drops. The figure shows a summary of procedures in each layer (timers and constants used to detect RLF) and the call re-establishment procedures. It also lists some of the common reasons for observing such failure in any of the layers (i.e. coverage, parameters, RF issues, etc.). Besides a weak RF condition or coverage issues causing RLF, the other common reason is handover failure. Troubleshooting and optimizing handover success rate is essential in ensuring a satisfactory end user experience and stabilizing the network KPIs.

1.16.12 RLF Timers in Idle and Connected Modes

In 3GPP, RLF parameters can be set differently in order to distinguish RLF timers for services like QCI = 1 and QCI = 9.

According to the 3GPP (36.331), RLF parameters T301, T310, N310, T311, and N311 can be set in such a way as to distinguish between the SIB2 RLF timers and the Connected mode RLF timer, which can be set per QCI:

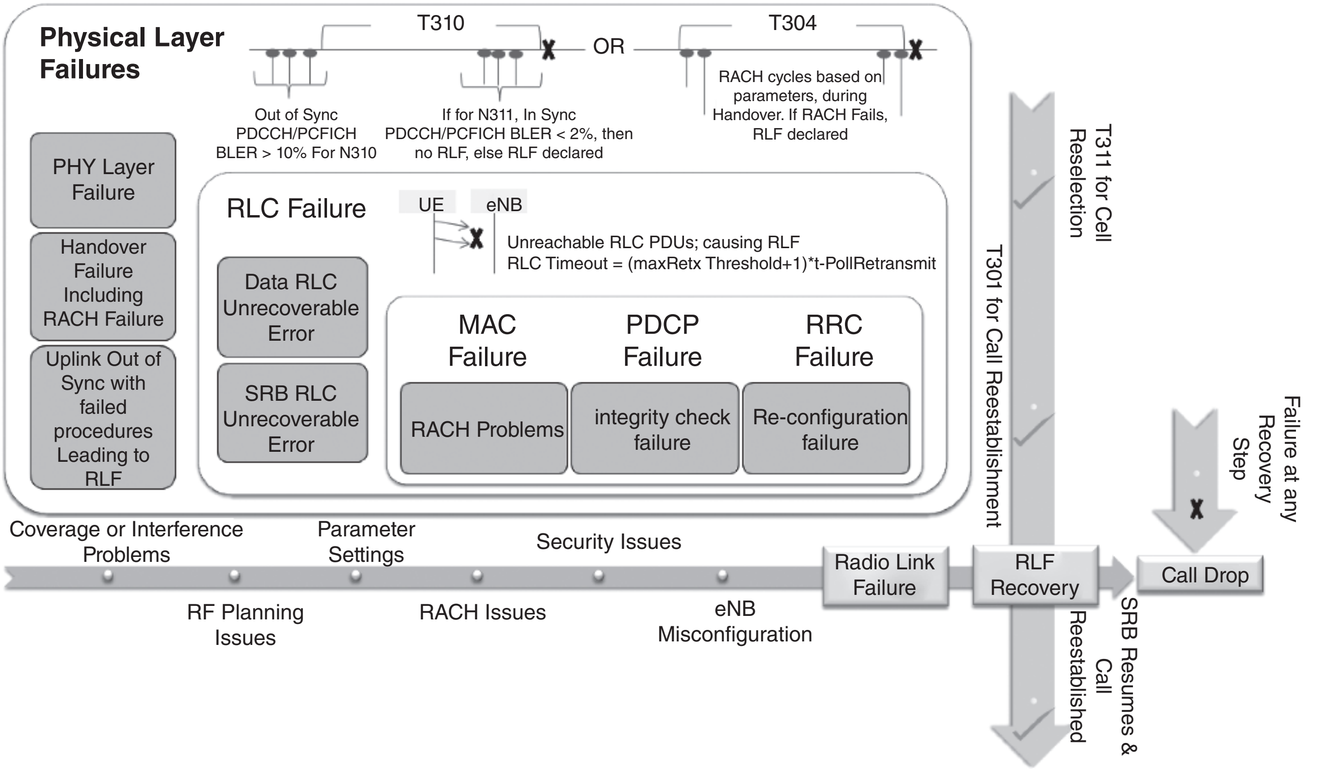


Figure 1.71 Radio link failure and re-establishment procedure.

In addition to SIB2, an RRC Reconfiguration message in Connected mode can be re-signaled when certain services are established (i.e. VoLTE).

If used, the values will override those in SIB2.

New IE rlf-TimersAndConstants including RLF-related timers and counters is introduced, allowing for these to be set per UE.

The IE is to be signaled within RadioResourceConfig Dedicated.

1.16.13 RLF Parameter Tradeoffs

The RLF parameters in SIB2 applied to PS data QCIs are explained in Table 1.52. RLF parameters in Connected mode applied to VoIP QCIs are explained in Table 1.53.

1.16.13.1 Timers/Counters Definitions

T311: This timer is started when the UE starts the RRC connection re-establishment procedure. The timer is stopped if, before the timer expires, the UE selects an E-UTRAN or inter-RAT cell to camp on. After the timer expires, the UE enters the RRC Idle mode.

T301: This timer is started when the UE sends an RRC Connection Re-establishment Request message. The timer is stopped if, before it expires, the UE receives an RRC Connection Re-establishment or RRC Connection Re-establishment Reject message. The timer is also stopped if the selected cell becomes an unsuitable cell.

T310: This timer is started when the UE detects any fault at the physical layer. The timer is stopped if the UE detects one of the following before the timer expires: (1) The physical-layer fault is rectified; (2) a handover is triggered; (3) the UE initiates an RRC connection re-establishment procedure. After the timer expires, the UE enters RRC Idle mode if the security mode is not activated. If the security mode is activated, the UE initiates an RRC connection re-establishment procedure.

N310: Indicates the maximum number of successive "out-of-sync" indications received from L1.

N311: Indicates the maximum number of successive "in-sync" indications received from L1.

A UE detects an RLF when any of the following conditions is met:

The timer T310 expires.

An RA failure occurs and the timer T300, T301, T304, or T311 is not running.

Upon receiving consecutive N310 "out-of-sync" indications from lower layers while timers T300, T301, T304, and T311 are not running, the UE starts T310.

Upon receiving consecutive N311 "in-sync" indications from lower layers while T310 is running, the UE stops T310.

Table 1.52 RLF parameters in SIB2 applying to PS data QCIs (i.e. QCI = 9).

Parameter	Sample Guideline	Discussion
T301	1000 ms	• The current parameters are set to delay RLF in LTE for QCI = 9. • However, for VoLTE-related services, this may cause a high RTP interruption and hence RTP timeout or longer mute time (one-way audio). • These current QCI = 9 timers aim to delay the RLF as long as possible to improve call drop rate KPIs, but may not be suitable for VoLTE traffic.
T310	1000 ms	
N310	10	
T311	3000 ms	
N311	1	

Table 1.53 RLF parameters in Connected mode applying to VoIP QCIs (i.e. QCI = 1).

Parameter	Sample Guideline	Discussion
T301	600 to 1000 ms	• The target of these settings is to drop quickly and re-establish quickly. • Can be set to a lower value for VoLTE to do quicker re-establishment rather than higher mute time, depending on how stable the re-establishment process is. • If re-establishment is unstable, then set N311 = 1 to delay RLF as RTP interruption may be higher due to the UE going to Idle if re-establishment does not succeed.
T310	1000 ms (600 ms if the call re-establishment is stable)	
N310	5	
T311	1000 ms	
N311	2	

1.17 Interworking with Other 3GPP Radio Access

1.17.1 E-UTRA States and Inter-RAT Mobility Procedures

The EPS system is designed to be able to interwork with other RATs. When making a mobility decision between cells in the same RAT, different RATs or frequencies, many criteria (e.g. coverage, load balancing, terminal capabilities, access restrictions, and subscription attributes) are considered at the network design stage. The optimization process can be extremely complex when multiple systems are deployed in the same network, for example, multiple UTRAN frequencies/bands, GERAN, multiple LTE-FDD frequencies/bands, and/or LTE-TDD. The legacy UTRAN to GERAN inter-RAT must be revisited to adopt the new frequency(s) deployed for the LTE system. State transition for different RATs is shown in Figure 1.72.

