CHAPTER 14

FOURTH GENERATION SYSTEMS AND LTE-ADVANCED

LEARNING OBJECTIVES

After studying this chapter, you should be able to:

- Describe the purpose and motivation for 4G.
- Describe the roles of the Evolved Packet Core and the Evolved-UTRAN in LTE.
- Explain the roles of the entities of the EPC.
- Define the roles of bearers and resource blocks in LTE resource allocation.
- Describe and compare FDD and TDD frame structures.
- Explain the full LTE power-on procedure.
- Describe the major improvements in the LTE-Advanced releases.

Fourth-generation (4G) cellular technology provides a high-speed, universally accessible wireless service capability. This is creating a revolution of the same proportion for networking at all locations as the development of user-friendly tablets, smartphones, and widespread deployment of Wi-Fi 802.11 networks provided for indoor wireless networking.

The focus of this chapter is on Long-Term Evolution (LTE) and its 4G enhancement, LTE-Advanced. The chapter first considers the goals and requirements for 4G systems. Then the architecture of LTE-Advanced is presented from a complete wireless system architecture perspective. After that, the core network called the Evolved Packet System is discussed, followed by the LTE channel and physical layer structures. The technologies of LTE Release 8 are first discussed, then the enhancements in Releases 9 through 12.

14.1 PURPOSE, MOTIVATION, AND APPROACH TO 4G

The evolution of smartphones and cellular networks has ushered in a new generation of capabilities and standards, which is collectively called 4G. 4G systems provide ultra-broadband Internet access for a variety of mobile devices including laptops, smartphones, tablets, and device-to-device communications. 4G networks support Mobile Web access and high-bandwidth applications such as high-definition mobile TV, mobile video conferencing, and gaming services.

These requirements have led to the development of a 4G mobile wireless technology that is designed to maximize bandwidth and throughput while also maximizing spectral efficiency. The International Telecommunication Union (ITU) has issued directives for 4G networks. According to the ITU, an IMT-Advanced (or 4G) cellular system must fulfill a number of minimum requirements, including the following:

- Be based on an all-IP packet-switched network.
- Support peak data rates of up to approximately 100 Mbps for high-mobility mobile access and up to approximately 1 Gbps for low-mobility access such as local wireless access.
- Dynamically share and use the network resources to support more simultaneous users per cell.

Table 14.1 Wireless Network Generations

Technology	1G	2G	2.5G	3G	4G
Design began	1970	1980	1985	1990	2000
Implementation	1984	1991	1999	2002	2012
Services	Analog voice	Digital voice	Higher capacity packetized data	Higher capacity, broadband	Completely IP based
Data rate	1.9. kbps	14.4 kbps	384 kbps	2 Mbps	200 Mbps
Multiplexing	FDMA	TDMA, CDMA	TDMA, CDMA	CDMA	OFDMA, SC-FDMA
Core network	PSTN	PSTN	PSTN, packet network	Packet network	IP backbone

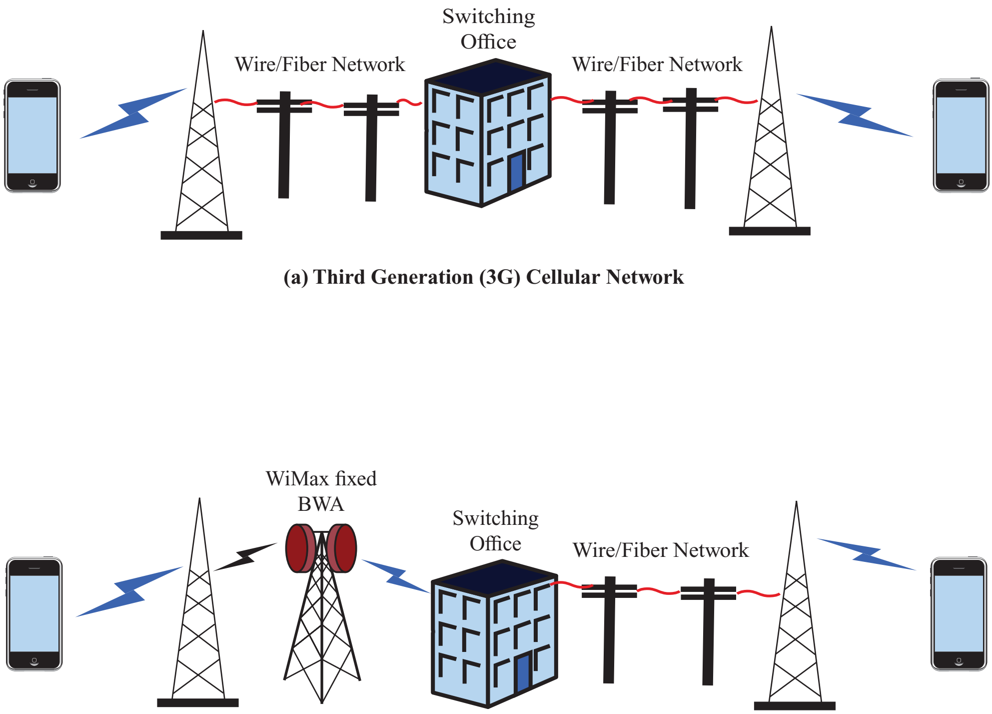
- Support smooth handovers across heterogeneous networks, including 2G and 3G networks, small cells such as picocells, femtocells, and relays, and WLANs.
- Support high quality of service for next-generation multimedia applications.

In contrast to earlier generations, 4G systems do not support traditional circuit-switched telephony service, providing only IP telephony services known as Voice over LTE (VoLTE). As may be observed in Table 14.1, the spread spectrum radio technologies that characterized 3G systems are replaced in 4G systems by orthogonal frequency division multiple (OFDM) multicarrier transmission and frequency-domain equalization schemes.

Figure 14.1 illustrates some major differences between 3G and 4G cellular networks. As shown in Figure 14.1a, the connections between **base stations** and switching offices in 3G networks are typically cable-based, either copper or fiber wires. Circuit switching is supported to enable voice connections between mobile users and phones connected to the PSTN. Internet access in 3G networks may also be routed through switching offices. By contrast, in 4G networks, IP telephony is the norm as are IP packet-switched connections for Internet access. These are enabled by wireless connections, such as fixed broadband wireless access (BWA) WiMAX, between base stations and switching offices (Figure 14.1b). Connections among mobile users with 4G-capable smartphones may never be routed over cable-based, circuit-switched connections—all communications between them can be IP-based and handled by wireless links. This setup facilitates deployment of mobile-to-mobile video call/video conferencing services and the simultaneous delivery of voice and data services (such as Web browsing while engaged in a phone call). 4G mobile users can still connect with 3G network users and PSTN subscribers over cable/fiber circuit-switched connections between the switching offices.