1.17.2 Inter-RAT Cell Reselection

3GPP introduces a priority layer concept for cell reselection. Any IRAT or inter-frequency cell reselection between cells or frequencies (or even bands) is controlled by the assigned priority. The layer priority is not applied to cells from the same frequency as that of the serving cell, as illustrated in Table 1.54.

As the complexity of the deployed system topologies increases, such priority-based reselection becomes important. With the diversity of cells deployed in the network (femto, micro, or macro) within the same or different RATs, priority reselection can assist the operator in enforcing the targeted camping strategy. In this situation, cell reselection can be layered up by assigning the cells into high, low, or equal priorities. Priorities are typically provided to the UE via system information or RRC Release messages.

Table 1.54 summarizes the concept of layer priority and the measurements requirements by the UE for

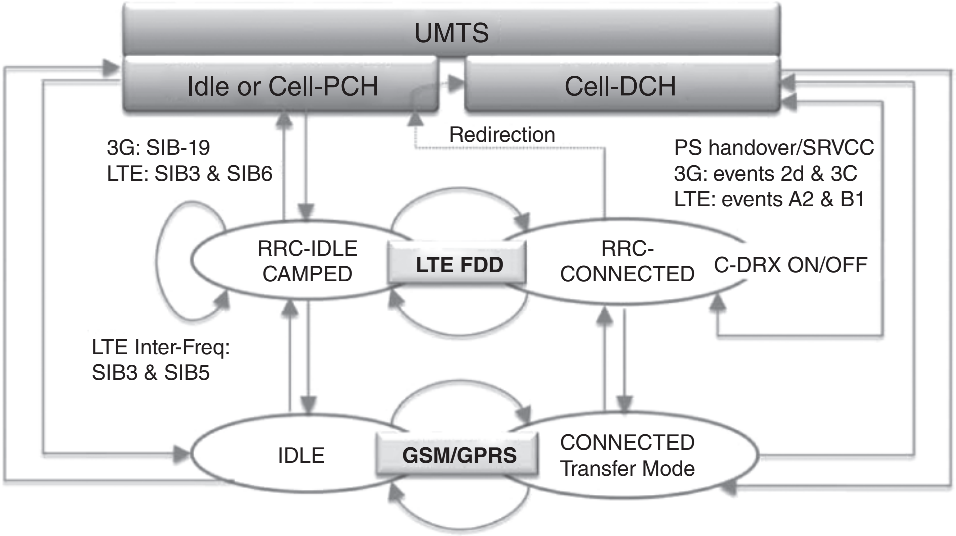


Figure 1.72 E-UTRA states and inter-RAT mobility procedures.

Table 1.54 Measurement configurations for different priorities.

		Lower		Equal		Higher
Priority Configured by Network	**No Priority**	**Serving cell signal power > threshold**	**Serving cell signal power < threshold**	**Serving cell signal power > threshold**	**Serving cell signal power < threshold**	**Thresholds to regulate the measurements**
LTE inter-frequency	No reselection allowed	Measurements not mandatory	Measurements mandatory	Measurements not mandatory	Measurements mandatory	Measurements mandatory
Inter-RAT from LTE to WCDMA	No reselection allowed	Measurements not mandatory	Measurements mandatory	Not allowed in standard		Measurements mandatory but regulated for battery saving
Inter-RAT from WCDMA to LTE	No reselection allowed	Measurements not mandatory	Measurements mandatory			

inter-frequency and inter-RAT. In LTE deployment, it is expected that the priority of LTE will be higher than other RATs, especially as LTE provides a higher data rate than other RATs (for example, UMTS). In other scenarios, the LTE priority might be lower than non-LTE femto cells (i.e. home NodeB) in the deployed areas. Hence, the priority setting is an optimization choice that depends on the designed camping strategy, LTE deployment coverage, the targeted performance, and the end user's perceived experience.

1.17.3 E-UTRAN to UTRAN Cell Reselection Flow

The E-UTRAN to UTRAN cell reselection flow is illustrated in Figure 1.73.

SIB type 6 defines the reselection parameters for UTRAN. Reselection from LTE is always based on the comparative priority of the other RAT. LTE and any other RAT cannot be defined to have the same priority, and other RATs will not be considered for reselection unless a priority (cell reselection priority) is specified in SIB6. Based on the priority level defined in SIB6, the UE will use the RAT-specific value of either $\text{Thresh}_{x,high}$ or $\text{Thresh}_{x,low}$ (and $\text{Thresh}_{serving,low}$) to decide if reselection takes place. Additionally, each RAT will have an associated value for $T_{reselection}$ as well as the optional mobility state-related parameters (discussed previously) and maximum allowed transmit power. Moreover, the maximum UE transmit power for UTRAN is specified along with suitably related values of $Q_{rxlevmin}$ and $Q_{qualmin}$ for RSCP and Ec/No, respectively.

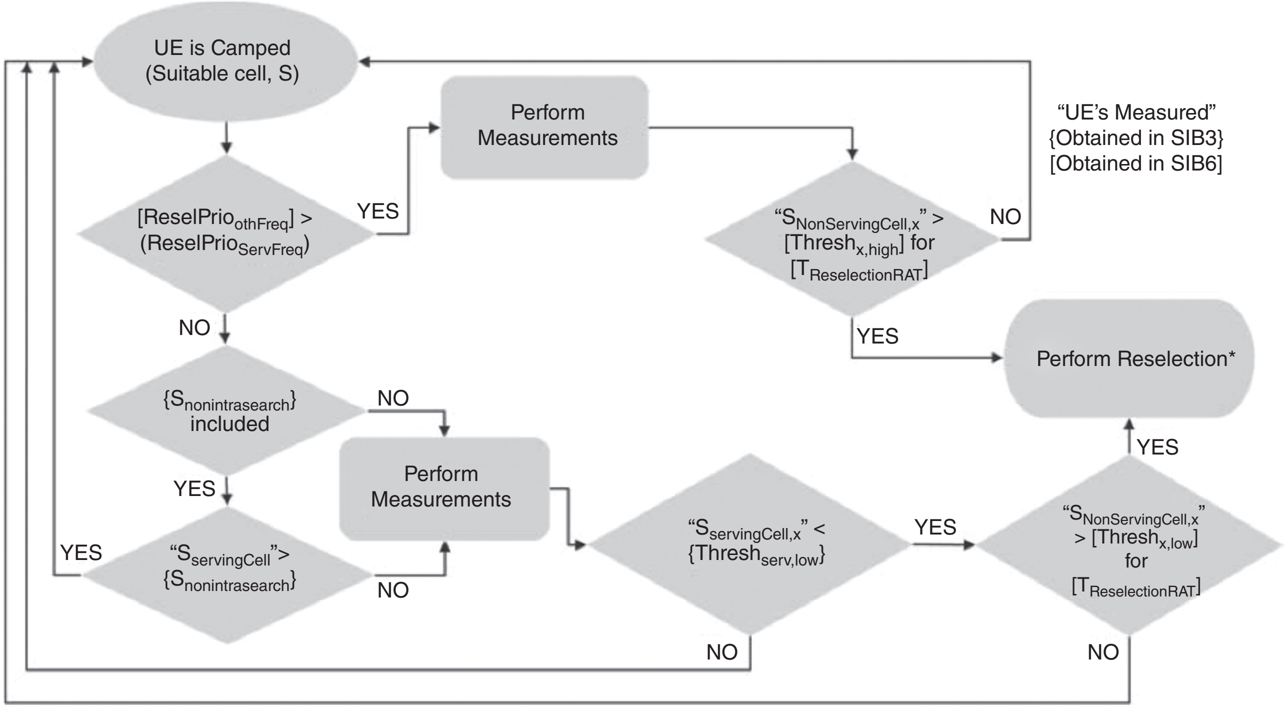
1.17.4 E-UTRAN to UTRAN Measurement Rules

3GPP 36.133 provides the following *minimum* requirements for UTRAN cell measurements while camped in LTE Idle mode. The eNB is only required to provide a list of frequencies on which UTRAN measurements need to be conducted in SIB6. This means that detailed neighbor list information (via PSCs) is not available to the UE.

Table 1.55 shows, in detail, the timer values for different DRX cycle lengths. There are three different timers: detection of UTRAN frequency, measurements of UTRAN frequency, and evaluation of UTRAN frequency. The UTRAN neighboring cells need to be

Table 1.55 UTRAN FDD timers based on DRX cycle length.