14.2 LTE ARCHITECTURE

Two candidates emerged for 4G standardization. One is known as **Long-Term Evolution (LTE)**, which has been developed by the Third Generation Partnership Project (3GPP), a consortium of Asian, European, and North American telecommunications



(b) Fourth Generation (4G) Cellular Network

Figure 14.1 Third versus Fourth Generation Cellular Networks

standards organizations. The other effort is from the IEEE 802.16 committee, which has developed standards for high-speed fixed wireless operations known as WiMAX (described in Chapter 16). The IEEE 802.16 committee specified an enhancement of WiMAX to meet mobile 4G needs. The two efforts are similar in terms of both performance and technology. Both are based on the use of orthogonal frequency division multiple access (OFDMA) to support multiple access to network resources. WiMAX uses a pure OFDMA approach of both uplink (UL) and downlink (DL). LTE uses pure OFDMA on the DL, but instead a single-carrier orthogonal frequency-division multiplexing (SC-OFDM) technique based on OFDMA offers enhanced power efficiency for the uplink. While WiMAX retains a role as the technology for fixed broadband wireless access, LTE has become the universal standard for 4G wireless. For example, all of the major carriers in the United States, including AT&T and Verizon, have adopted a version of LTE based on **frequency division duplex (FDD)**, whereas China Mobile, the world's largest telecommunication carrier, has adopted a version of LTE based on **time division duplex (TDD)**.

Development of some features of LTE began in the 3GPP 3G era and initial LTE releases provided data rates similar to 3G or enhanced 3G. 3GPP Release 8, LTE, however, was a *clean slate* approach with a completely new air interface that implemented OFDM, OFDMA, and multiantenna transmission and reception

(MIMO) from the beginning. The radio interface aims for LTE of the cellular system, hence the appropriateness of the name.

Beginning with Release 10, LTE provides a 4G service, known as **LTE-Advanced**. Table 14.2 compares the performance goals of LTE and LTE-Advanced. LTE has further been improved with Releases 11 and 12, which will be discussed.

The specifications for LTE releases are immense. This section provides a discussion of the architecture. Figure 14.2 illustrates the principal elements in an LTE network. The heart of the system is the base station, designated **evolved NodeB (eNodeB)**. Mobile devices connect into the network through an eNodeB. In previous 3GPP standards, the base station was referred to as the NodeB. The key differences between the two base station technologies are:

- The NodeB station interface with subscriber stations (referred to as **user equipment (UE)**) is based on CDMA, whereas the eNodeB air interface is based on OFDMA.
- eNodeB embeds its own control functionality, rather than using an RNC (Radio Network Controller) as does a NodeB. This means that the eNodeB now supports radio resource control, admission control, and mobility management, which was originally the responsibility of the RNC.

The simpler structure without an RNC results in simpler operation and higher performance.

Evolved Packet System

3GPP standards divide the network standards between the radio access network (RAN) and the core network (CN), which allow each to evolve independently. LTE is called the **Evolved UMTS Terrestrial Radio Access (E-UTRA)** and its enhancement of 3GPP's 3G RAN is called the **Evolved UMTS Terrestrial Radio Access Network (E-UTRAN)**. As seen in Figure 14.2, the eNodeB is the only logical node in the E-UTRAN since the RNC has been removed from the architecture.

The operator, or carrier, core network that interconnects all of the base stations of the carrier is referred to as the **Evolved Packet Core (EPC)**. Together LTE and

Table 14.2 Comparison of Performance Requirements for LTE and LTE-Advanced

System Performance		LTE	LTE-Advanced
Peak rate	Downlink	100 Mbps @20 MHz	1 Gbps @100 MHz
	Uplink	50 Mbps @20 MHz	500 Mbps @100 MHz
Control plane delay	Idle to connected	<100 ms	<50 ms
	Dormant to active	<50 ms	<10 ms
User plane delay		<5 ms	Lower than LTE
Spectral efficiency (peak)	Downlink	5 bps/Hz @2×2	30 bps/Hz @8×8
	Uplink	2.5 bps/Hz @1×2	15 bps/Hz @4×4
Mobility		Up to 350 km/hr	Up to 350–500 km/hr

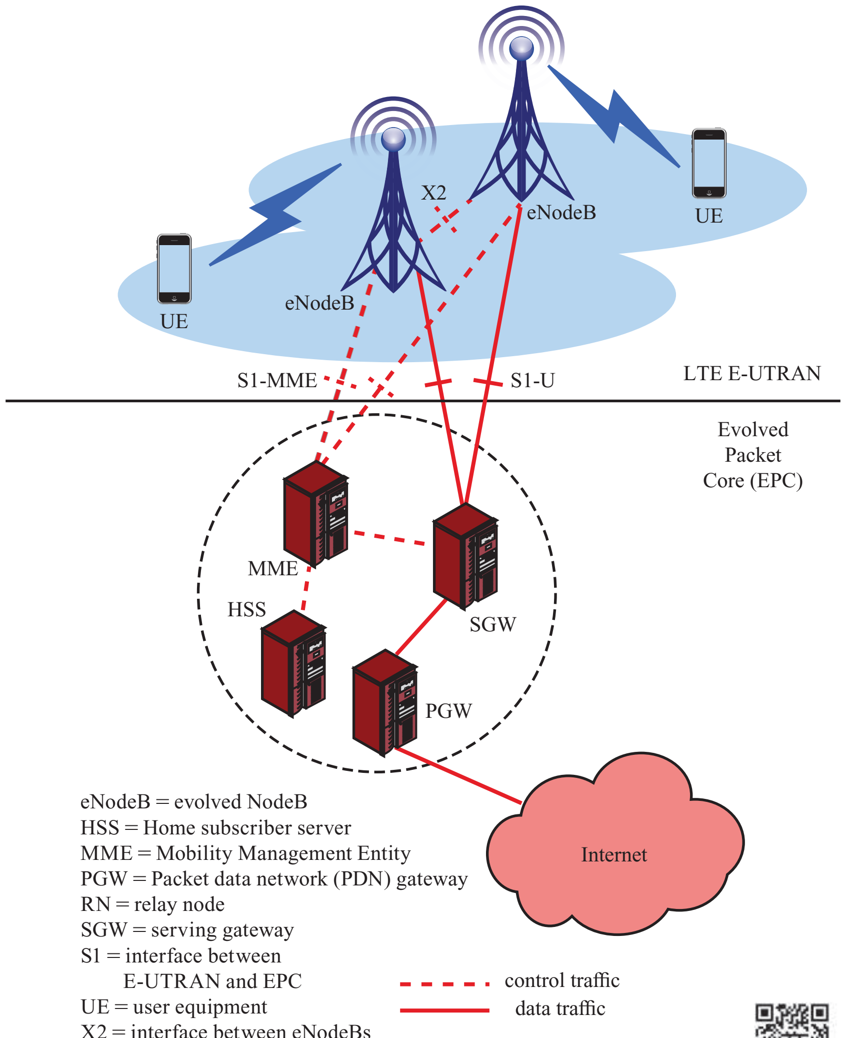


Figure 14.2 Overview of the EPC/LTE Architecture

the EPC form the **Evolved Packet System (EPS)** as shown in Figure 14.2. Because the purpose of this text is both to understand wireless networks and the complete wireless systems within which they operate, we will study both LTE and the EPC. It is certainly the goal of the EPS to provide everything needed to support a 4G communication session, from session management, accounting, and security to physical layer resource allocations, quality of service, delay bounds, and packet error control.

Design Principles

The following design principles were foundational to the design of the EPC and LTE.

- Clean slate design.
- Packet-switched IP core network.

- Minimum numbers of interfaces and network elements.
- Packet-switched transport for traffic belonging to all Quality of Service (QoS) classes, including conversational, streaming, real-time, non-real-time, and background traffic.
- Maximum performance or minor degradation for mobility speeds up to 120 km/hr. Sustained connections up to 500 km/hr for LTE-Advanced.
- Other performance requirements listed in Table 14.2.
- Radio resource management for the following: end-to-end QoS, transport for higher layers, load sharing/balancing, and policy management/enforcement across different radio access technologies.
- Integration with existing 3GPP 2G and 3G networks.
- Flexibility of spectrum deployment depending on geographic regions.
- Support for broadcast and multicast services, especially for emergency situations.
- Scalable bandwidth from 1.4 to 20 MHz.
- Carrier aggregation for overall bandwidths up to 100 MHz.
- FDD and TDD modes.
- Reduced cost: high spectral efficiency, reuse of existing spectrum allocations, flat architecture with fewer network components, base stations with lower power and space requirements, self-configuration and self-optimization.

High Level Functions of the EPS

The following functions are performed by the EPS.

- Network access control, including network selection, authentication, authorization, admission control, policy and charging enforcement, and lawful interception.
- Packet routing and transfer.
- Security, including ciphering, integrity protection, and network interface physical link protection.
- Mobility management to keep track of the current location of the UE.
- Radio resource management to assign, reassign, and release radio resources taking into account single and multicell aspects.
- Network management to support operation and maintenance functions.
- Selection of packet gateways, serving gateways, and mobility management entities for a UE session (more details follow).
- IP networking functions, connections of eNodeBs to the multiple mobility management entities, E-UTRAN sharing, emergency session support, among others.

The next section discusses the Release 8 EPC and then this chapter in successive sections works its way down through Release 8 LTE resource management functions and channel structures to the LTE physical layer. Concluding this chapter is a discussion of the innovations of LTE-Advanced in Release 10 (carrier aggregation, enhanced MIMO, heterogeneous environments, relaying) and the other enhancements in Releases 9, 11, and 12.

It is best to first understand the features of the Release 8 EPC and LTE E-UTRAN (called simply LTE), because many of today's deployments are Release 8. Therefore, the chapter first discusses Release 8. After that the chapter shows how the subsequent releases move to LTE-Advanced to change, enhance, and substantially add to those features. Such enhancements include carrier aggregation, support for **heterogeneous networks (HetNets)** using small cells such as picocells and femtocells, MIMO expansion, interference cancellation, coordinated multipoint transmission, and relaying.

14.3 EVOLVED PACKET CORE

Traditionally, the core cellular network was circuit switched, but for 4G the core is entirely packet switched. It is based on IP and supports voice connections using voice over IP (VoIP). Within 3GPP, the work on the evolved core network was first called the ***System Architecture Evolution (SAE)***. The core network is interchangeably called the SAE or the EPC.

EPC Components

Figure 14.2 illustrates the essential components of the EPC:

- **Mobility Management Entity (MME):** Supports user equipment context, identity, authentication, and authorization.
- **Serving Gateway (SGW):** Receives and sends packets between the eNodeB and the core network.
- **Packet Data Network Gateway (PGW):** Connects the EPC with external networks.
- **Home Subscriber Server (HSS):** Database of user-related and subscriber-related information.
- **S1 interface:** Creates communication between the E-UTRAN and the EPC. For control purposes, the eNodeBs communicate with the MMEs through the S1-MME interface. The S1-U is for user plane data traffic between the eNodeB and the SGW.
- **X2 interface:** The X2 interface is used for eNodeBs to interact with each other. Although not shown in Figure 14.2, there are actually two X2 interfaces, the X2-U for user plane and the X2-C for control plane protocols.

Figure 14.2 shows two eNodeBs and only a single instance of each other configuration element. In practice, there are multiple eNodeBs and multiple instances of each of the EPC elements. And there are many-to-many links between eNodeBs and MMEs, between MMEs and SGWs, and between SGWs and PGWs. Each of these has defined interfaces. Now, the components of the EPC are examined in more detail.

Mobility Management Entity (MME) The MME manages control signaling related to UE mobility and security. This involves managing UE access to network connections and network resources. When a UE requires a handover into a cell in a new area, the MME initiates the transfer. This transfer can occur to another LTE U-TRAN area or to 2G or 3G access networks. The MME is responsible for the tracking and the paging of a UE in idle-mode. The MME provides security functions including temporary identities for user terminals, interacting with home subscriber servers for authentication, and negotiation of security algorithms. It also selects the appropriate SGWs and PGWs and gateways to other 2G and 3G networks.

The MME implements EPS Mobility Management (EMM) and EPS Session Management (ESM) protocols. EMM protocols support connection management, control of security, and mobility of the UE in the U-TRAN. A UE can stay registered with an MME or deregister, in which case the MME has no knowledge of the location of the MME until it attaches again.

The MME coordinates with the HSS to retrieve subscription information and with the SGW to establish communication session bearers. The HSS information is also used to generate the security keys used to protect control plane messages.

Serving Gateway (SGW) The SGW deals with user data transmitted and received by UEs in packet form, using IP. The Serving GW is the point of interconnect between the radio side and the EPC. As its name indicates, this gateway serves the UE by routing the incoming and outgoing IP packets. It is the anchor point for the intra-LTE mobility (i.e., in case of handover between eNodeBs under the same MME). Thus packets can be routed from an eNodeB to an eNodeB in another area via the SGW, and can also be routed to external networks such as the Internet via the PGW. The SGW also performs packet buffering, transport-level packet marking for UL and DL, and accounting functions.

Packet Data Network Gateway (PGW) The PGW is the point of interconnect between the EPC and the external IP networks such as the Internet. The PGW routes packets to and from the external networks. It also performs various functions such as routing, IP address/IP prefix allocation, policy control, deep packet inspection for filtering purposes, lawful interception, transport level packet marking, accounting for inter-operator charging, and access to non-3GPP access networks.

Home Subscriber Server (HSS) The HSS maintains a database that contains user-related and subscriber-related information. It also provides support functions in mobility management, call and session setup, user authentication, and access authorization.

S1 Interfaces The S1 interfaces involve both the S1-MME and S1-U interfaces. The S1-MME interface is defined for the control plane between the eNodeB and the MME. It has functions to establish, maintain, and release E-UTRAN radio access bearers (more details on bearers later in this chapter). It supports mobility functions for handovers intra-LTE, with other 3GPP technologies, and with CDMA2000 3G systems. The S1-MME also has paging procedures for the EPC to find the location of a UE.

The S1-U interface is for the user plane data transmission to connect with an SGW for each bearer. Multiple S1-U logical interfaces may exist between the eNodeB and the SGW.

X2 Interfaces The X2 interface is used for eNodeBs to interact with each other. The architecture is open so that there can be interconnections between different manufacturers. There is a control plan X2-C interface that supports mobility management, handover preparation, status transfer, UE context release, handover cancel, inter-cell interference coordination, and load management. The X2-U interface is the user plane interface used to transport data during X2 initiated handover.