DRX Cycle Length (s)	$T_{DetectUTRA,FDD}$ (s)	$T_{MeasureUTRA,FDD}$ (s)	$T_{EvaluateUTRA,FDD}$ (s)
0.320	30	5.12	15.36
0.640	30	5.12	15.36
1.28	30	6.4	19.20
2.560	60	7.68	23.04



*Only if at least 1 sec has elapsed since camping on serving cell

Figure 1.73 E-UTRAN to UTRAN cell reselection flow.

measured according to the following rules from 3GPP 36.133:

Inter-RAT cell reselection evaluation will be performed only on those cells for which priority has been assigned.

In Idle mode, in 3GPP Release 8, the eNB is only required to provide a list of frequencies on which UTRAN measurements need to be conducted in SIB6. This means that detailed neighbor list information (via PSCs) is not available to the UE.

A new UMTS cell needs to be detected by N_{UTRA}* $T_{DetectUTRA,FDD}$ seconds.

An already-detected lower-priority UMTS cell needs to be measured at least once every N_{UTRA}*$T_{MeasureUTRA,FDD}$ seconds.

An already-detected higher-priority UMTS cell needs to be measured at least once every $T_{MeasureUTRA,FDD}$ seconds.

The measurements need to be filtered using at least two measurements.

Measurements should be spaced by at least (N_{UTRA}* $T_{MeasureUTRA,FDD}$)/2.

The filtering should be such that the time constant of the filter is < N_{UTRA}*$T_{EvaluateUTRA,FDD}$.

N_{UTRA} is the number of carriers which are measured for UTRAN cells.

1.17.5 E-UTRAN to UTRAN Measurement Stages

A UTRAN cell search by a UE camped in LTE is categorized into two phases:

Cell-detection phase: The UE is trying to find the best cell among the 512 primary scrambling codes (PSCs). The cell is considered detectable when any UTRAN cell CPICH Ec/Io ≥ −20 dB:

Once every N_{UTRA}*94 DRX cycles (for 0.32 second DRX).
Once every 47 DRX cycles (for 0.64 second DRX).
Once every 47 DRX cycles (for 1.28 second DRX).
Once every 24 DRX cycles (for 2.56 second DRX).

Cell-measurement phase: When any cell is considered detectable in the previous phase, the UE is required to keep measuring that particular cell for a possible inter-RAT reselection:

Once every 8 DRX cycles (for 0.32 second DRX).
Once every 4 DRX cycles (for 0.64 second DRX).
Once every 2 DRX cycles (for 1.28 second DRX).
Once every 2 DRX cycles (for 2.56 second DRX).

Both phases – the cell-detection phase and the cell-measurement phase – have different configurations for different DRX cycles, as illustrated in Figure 1.74.

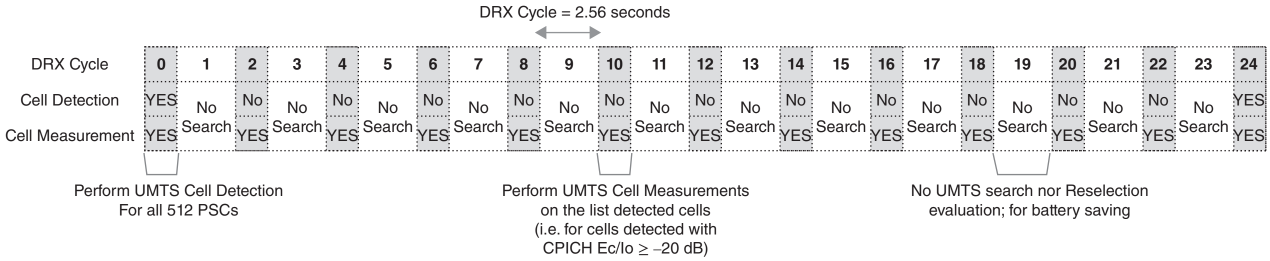
1.17.6 LTE Inter-RAT to UTRAN Cell Reselection with Low Priority

Inter-RAT UTRAN-FDD cell measurement criteria are as follows:

$S_{rxlev} < S_{nonIntraSearchP}$ or $S_{qual} < S_{nonIntraSearchQ}$

A description of the threshold parameters for serving and neighboring cells is provided in Table 1.56.

Figure 1.75 illustrates an example of LTE inter-RAT UTRAN-FDD reselection parameters based on low priority. The UE initially camps on the LTE F1 cell (first frequency) with physical cell ID 1 with high priority (such as priority 6). The only other neighbor defined is the F2 (UTRAN-FDD frequency) cell with PSC = 12 with a lower priority than the serving cell (such as priority 3). Before point 1, the serving cell fulfills $S_{rxlev} > S_{nonIntraSearchP}$ and $S_{qual} > S_{nonIntraSearchQ}$, so the UE may choose not to perform inter-RAT measurements. At



DRX Cycle	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24
Cell Detection	YES	No Search	No	No Search	No	No Search	No	No Search	No	No Search	No	No Search	No	No Search	No	No Search	No	No Search	No	No Search	No	No Search	No	No Search	YES
Cell Measurement	YES		YES		YES		YES		YES		YES		YES		YES		YES		YES		YES		YES		YES

Perform UMTS Cell Detection For all 512 PSCs

Perform UMTS Cell Measurements on the list detected cells (i.e. for cells detected with CPICH Ec/Io ≥ −20 dB)

No UMTS search nor Reselection evaluation; for battery saving

Figure 1.74 Cell detection and cell measurements for different DRX cycles.

Table 1.56 Serving and neighboring cell thresholds.

Parameter	Serving Cell	Neighboring Cell
threshServingLowQ provided in SIB3	$S_{qual} < Thresh_{Serving,LowQ}$	$S_{qual} > Thresh_{X,LowQ}$
threshServingLowQ not provided in SIB3	$S_{rxlev} < Thresh_{Serving,\ LowP}$	$S_{rxlev} > Thresh_{X,\ LowP}$

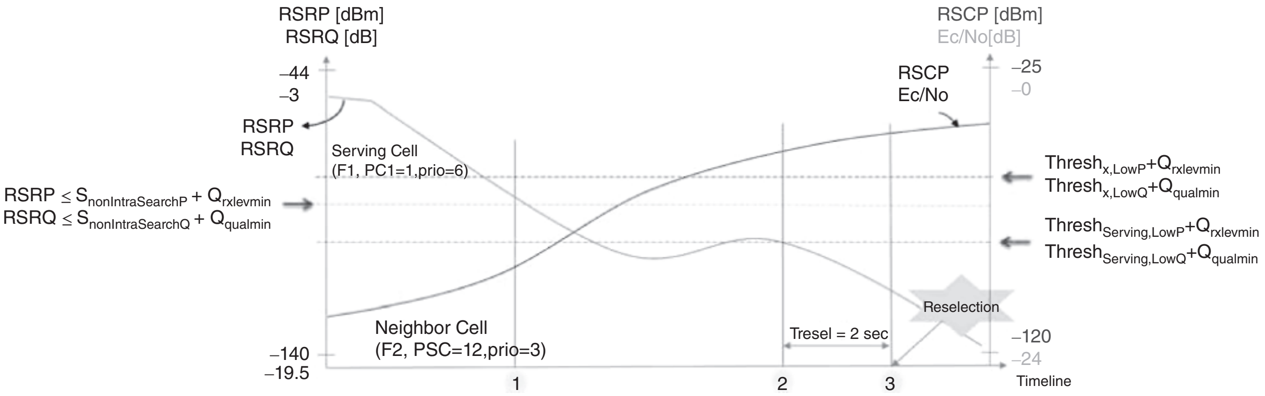


Figure 1.75 LTE inter-RAT to UTRAN cell reselection with low priority.

point 1, $S_{\text{rxlev}} < S_{\text{nonIntraSearchP}}$ or $S_{\text{qual}} < S_{\text{nonIntraSearchQ}}$ and thus the UE begins the search for an inter-RAT neighbor. The quality of the serving cell is lower than a threshold ($S_{\text{qual}} < \text{Thresh}_{\text{Serving, LowQ}}$ or $S_{\text{rxlev}} < \text{Thresh}_{\text{Serving, LowP}}$), meanwhile the quality of the neighboring inter-RAT cell is better than a threshold ($S_{\text{qual}} > \text{Thresh}_{\text{X, LowQ}}$ or $S_{\text{rxlev}} > \text{Thresh}_{\text{X, LowP}}$) at point 2 to meet lower priority cell reselection criteria. The UE reselects to the inter-RAT UTRAN-FDD PSC = 12 cell when the timer expires (set at two seconds – at point 3 in this example).