Non-Access Stratum Protocols

The LTE E-UTRAN implements protocols are part of the **Access Stratum** that carries data across the wireless part of the network; these are discussed in Section 14.5. In addition to these protocols for management of connections within the LTE E-UTRAN, other protocols exist for the ***Non-Access Stratum***. These involve interaction between the UE and the EPC core network and are as follows:

- **EPS Mobility Management (EMM):** Manage the mobility of the UE.
- **EPS Session Management (ESM):** Activate, authenticate, modify, and deactivate user-plane channels for connections between the UE, SGW, and PGW.

14.4 LTE RESOURCE MANAGEMENT

Now we elaborate on the functions that these entities and interfaces accomplish for management of LTE resources. This section discusses Release 8 LTE quality of service, handover, and interference coordination functions. The sections after this one work their way down to the LTE physical layer.

Quality of Service

LTE uses the concept of **bearers** for QoS control in its protocol architecture. Because LTE is packet switched from end to end, a bearer is LTE's central element of QoS control instead of a circuit. Each ***EPS bearer*** is defined between the PGW and the UE. It maps to specific QoS parameters such as data rate, delay, and packet error rate. Traffic flowing between applications on a client and a service can be differentiated by separate **Service Data Flows (SDFs)**. These SDFs must be mapped to EPS bearers for QoS treatment.

Applications such as voice or video might have fairly stringent data rate and delay requirements, whereas others such as e-mail might not. As discussed in Chapter 3, data applications might have a data rate expectation and some loss requirements, but would be elastic, meaning they could tolerate variations in data rate during transmissions as long as they are completed expeditiously. Voice and video traffic, however, has a much stronger expectation of steady packet delivery but can tolerate some level of packet loss. If voice or video streams are highly compressed, packet loss would have a more significant impact but in general an end user may not notice a few missed audio samples or erroneous pixels.

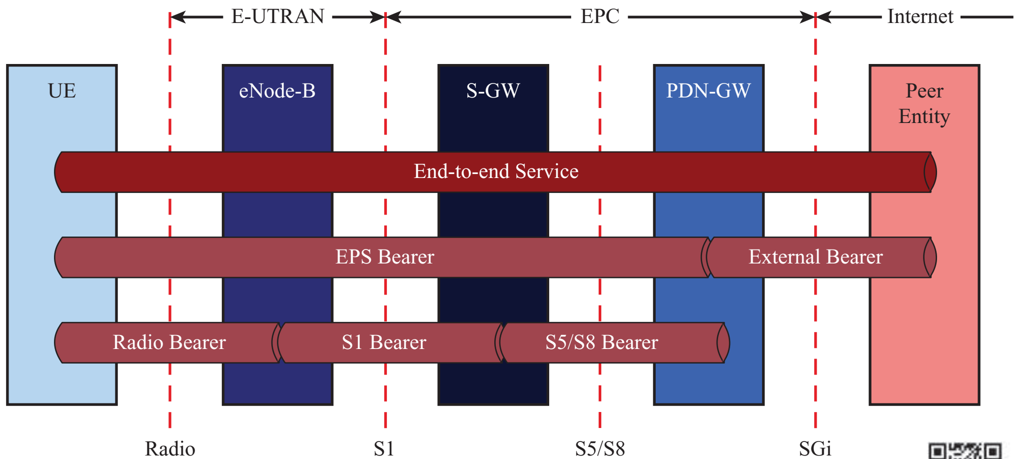


Figure 14.3 LTE QoS Bearers

Therefore, LTE allows these traffic types to be placed on separate bearers for different treatment and priority by the EPS through the different interfaces. End-to-end service between applications on different networks of course cannot be completely controlled by LTE, but inside the EPS (between the UE and the PGW) an EPS bearer is defined as illustrated in Figure 14.3. Across different interfaces, this EPS bearer is also bound to a bearer for that type of interface, whether it is an E-UTRAN radio access bearer, S1 bearer, or S5/S8 bearer.

Bearers are broadly categorized into two classes:

- **Guaranteed Bit Rate (GBR) bearers:** These are guaranteed a minimum bit rate and possibly higher bit rates if system resources are available. These would be most useful for voice, interactive video, or real-time gaming.
- **Non-Guaranteed Bit Rate (non-GBR) bearers:** These are not guaranteed a minimum bit rate. Performance is more dependent on the number of UEs served by the eNodeB and the system load. Non-GBR bearers are more useful for e-mail, file transfer, and P2P file sharing. Web browsing might also be appropriate here as long as web page response times are acceptable.

Each bearer is assigned a **QoS class identifier (QCI)** that refers to a priority, packet delay budget, maximum packet error loss rate, and GBR or non-GBR classification. Nine standard QCIs have been defined by LTE as shown in Table 14.3. Each QCI is given a set of standard forwarding treatments by an operator. These can include scheduling policy, admission thresholds, rate-shaping policy, queue management thresholds, and link layer protocol configuration. Operators preconfigure the set of QCIs and how they are handled by each network element. Because all traffic is ultimately mapped to this small set of nine QCI values, processing is greatly simplified and scalability is improved so that many bearers can be supported.

Table 14.3 Standardized QCI Characteristics

QCI	Resource Type	Priority	Packet Delay Budget	Packet Error Loss Rate	Example 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}	Nonconversational Video (buffered streaming)
5	Non-GBR	1	100 ms	10^{-6}	IMS Signalling
6		6	300 ms	10^{-6}	Video (buffered streaming) TCP-based (e.g., www, e-mail, chat, ftp, p2p file sharing, progressive video, etc.)
7		7	100 ms	10^{-3}	Voice, Video (live streaming) Interactive Gaming
8		8	300 ms	10^{-6}	Video (buffered streaming) TCP-based (e.g., www, e-mail, chat, ftp, p2p file sharing, progressive video, etc.)
9*		9			

*QCI value typicaly used for the default bearer

For each bearer the following information is associated:

- QoS class identifier (QCI) value.
- Allocation and Retention Priority (ARP): Used by call admission control to decide if a bearer request should be accepted or rejected. It is also used when networks are overloaded to decide which bearers to release and which can preempt others.

Additionally for GBR bearers:

- Guaranteed Bit Rate (GBR): minimum rate expected from the network.
- Maximum Bit Rate (MBR): bit rate not to be exceeded from the UE into the bearer.

3GPP additionally defines the following for groups of bearers:

- UE-Aggregate Maximum Bit Rate (UE-AMBR): Upper limit on the aggregate bit rate across all non-GBR bearers for a UE. This is enforced by the eNodeB.
- APN-Aggregate Maximum Bit Rate (APN-AMBR): Upper limit on the aggregate bit rate across all non-GBR bearers over all packet data network connections in the same network.

When a UE connects to the EPS, an EPS bearer is established that persists through the lifetime of the connection. This is called the **default bearer** and has a standard configuration established by the core network. This provides always-on connectivity. An additional bearer for special treatment can be established with the same network and is denoted as a **dedicated bearer**.

LTE uses a user plane protocol stack and a control plane protocol stack. The user plane transports IP packets between the PGW and UE. IP packets are encapsulated in an EPC-specific protocol, then tunneled using the ***GPRS Tunneling Protocol (GTP)***, and then from eNodeB to UE by the ***Packet Data Convergence Protocol (PDCP)***. The control plane protocols involve interactions between the MME and UE for bearer management, QoS management, and mobility management for handovers and paging. These protocols are discussed in more detail in Section 14.5.