1.17.7 LTE Inter-RAT to UTRAN Cell Reselection with High Priority

Measurements of higher priority are always performed, but are regulated with the threshold parameters described in Table 1.57 for serving and neighboring cells.

Table 1.57 Serving and neighboring cell thresholds.

Parameter	Neighboring Cell
threshServingLowQ provided in SIB3	$S_{\text{qual}} > \text{Thresh}_{\text{X,HighQ}}$
threshServingLowQ not provided in SIB3	$S_{\text{rxlev}} > \text{Thresh}_{\text{X,HighP}}$

Figure 1.76 illustrates an example of LTE inter-RAT reselection parameters based on high priority. The UE initially camps on the LTE F1 cell (first frequency) with physical cell ID 1 with lower priority (such as priority 3). The only other neighbor defined is the F2 (UTRAN-FDD frequency) cell with PCS = 12 with a higher priority than the serving cell (such as priority 6). Before point 1, the UE always performs high-priority measurements. At point 1, the quality of the neighboring inter-RAT UTRAN-FDD cell is better than a threshold ($S_{\text{rxlev}} > \text{Thresh}_{\text{X, HighP}}$ or $S_{\text{qual}} > \text{Thresh}_{\text{X, HighQ}}$). The UE reselects to the inter-RAT UTRAN-FDD PSC = 12 cell when the timer expires (set at two seconds – at point 2 in this example).

1.17.8 UTRAN to E-UTRAN Cell Reselection Flow

3GPP defines a new SIB type (SIB19) for broadcasting LTE-related information. If SIB19 is broadcast with a list

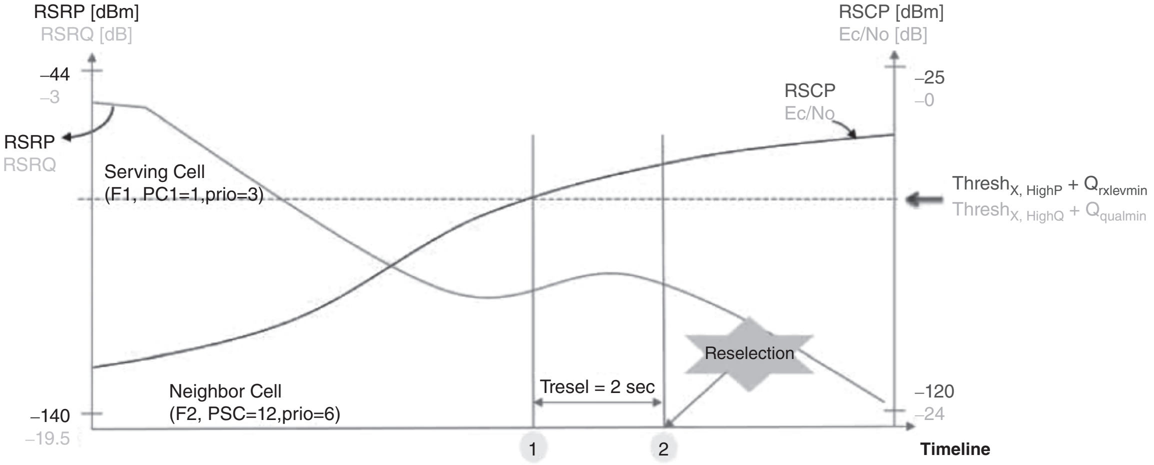


Figure 1.76 LTE inter-RAT to UTRAN cell reselection with high priority.

of E-UTRAN frequencies and priorities, the UE will measure and reselect to the LTE E-UTRAN cells according to the rules explained below.

The UE follows the Absolute Priority reselection according to the criteria defined by 3GPP:

Criterion 1: The $S_{rxlev,nonServingCell,x}$ of a cell on an evaluated higher absolute priority layer is greater than $Thresh_{x,high}$ during a time interval $T_{reselection}$.
Criterion 3: $S_{rxlev,ServingCell} < Thresh_{serving,low}$ or $S_{qual,ServingCell} < 0$ and the $S_{rxlev,nonServingCell,x}$ of a cell on an evaluated lower absolute priority layer is greater than $Thresh_{x,low}$ during a time interval $T_{reselection}$.

As described in Figure 1.77, cell reselection to a cell on a higher absolute priority layer than the camped frequency is performed if Criterion 1 is fulfilled. Cell reselection to another UTRAN inter-frequency cell on an equal absolute priority layer to the camped frequency is performed if Criterion 2 is fulfilled (this is not shown above since it is not related to inter-RAT).

Reselection to a cell on a lower absolute priority layer than the camped frequency is performed if Criterion 3 is fulfilled. If more than one cell meets the criterion, the UE shall reselect the cell with the highest $S_{rxlev,nonServingCell,x}$. The UE shall not perform cell reselection until more than 1 second has elapsed since the UE camped on the current serving cell. For UE in RRC Connected mode state CELL_PCH or URA_PCH, the interval $T_{reselections,PCH}$ applies if provided in SIB4.The reselection rules discussed here are specified in 3GPP Release 8.

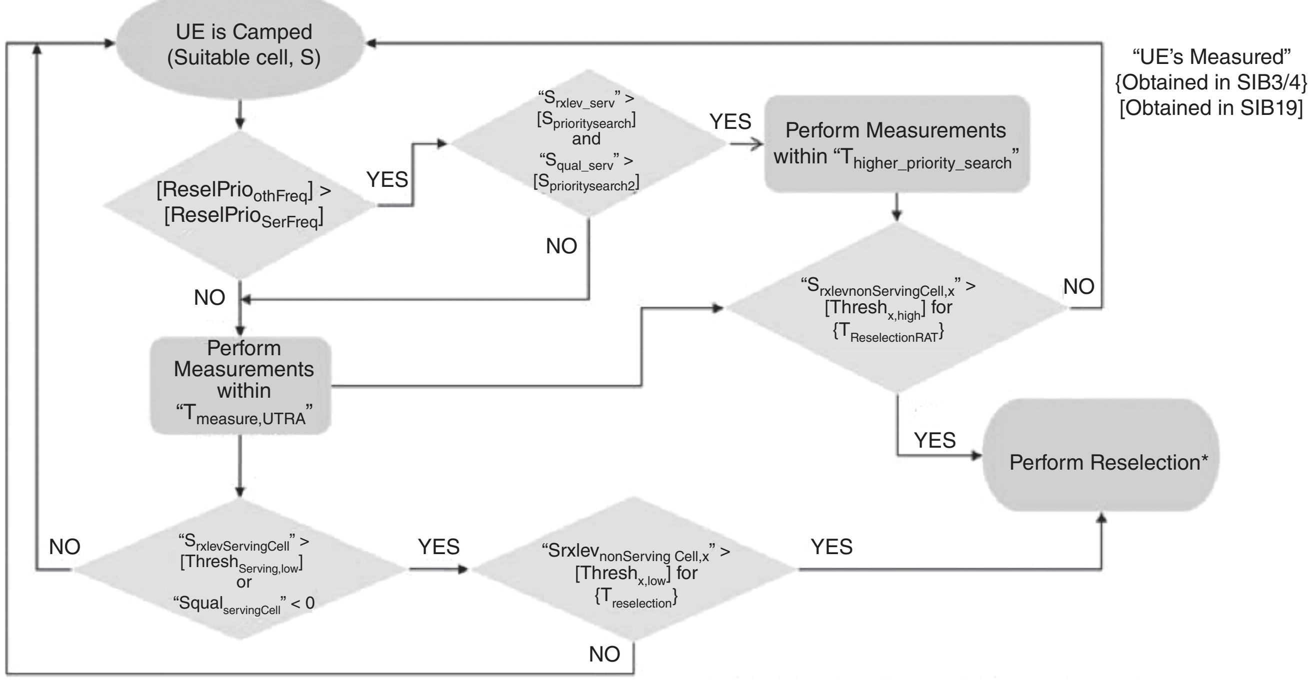
3GPP Release 9 provides slightly different criteria for introducing cell reselection based on RSRQ measurements. The same concepts discussed here also apply, but with different parameters.