Details on bearer binding between EPS bearers for assignment of physical resources (time slots and OFDM subcarriers in units of resource blocks) are discussed in a subsequent section after the details of the physical layer are introduced.

Mobility Management

The EPC supports mobility within the LTE system and mobility to other 3GPP systems. When moving within the LTE system, the X2 interface can be used if moving within the same RAN with nodes all coordinated under the same MME and if an X2 interface exists between the eNodeBs. If moving to an eNodeB that belongs to a different RAN that is using different MMEs, the S1 interface is used. The S1 is also used if eNodeBs are not connected with X2 interfaces or UEs moving to a different radio access technology. Both the X2 and S1 options are discussed here. Within LTE Release 8, all handovers are *hard handovers*; the UE can only be connected to one eNodeB at a time.

S1 Mobility The following steps are involved with S1 mobility:

1. **Preparation:** A decision has been made for handover and the destination MME and eNodeB have been identified, so the network needs to allocate resources at the destination. The MME sends a handover request to the destination eNodeB. Once this eNodeB has allocated resources, it responds with an acknowledgement (ACK) to the MME. The MME then sends the handover command to the UE.
2. **Execution:** Then the UE performs RAN-related procedures for the handover. While the UE is executing these procedures, the source eNodeB transfers the PDCP context of the UE to the destination eNodeB. The source eNodeB also sends the data in its PDCP buffer to the target eNodeB. Once all is completed and the UE has established a new Radio Access Bearer (RAB) with the destination eNodeB, the source eNodeB sends the handover confirmation message.
3. **Completion:** The target eNodeB notifies the MME. The MME then directs the source eNodeB to release the resources that had been used by the UE.

X2 Mobility The following steps are involved with X2 mobility when source and destination eNodeBs can work together directly through the X2 interface.

1. **Preparation:** A decision has been made for handover, so the source eNodeB sends a handover request message to the destination eNodeB. Then the

destination eNodeB works with the MME and SGW to establish resources for the UE. It is possible for the UE to continue to use the same RAB on the destination eNodeB with the same resources and QoS. This enables quick and seamless handover, because the UE is not required to set up a new RAB. The destination eNodeB responds with an ACK once it is ready.

2. **Execution:** The source eNodeB then signals the UE, and in response the UE performs RAN-related procedures for the handover. While the UE is working, the source eNodeB transfers status and data to the destination eNodeB on a per-RAB basis.
3. **Completion:** Once the handover is completed, the UE sends a handoff complete message to the MME/SGW and the SGW switches the GTP tunnel to the destination eNodeB. When the data path is established, the destination eNodeB sends a message for the source eNodeB to release the resources for the UE.

For X2 mobility, lossless handover can be performed between one or more RABs, by having the source eNodeB send all packets to the destination eNodeB that have not been sent or have been sent but not yet acknowledged by the UE. The destination eNodeB, however, may use *selective retransmission*, in which it may choose not to retransmit the unacknowledged packets.

Radio Access Network Procedures for Mobility The previous discussion assumed decisions had already been made about whether a handover should occur and about the selection of a destination eNodeB. Here are the RAN procedures that support these determinations. RAN-related mobility management procedures happen between UE and eNodeB or between UE and MME. Mobility occurs in two distinct cases, either in RRC_IDLE state or in RRC_CONNECTED state. The mobility management procedures are designed to be consistent during changes in these two states and in a host of other different scenarios (e.g., network sharing, country border, femtocells).

Information that might be included in different types of handover decision scenarios include radio link quality, UE capability, call type, QoS requirements, and policy-related aspects. The Reference Signal Received Power (RSCP) indicates radio link quality for a connection in an LTE cell. The UE prepares the *measurement report* which contains the RSCP for the neighboring eNodeBs; this is used to trigger and control the handover procedure. The serving eNodeB provides a list of neighboring cells and frequencies on which a report is requested from the UE.

For intra-LTE handover between eNodeBs in the same EPC, there are five events that trigger measurement reporting:

- **Event A1:** Serving cell radio link quality goes above an absolute threshold.
- **Event A2:** Serving cell radio link quality goes below an absolute threshold.
- **Event A3:** A neighbor cell radio link quality becomes better by an amount relative to the serving cell.
- **Event A4:** A neighbor cell radio link quality goes above an absolute threshold.
- **Event A5:** Serving cell radio link quality goes below an absolute threshold and a neighbor radio link quality goes above a different absolute threshold.

There are similar events for handovers between LTE and 2G or 3G 3GPP networks.

For all of these events, the E-UTRAN uses a *TimeToTrigger* parameter, which determines how long these events must be satisfied before a measurement report is to be sent. This prevents the UE from ping-ponging between eNodeBs due to temporary multipath fading dips or shadows. In the RRC_IDLE state, the UE decides when to conduct handover and the target cell and frequency. In RRC_CONNECTED state, the E-UTRAN determines the optimum cell and frequency.

Inter-Cell Interference Coordination

A UE will suffer from Inter-cell Interference (ICI) when the same frequency is used for a UE in a neighboring cell. This ICI limits the capacity of cellular systems. There are several ICI mitigation techniques that can be used as follows. Subsequent LTE releases have enhanced these capabilities.

To meet LTE spectrum efficiency targets, LTE uses universal **frequency reuse**, that is, all frequencies are reused in each cell. This is equivalent to using a cluster size of $N = 1$ and a **reuse factor** of 1, according to the discussion in Section 13.1 of the previous chapter. This means that two mobiles on the edges of cells could be using the same frequencies in close proximity to each other. At the same time, however, LTE has specific targets for cell edge throughput. Therefore, ICI control techniques are used in Release 8 using three major methods.

- **ICI randomization:** Scrambling the codeword with a cell-specific pseudorandom sequence after error control channel coding. If a neighboring cell uses the same frequency, its codeword will be scrambled differently. Similar to the direct sequence approach for spread spectrum, with the proper code the decoder will only decipher the intended codeword and the effect of others using the same frequency will be reduced.
- **ICI Cancellation:** If the UE can decode the interfering signal, it can recreate that signal and subtract it from the arriving signal. To do this, however, it would require the knowledge of the modulation and coding format of that interfering signal, but this is not usually available.
- **ICI Coordination and Avoidance:** If cells coordinate their use of time/frequencies and transmit power, ICI can be avoided. This can be done statically during the cell planning process, or it can be done semistatically to reconfigure (on time scales of seconds) transmission power and/or traffic loads on resource blocks. The eNodeBs use the X2 interface to share this information.

For LTE Release 8, indicators are included to assist ICI coordination/avoidance. For the DL, eNodeBs can send a ***Relative Narrowband Transmit Power (RNTP)*** indicator to tell where frequencies are going to be used, but with limited power. Therefore, neighboring cells might also be able to use those frequencies. For the UL, LTE sends two indicators between eNodeBs. The ***High Interference Indicator (HII)*** tells neighboring cells which parts of the channel bandwidth are being allocated to cell-edge users. A neighboring cell might wish to avoid those frequencies for cell-edge users in the area. An eNodeB can use an ***Overload Indicator (OI)*** to tell neighbor cells about interference levels experienced in parts of the cell bandwidth. A neighbor eNodeB receiving such an indication may help its neighbor reduce its interference by changing its scheduling to reduce the interference that the neighboring cell is experiencing from this cell.