1.17.9 UTRAN to E-UTRAN Measurement Rules

The UE must be able to identify new E-UTRA cells and perform RSRP measurements on identified E-UTRA cells if carrier frequency information is provided by the serving cell, even if no explicit neighbor list with physical layer cell identities is provided. Figure 1.78 shows the UTRAN to E-UTRAN measurement rules flow chart.

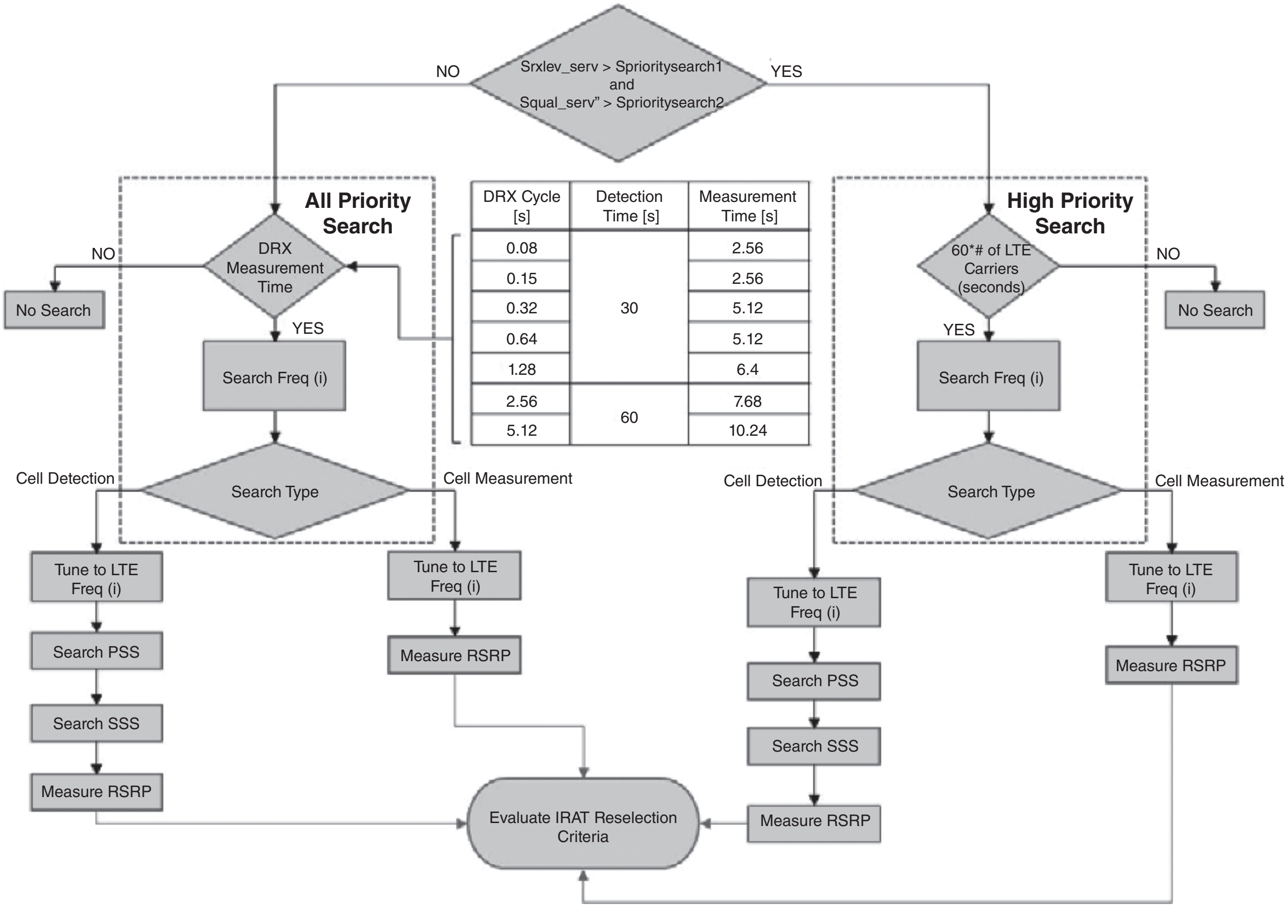
There are mainly two different rates of E-UTRAN cell search defined by 3GPP to prevent high consumption of UE battery life. If $S_{rxlev,ServingCell} > S_{prioritysearch1}$ and $S_{qual,ServingCell} > S_{prioritysearch2}$ then the UE shall search for E-UTRA layers of higher priority at least every $T_{\_higher\_priority\_search}$ where $T_{\_higher\_priority\_search}$ is "60*N_layer" seconds, where N_layer is the number of high-priority frequencies across all RATs. Hence, the purpose of this procedure is to save battery consumption by reducing the amount of UE measurements.

If $S_{rxlev,ServingCell} \leq S_{prioritysearch1}$ or $S_{qual,ServingCell} \leq S_{prioritysearch2}$ then the UE must search for and measure E-UTRA frequency layers of higher or lower priority in preparation for possible reselection. In this



*Only if at least 1 sec has elapsed since camping on serving cell

Figure 1.77 UTRAN to E-UTRAN cell reselection flow.



DRX Cycle [s]	Detection Time [s]	Measurement Time [s]
0.08	30	2.56
0.15		2.56
0.32		5.12
0.64		5.12
1.28		6.4
2.56	60	7.68
5.12		10.24

Figure 1.78 UTRAN to E-UTRAN measurement rules.

scenario, the minimum rate at which the UE is required to search/measure higher-priority layers is the same as that defined for lower-priority layers.

1.17.10 UTRAN to E-UTRAN Measurement Stages

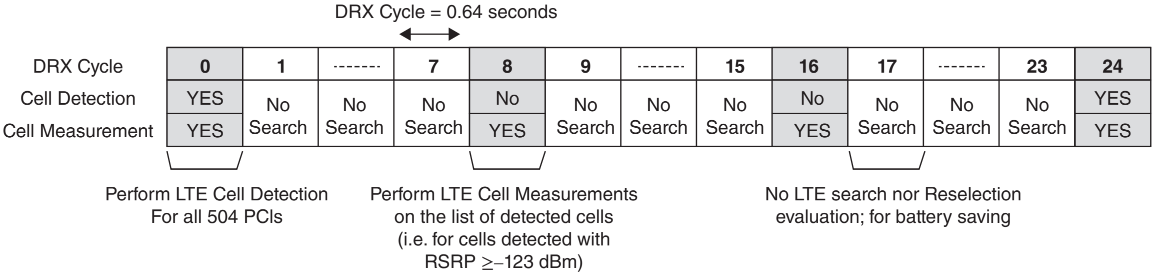
An E-UTRAN cell search by a UE camped in 3G is categorized into two phases:

Cell-detection phase: The UE is trying to find the best cell that is considered detectable when any E-UTRAN cell RSRP ≥ −123 dBm. The UE is required to detect a new LTE cell within K_carrier * 30 seconds (K_carrier is the number of LTE frequencies).

Cell-measurement phase: When any cell is considered detectable in the previous phase, the UE is required to keep measuring the cell for a possible inter-RAT reselection.

Figure 1.79 describes the characteristics of cell detection and cell measurements for different DRX cycles.

Similar to the search phases described earlier for UTRAN, 3GPP also allows different searches for



DRX Cycle	0	1	-------	7	8	9	-------	15	16	17	-------	23	24
Cell Detection	YES	No Search	No Search	No Search	No	No Search	No Search	No Search	No	No Search	No Search	No Search	YES
Cell Measurement	YES				YES				YES				YES

Perform LTE Cell Detection For all 504 PCIs

Perform LTE Cell Measurements on the list of detected cells (i.e. for cells detected with RSRP ≥–123 dBm)

No LTE search nor Reselection evaluation; for battery saving

Figure 1.79 UTRAN to E-UTRAN measurement stages.

E-UTRAN cells to reduce the amount of full-space (504 PCI) searches.

Cell-detection phase: (K_carrier is the number of LTE frequencies configured in SIB19):
0.08 s DRX: Once every 96*K_carrier DRX cycles.
0.16 s DRX: Once every 48*K_carrier DRX cycles.
0.32 s DRX: Once every 24*K_carrier DRX cycles.
0.64 s DRX: Once every 24*K_carrier DRX cycles.
1.28 s DRX: Once every 12*K_carrier DRX cycles.
2.56 s DRX: Once every 6*K_carrier DRX cycles.
5.12 s DRX: Once every 3*K_carrier DRX cycles.