Later in the chapter, more advanced ICI control schemes from the later LTE releases will be discussed, especially Coordinated Multi-Point Transmission (CoMP). In CoMP, eNodeBs can implement tight coordination of scheduling, beamforming, or multicell joint transmission.

14.5 LTE CHANNEL STRUCTURE AND PROTOCOLS

LTE implements a hierarchical channel structure between the layers of its protocol stack. This provides efficient support for QoS. This section first provides understanding of the radio interface protocols, and then the logical, transport, and physical channel structures are presented.

Radio Interface Protocols

The LTE radio interface protocol stack is divided into control plane and user plane stacks and is illustrated in Figure 14.4. More details on the protocols are shown in Figures 14.5 and 14.6 where the various EPC entities and interfaces are also shown in relation to the protocols. As we have seen for protocol layering elsewhere in previous chapters, each protocol adds a header for its own purposes to carry out its own functions. The user plane protocols in Figure 14.5 are part of the ***Access Stratum*** that carries data across the wireless part of the network. The user plane transports IP packets between the UE and PGW. The PDCP transports packets from UE to eNodeB, then IP packets are encapsulated in an EPC-specific protocol and tunneled

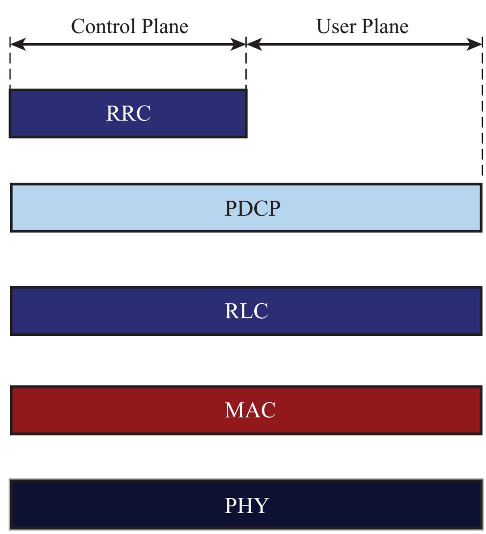


Figure 14.4 The LTE Radio Interface Protocol Stack

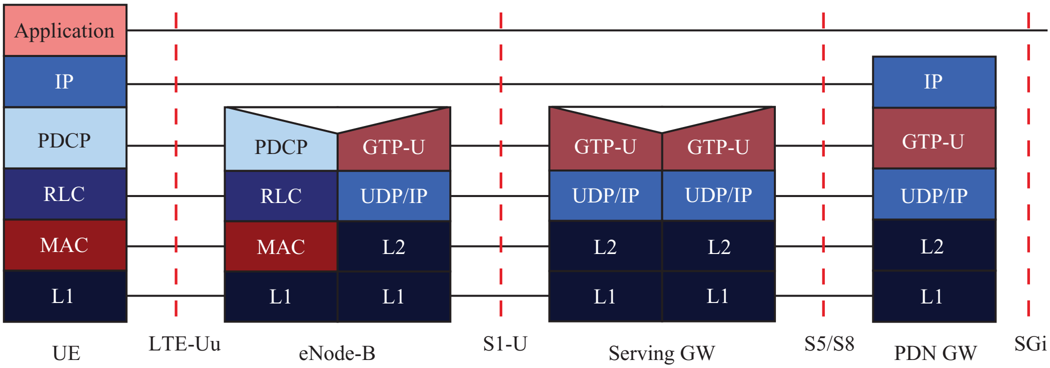


Figure 14.5 User Plane Protocol Stack

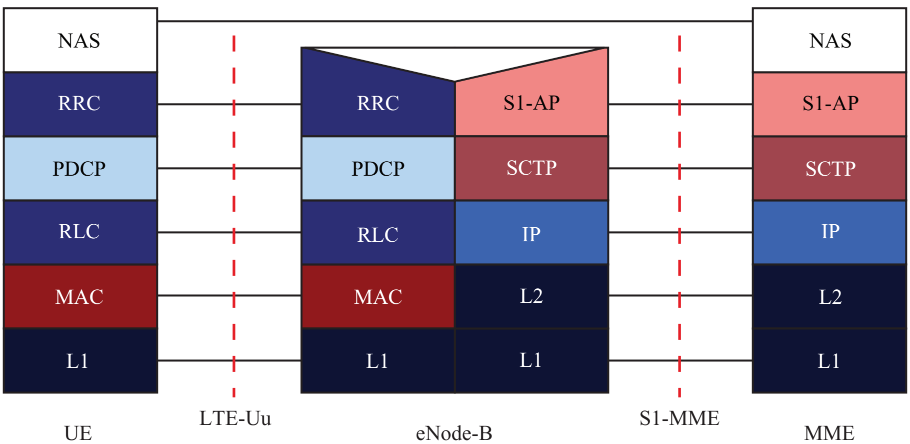


Figure 14.6 Control Plane Protocol Stack

using the GTP through the interfaces to the PGW. The top of the control plane in Figure 14.6 shows the NAS, which corresponds to the Non-Access Stratum for communication between the MME and the UE for bearer management, QoS management, and mobility management. The protocol layers are as follows:

Radio Resource Control (RRC) The RRC layer performs control plane functions for reliable and efficient control of the radio resource. It supervises management of RRC connections, radio bearers, mobility, and UE measurement reporting. Functionality also includes broadcasting system information. Important aspects of the RRC layer are as follows:

- **Two connection states:** LTE has two states for a UE, ***RRC_IDLE*** and ***RRC_CCONNECTED***, in contrast to UMTS, which had four states. In RRC_IDLE state, a UE can receive system information and paging, but does not transmit or receive data. UEs control their own mobility in RRC_IDLE state by performing measurements of neighboring cells and cell selection. In RRC_CONNNECTED state, the UE has an E-UTRAN RRC connection and can transmit and/or receive data. The UE monitors PDCCH channels to see if data are ready to be sent to it. In this state, the network controls mobility/handover decisions.

- **Signaling Radio Bearers (SRBs):** SRBs are radio bearers used only for transmission of RRC and NAS messages. There are three different types of SRBs.
- **System control information:** LTE uses the Master Information Block (MIB) and System Information Block (SIB). The MIB provides the most essential information and parameters that UEs need to know about a cell and how to demodulate the SIB. The SIB contains more parameters to determine if a cell is suitable for cell selection, such as downlink system bandwidth, antenna configuration, and reference signal power.
- IP packet header compression, ciphering of data, and integrity protection for signaling. This supports interaction between higher layers of the protocol stack (e.g., RRC, RTP, TCP, UDP) and the RLC. It supports lossless handovers by sharing data with a destination eNodeB during a handover so no packets are lost.