Cell-measurement phase:
0.08 s DRX: Once every 32*K_carrier DRX cycles.
0.16 s DRX: Once every 16*K_carrier DRX cycles.
0.32 s DRX: Once every 16*K_carrier DRX cycles.
0.64 ms DRX: Once every 8*K_carrier DRX cycles.
1.28 ms DRX: Once every 4*K_carrier DRX cycles.
2.56 ms DRX: Once every 2*K_carrier DRX cycles.
5.12 ms DRX: Once every 1*K_carrier DRX cycles.

1.17.11 LTE Inter-RAT to GERAN Cell Reselection with Low Priority

The inter-RAT UTRAN-FDD cell measurement criteria are as follows:

$S_{\mathrm{rxlev}} < S_{\mathrm{nonIntraSearchP}}$ or $S_{\mathrm{qual}} < S_{\mathrm{nonIntraSearchQ}}$

A description of the threshold parameters for serving and neighboring cells is provided in Table 1.58.

Figure 1.80 illustrates an example of LTE inter-RAT GERAN reselection parameters based on low priority. The UE initially camps on the LTE F1 cell (first frequency) with physical cell ID 1 with a high priority (such as priority 6). The only other neighbor defined is the F2 (GERAN frequency) cell with BSIC = 12 with a lower priority than the serving cell (such as priority 3). Before point 1, the serving cell fulfills $S_{\mathrm{rxlev}} > S_{\mathrm{nonIntraSearchP}}$ and $S_{\mathrm{qual}} > S_{\mathrm{nonIntraSearchQ}}$, so the UE may choose not to perform inter-RAT measurements. At point 1, $S_{\mathrm{rxlev}} < S_{\mathrm{nonIntraSearchP}}$ or $S_{\mathrm{qual}} < S_{\mathrm{nonIntraSearchQ}}$ and thus the UE begins the search for an inter-RAT neighbor. The quality of the serving cell is lower than a threshold ($S_{\mathrm{qual}} < \mathrm{Thresh}_{\mathrm{Serving,\ LowQ}}$ or $S_{\mathrm{rxlev}} < \mathrm{Thresh}_{\mathrm{Serving,\ LowP}}$), meanwhile the quality of the neighboring inter-RAT cell is better than a threshold ($S_{\mathrm{rxlev}} > \mathrm{Thresh}_{\mathrm{X,\ LowP}}$) at point 2 to meet lower-priority cell reselection criteria. The UE reselects to the inter-RAT GERAN BSIC = 12 cell when the timer expires (set at two seconds – at point 3 in this example).

1.17.12 LTE Inter-RAT to GERAN Cell Reselection with High Priority

The UE always performs measurements of higher priority, but these are regulated by the following parameters; the neighboring cell fulfills $S_{\mathrm{rxlev}} > \mathrm{Thresh}_{\mathrm{X,\ HighP}}$.

Figure 1.81 illustrates an example of LTE inter-RAT reselection parameters based on high priority. The UE initially camps on the LTE F1 cell (first frequency) with physical cell ID 1 with a lower priority (such as priority 3). The only other neighbor defined is the F2 (GERAN frequency) cell with BSIC = 12 with a higher priority than the serving cell (such as priority 6). Before point 1, the UE always performs high-priority measurements. At point 1, the quality of the neighboring inter-RAT GERAN cell is better than a threshold ($S_{\mathrm{rxlev}} > \mathrm{Thresh}_{\mathrm{X,\ HighP}}$). The

Table 1.58 Serving and neighboring cell thresholds.

Parameter	Serving Cell	Neighboring Cell
threshServingLowQ provided in SIB3	$S_{\mathrm{qual}} < \mathrm{Thresh}_{\mathrm{Serving,LowQ}}$	$S_{\mathrm{rxlev}} > \mathrm{Thresh}_{\mathrm{X,LowP}}$
threshServingLowQ not provided in SIB3	$S_{\mathrm{rxlev}} < \mathrm{Thresh}_{\mathrm{Serving,\ LowP}}$	

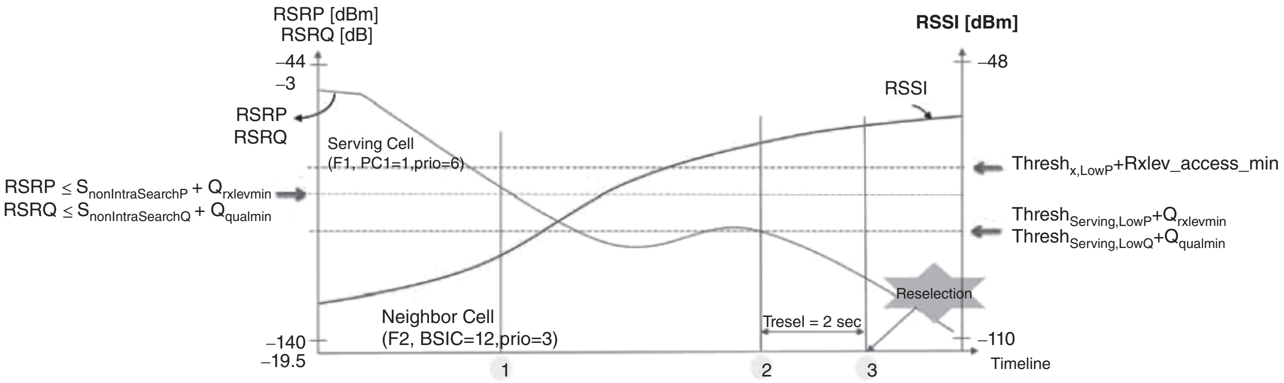


Figure 1.80 LTE inter-RAT to GERAN cell reselection with low priority.

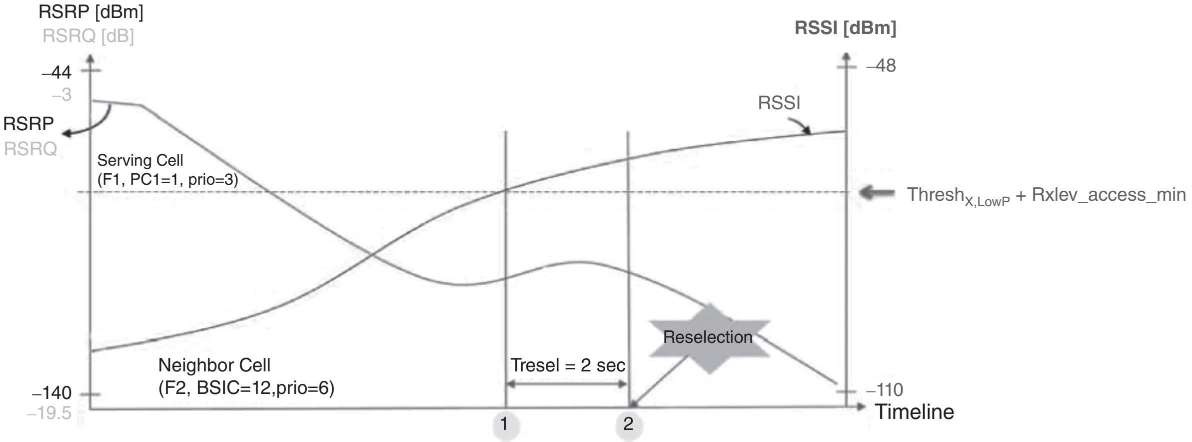


Figure 1.81 LTE inter-RAT to GERAN cell reselection with high priority.

UE reselects to the inter-RAT GERAN BSIC = 12 cell when the timer expires (set at two seconds – at point 2 in this example).

1.17.13 Inter-RAT Handover

Inter-RAT measurement procedures in RRC Connected mode include the following characteristics:

The start of inter-RAT measurements, based on event A2.

The stopping of inter-RAT measurements, based on event A1.

The triggering of an inter-RAT handover. For inter-RAT handover, either event B1 or event B2 can be used. The difference is that event B2 considers the current LTE serving cell before entering into triggering conditions. Usage is typically dependent on the deployment strategy. Inter-RAT handover events were listed in Table 1.50.

1.17.14 Event B1 Measurement Report Triggering

The procedure for triggering event B1 measurements is shown in Figure 1.82.

Inter-RAT handover (or SRVCC) may be blind or non-blind. In the blind scenario, the handover takes place without knowledge of the radio conditions of the other technology. The handover may be triggered by the radio conditions of the serving cell or by other considerations such as cell or infrastructure loading. The disadvantage of this approach is the unknown coverage quality of the target cell, while the advantage is that the handover can be executed quickly without additional measurements. This is particularly helpful in circuit-switch fallback (CSFB) voice calls from LTE.

For non-blind inter-RAT handover, the eNB configures the UE with one of the following events:

Event B1: The inter RAT neighboring cell becomes better than a threshold.

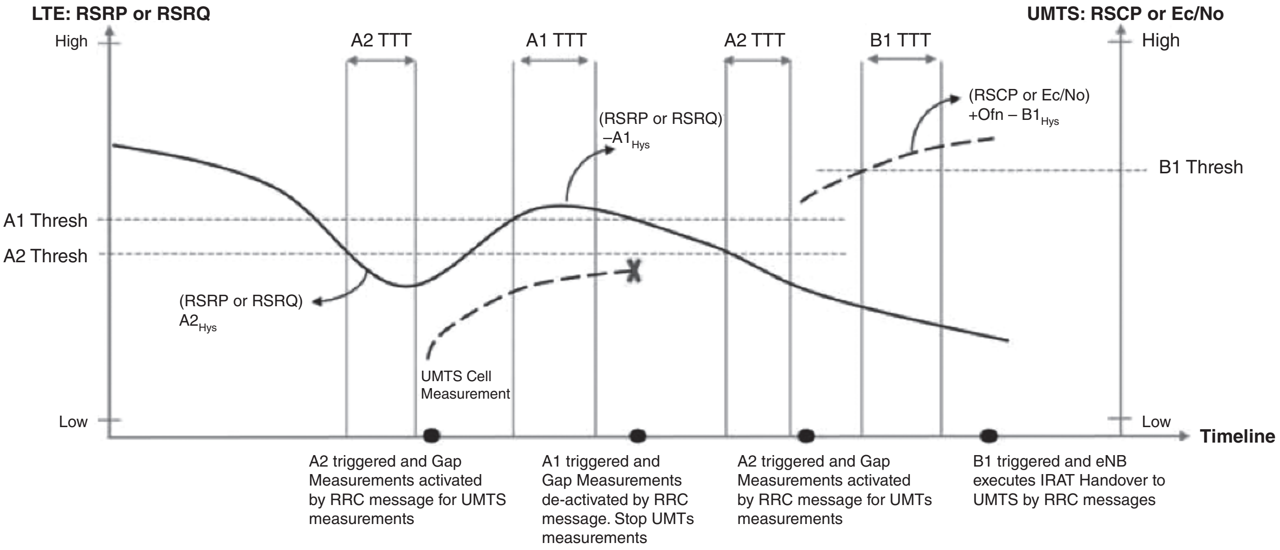


Figure 1.82 Event B1 measurement report triggering.

Event B2: The serving cell becomes worse than threshold 1 and the inter-RAT neighboring cell becomes better than threshold 2.

Other events like A2 + B2 can be configured, and this is a vendor-related implementation.

1.17.15 Inter-RAT Handover Gap Measurements

For the UE to report an inter-RAT or inter-frequency handover, the eNB needs to configure the UE with a measurement gap:

The gap duration is always 6 ms with a repetition period of either 40 or 80 ms, corresponding to 15% or 7.5% of the available subframes respectively, and referred to as gp0 or gp1.

The specific starting SFN (System Frame Number) and subframe for each gap are defined for the UE via the RRC, enabling diversity of gap location throughout the available time slots.

The UE reports when gaps are necessary for either inter-frequency and/or inter-RAT during its capability reporting based on the FGI (Feature Group Indicator).

For the duration of the 6 ms gap, no downlink transmissions are scheduled for the UE and the UE does not transmit on the uplink.

An additional restriction is that the UE cannot transmit in the first subframe following a measurement gap. This corresponds to a 7 ms silence period for the UE in the uplink.

With carrier aggregation devices, gapless inter-frequency handover is possible for certain bands, depending on the UE capabilities.

The measurement gap is a time period during which the UE performs measurements on a neighboring frequency of the serving frequency. Measurement gaps apply to inter-frequency and inter-RAT measurements. Each UE typically has only one receiver, and consequently, one UE can receive signals on only one frequency at a time. After receiving measurement gap configurations from the eNodeB, the UE starts gap-assisted inter-frequency or inter-RAT measurement based on the configurations.

Gap-assisted measurement may conflict with discontinuous reception (DRX), semi-persistent scheduling (SPS), or both. In the case of such a conflict, the gap-assisted measurement takes precedence. This, however, affects data transmission quality. To solve this problem, the design of measurement gaps takes DRX and SPS into consideration. The start time of the measurement gaps can be adjusted in such a way that the conflicts with DRX and/or SPS are minimized whereas gap-assisted measurements are performed on time.

1.17.16 Gap Measurement Example

When gap-assisted measurements for various handover types co-exist, the eNodeB records the measurements based on these handover types. Different gap-assisted measurements can share the same measurement gap configuration. A UE releases measurement gaps only after all gap-assisted measurements have stopped. Figure 1.83 shows an example of gap measurements; two

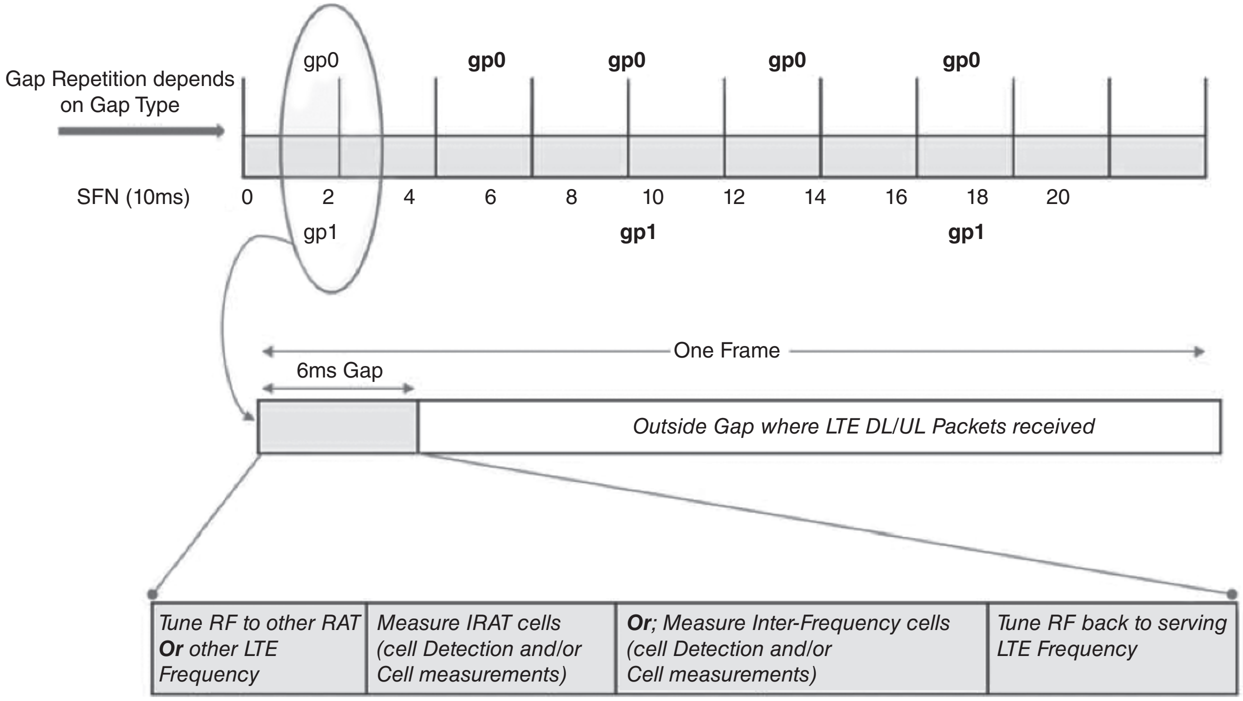
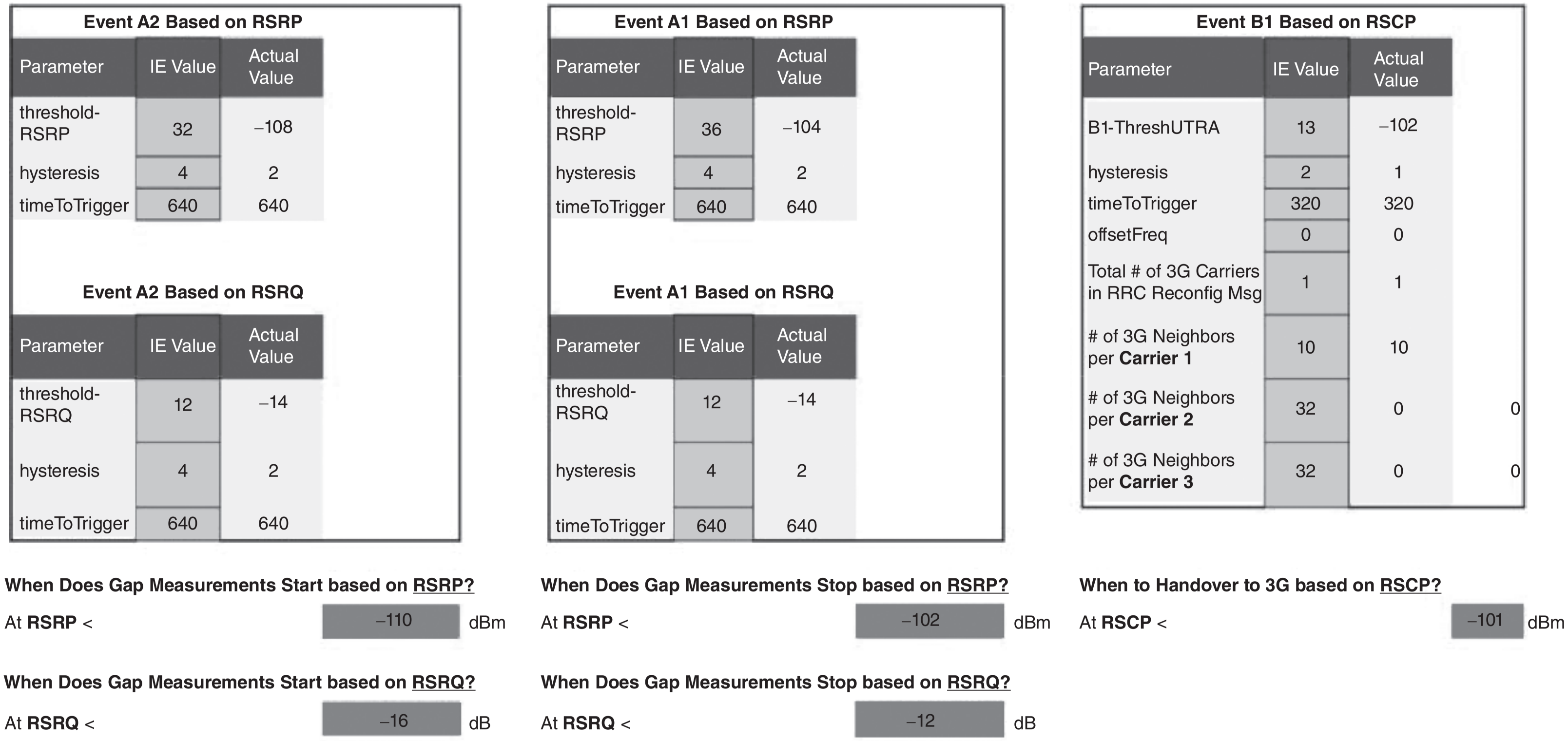