Packet Data Convergence Protocol (PDCP) Packets are delivered to the UE from the eNodeB using PDCP. The following functions are provided:

- Header compression using the Internet Engineering Task Force Robust Header Compression (ROHC) framework. LTE services are based on IP protocols, but these bring large headers with repetitive information in the IP, TCP, UDP, and RTP protocols (see Chapter 4). ROHC provides various header compression algorithms.
- Ciphering and deciphering of user and control plane data.
- Integrity protection and verification of control plane data.
- In-sequence delivery.
- Buffering and forwarding of data packets to serving eNodeBs during handover.

Radio Link Control (RLC) The RLC will segment or concatenate data units. Segmentation is needed when service data units (SDUs) from upper layers are too large for the MAC layer. Concatenation allows multiple smaller packets to be combined and share header information to reduce system overhead. RLC also performs ARQ retransmission functions for error correction when H-ARQ at the MAC layer has failed (i.e., all H-ARQ transmissions are exhausted). RLC also delivers packets in sequence at the receiver to higher layers. An RLC entity can operate in one of three modes.

- **Transparent Mode (TM):** Simple mode with no header with no RLC functions for segmentation or concatenation. This is used to broadcast system information messages and paging messages, not for user plane data transmission.
- **Unacknowledged Mode (UM):** Provides in-sequence delivery of data, but no retransmission. This can be used for delay-sensitive applications that can tolerate some data loss, for example VoIP.
- **Acknowledged Mode (AM):** Most complex mode which has the same functions as UM but also retransmits missing PDUs. This is best for error-sensitive but delay tolerant applications.

Figure 14.7 shows the formats of the RLC PDUs for the three different modes, either a TM Data PDU (TMD), UM Data PDU (UMD), AM Data PDU (AMD), or AM Data PDU segment. There are different fields for each format as follows:

- **Framing Info (FI):** Segmentation information.
- **Length Indicator (LI):** Length in bytes of corresponding data field.
- **Extension Bit (E):** Indicates whether data follows or another E-LI combination follows. This supports concatenation so multiple PDUs are carried in the data field.
- **Sequence Number (SN):** This is used for in-sequence delivery.
- **Data/Control (D/C):** To indicate the presence of a control or data PDU.
- **Re-segmentation Flag (RF):** Indicates if this is a full AMD or AMD segment.
- **Polling bit (P):** Indicates if a transmitter requests a STATUS report from the receiver.
- **Segment Offset (SO):** For AMD segment to indicate the position of this PDU within the overall PDU before it was segmented.
- **Last Segment Flag (LSF):** Indicates whether this is the last of the segments.

Medium Access Control (MAC) The MAC layer performs H-ARQ procedures to complete the implementation of a two-layer retransmission scheme. The MAC layer performs a fast H-ARQ protocol with low latency and low overhead; then highly reliable ARQ is performed at the RLC layer if H-ARQ is unsuccessful.

The MAC layer also multiplexes and demultiplexes data from logical channels and transport channels (more on channels below in this section); multiple packets can be delivered in a MAC protocol data unit. The eNodeB MAC layer prioritizes and decides which UEs and radio bearers will send or receive data on which shared physical resources. The eNodeB MAC layer also decides the transmission format, that is, the modulation format, code rate, MIMO rank, and power level.

Physical Layer (PHY) PHY functions primarily involve actual transmission of data. Also included are control mechanisms, such as signaling of H-ARQ feedback, power control, signaling of scheduling allocations, and channel measurements.

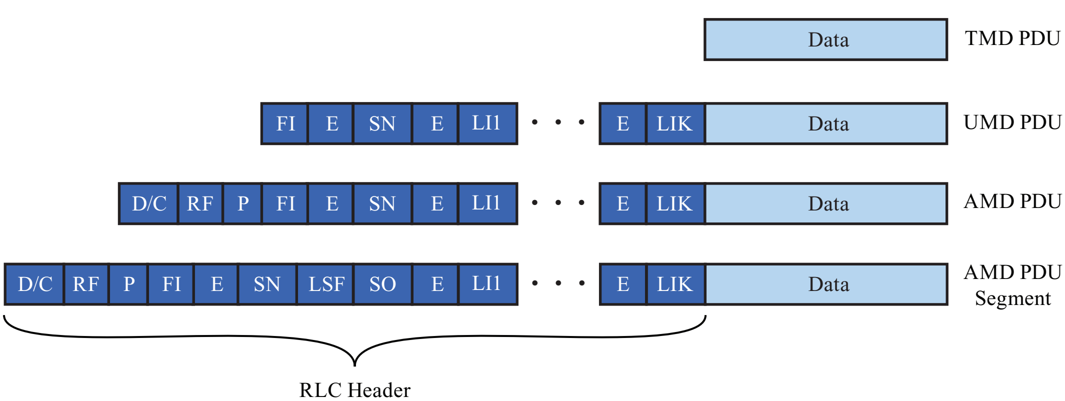


Figure 14.7 Formats of RLC Data PDUs

Channel Structure

There are three types of channels in LTE, and these are defined at the ***Service Access Points (SAPs)*** between protocol layers as shown in Figure 14.8. To simplify the architecture from previous 3GPP standards, LTE consists entirely of shared and broadcast channels; there are no dedicated transport or physical channels to carry data to specific UEs. By understanding the channel structure, one can understand the data flow for various LTE services and be ready to understand more detailed processing procedures in the physical layer.

Logical Channels Logical channels provide MAC services to the RLC, either for control purposes or traffic delivery. Logical control channels are as follows:

- **Broadcast Control Channel (BCCH)**: Downlink common channel to broadcast system control information to UEs, such as system bandwidth, antenna configuration, and reference signal power.
- **Multicast Control Channel (MCCH):** For UEs receiving broadcast or multicast services.
- **Paging Control Channel (PCCH):** Searching for a UE not connected to the network in idle mode.
- **Common Control Channel (CCCH):** Bidirectional channel for control information when a UE is not attached to the network.

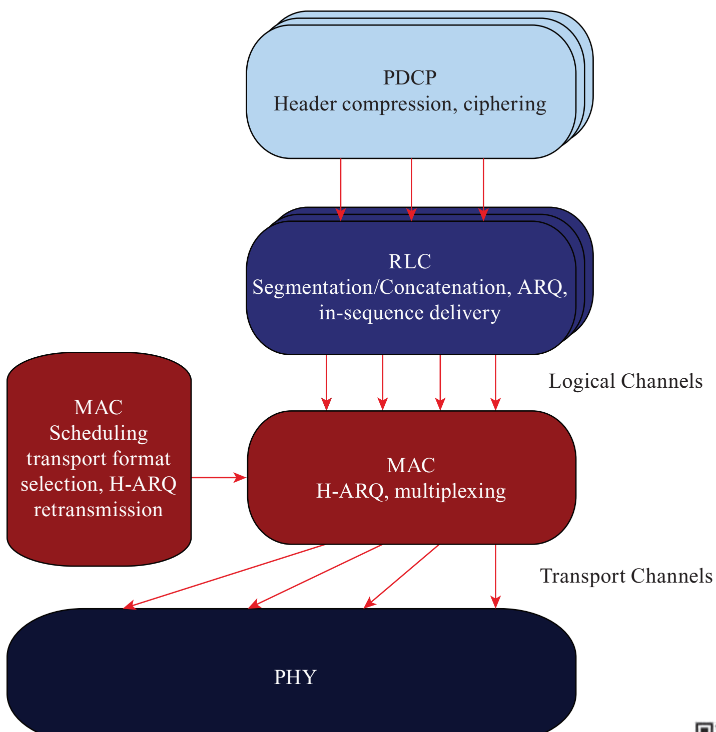


Figure 14.8 The Radio Interface Protocol Architecture and the SAPs between different Layers

- **Dedicated Control Channel (DCCH):** Point-to-point bidirectional channel for dedicated control information when the UE is attached to the network.