Figure 1.83 Gap measurement example.



Event A2 Based on RSRP

Parameter	IE Value	Actual Value
threshold-RSRP	32	−108
hysteresis	4	2
timeToTrigger	640	640

Event A2 Based on RSRQ

Parameter	IE Value	Actual Value
threshold-RSRQ	12	−14
hysteresis	4	2
timeToTrigger	640	640

When Does Gap Measurements Start based on RSRP?

At **RSRP** < −110 dBm

When Does Gap Measurements Start based on RSRQ?

At **RSRQ** < −16 dB

Event A1 Based on RSRP

Parameter	IE Value	Actual Value
threshold-RSRP	36	−104
hysteresis	4	2
timeToTrigger	640	640

Event A1 Based on RSRQ

Parameter	IE Value	Actual Value
threshold-RSRQ	12	−14
hysteresis	4	2
timeToTrigger	640	640

When Does Gap Measurements Stop based on RSRP?

At **RSRP** < −102 dBm

When Does Gap Measurements Stop based on RSRQ?

At **RSRQ** < −12 dB

Event B1 Based on RSCP

Parameter	IE Value	Actual Value	
B1-ThreshUTRA	13	−102	
hysteresis	2	1	
timeToTrigger	320	320	
offsetFreq	0	0	
Total # of 3G Carriers in RRC Reconfig Msg	1	1	
# of 3G Neighbors per **Carrier 1**	10	10	
# of 3G Neighbors per **Carrier 2**	32	0	0
# of 3G Neighbors per **Carrier 3**	32	0	0

When to Handover to 3G based on RSCP?

At **RSCP** < −101 dBm

Figure 1.84 Example of inter-RAT handover parameters.

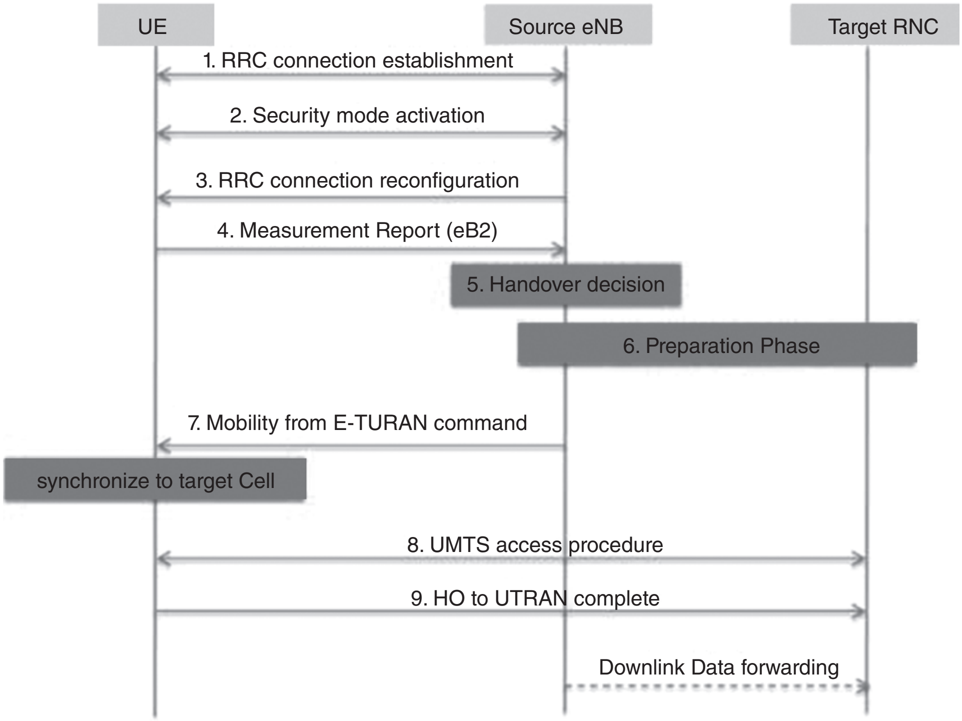


Figure 1.85 Inter-RAT handover to UTRAN call flow.

measurement gap patterns are available: pattern 1 and pattern 2. In pattern 1, the gap duration is 6 ms and the repetition of the gap is 40 ms. In pattern 2, there is a 6 ms gap every 80 ms period.

1.17.17 Example of Inter-RAT Handover Parameters

An example of inter-RAT handover parameters is shown in Figure 1.84.

1.17.18 Inter-RAT Handover to UTRAN Call Flow

The call flow for inter-RAT handover is illustrated in Figure 1.85. It is clear that:

The inter-RAT handover procedure is initiated only when AS security has been activated and SRB2 with at least one DRB has been set up and is not suspended.

Step 3: The NW will configure the measurement of the neighboring cell (inter-RAT).

Step 7: After the preparation phase, the source eNB prepares and sends the Mobility from E-UTRAN Command message to the UE for the handover to the target network. This will contain the parameters (i.e. mobility purpose, target RAT type, the handover message of target RAT, security parameter, etc.) for the handover.

Step 9: After accessing the target UMTS cell, the UE sends a Handover to UTRAN Complete message to the target RNC to indicate a successful handover.

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