Logical traffic channels are as follows:

- **Dedicated Traffic Channel (DTCH):** Dedicated point-to-point channel between a UE and the network.
- **Multicast Traffic Channel (MTCH):** One-way channel from the network to multicast or broadcast to groups of UEs.

Transport Channels The PHY layer offers services to the MAC layer through transport channels. These define the methods and characteristics of data transfer over the radio interface, such as modulation, coding, and antenna configurations.

Downlink Transport Channels:

- **Downlink Shared Channel (DL-SCH):** Transmits downlink data, including control and traffic data, used by both the logical control and traffic channels.
- **Broadcast Channel (BCH):** Broadcasts system information.
- **Multicast Channel (MCH):** Supports the *Multicast/Broadcast Single Frequency Network (MBSFN)* to transmit the same information from multiple base stations on the same radio resource to multiple UEs.
- **Paging Channel (PCH):** Associated with the logical PCCH to broadcast paging over the entire coverage area.

Uplink Transport Channels:

- **Uplink Shared Channel (UL-SCH):** Uplink counterpart to the DL-SCH.
- **Random Access Channel (RACH):** Not mapped to any channel, intended to transmit small amounts of data.

Physical Channels The physical channel defines the set of time and frequency resources used to carry information to the upper layers.

Downlink Physical Channels:

- **Physical Downlink Control Channel (PDCCH):** Carries information about the format and resources related to DL-SCH and PCH transmissions.
- **Physical Downlink Shared Channel (PDSCH):** Carries the user data and signaling for higher layers.
- **Physical Broadcast Channel (PBCH):** Carries the BCH transport channel.
- **Physical Multicast Channel (PMCH):** Carries information for the MBMS multicast service.
- **Physical Hybrid ARQ Indicator Channel (PHICH):** Carries H-ARQ ACK/NACKs for uplink transmissions.
- **Physical Control Format Indicator Channel (PCFICH):** Informs UE about number of OFDM symbols used by the PDCCH.

Uplink Physical Channels:

- **Physical Uplink Control Channel (PUCCH):** Carries control information using Channel Quality Indicators (CQIs).

- **Physical Uplink Shared Channel (PUSCH):** Carries the user data and signaling for higher layers. Supports the UL-SCH transport channel.

Besides the physical channels themselves, there are extra signals included in the downlink and uplink. The ***Reference Signal (RS)*** is used for channel quality measurements. This is especially important for MIMO. Later 3GPP releases have defined various special RSs for this purpose. The ***Synchronization Signal*** is on the downlink to acquire symbol timing and the precise frequency.

Based on this discussion of the channel structure, Figure 14.9 shows the relationships between the logical, transport, and physical channels.

14.6 LTE RADIO ACCESS NETWORK

LTE relies on two key technologies to achieve high data rates and spectral efficiency: OFDM and MIMO antennas. Both of these technologies are explored in summary in Chapter 5 and in more detail in Chapter 6.

For the downlink, LTE uses OFDMA and for the uplink SC-OFDM (single-carrier OFDM). OFDM signals have a high peak-to-average power ratio (PAPR), requiring a linear power amplifier with overall low efficiency and high cost. This is acceptable for base station transmitters on the downlink, but this is poor for battery-operated handsets. While complex, using SC-FDMA instead for the uplink has a lower PAPR and is better suited to implementation in mobiles.

Frame Structure

OFDM provides many benefits over the CDMA technologies used by 3G. It combats frequency-selective fading by using long symbol times. OFDMA provides further benefits by allowing multiple users to schedule transmission on the subcarriers

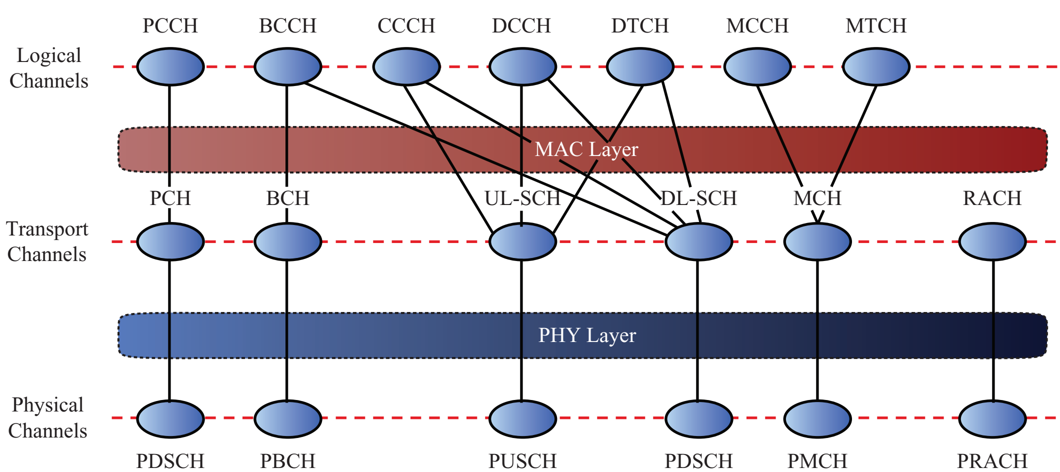


Figure 14.9 Mapping of Logical, Transport, and Physical Channels

which are best for them at the time. OFDM also has a low complexity transceiver structure by using FFT operations.

LTE uses subcarriers 15 kHz apart. The maximum FFT size is 2048, so this sets up a basic time unit in LTE of $T_s = 1/(15{,}000 \times 2048) = 1/30{,}720{,}000$ s. The downlink and uplink are organized into ***radio frames*** with duration 10 ms, which corresponds to $307{,}200T_s$.

LTE has been defined to accommodate both paired spectrum for FDD and unpaired spectrum for TDD operation. Both LTE TDD and LTE FDD are being widely deployed as each form of the LTE standard has its own advantages and disadvantages. Table 14.4 compares key characteristics of the two approaches.

FDD systems allocate different frequency bands for UL and DL transmissions. The UL and DL channels are usually grouped into two blocks of contiguous channels (paired spectrum) that are separated by a guard band of a number of vacant radio frequency (RF) channels for interference avoidance. Figure 14.10a illustrates

Table 14.4 Characteristics of TDD and FDD for LTE

Parameter	LTE-THD	LTE-FDD
Paired spectrum	Does not require paired spectrum as both transmit and receive occur on the same channel.	Requires paired spectrum with sufficient frequency separation to allow simultaneous transmission and reception.
Hardware cost	Lower cost as no diplexer is needed to isolate the transmitter and receiver. As cost of the UEs is of major importance because of the vast numbers that are produced, this is a key aspect.	Diplexer is needed and cost is higher.
Channel reciprocity	Channel propagation is the same in both directions which enables transmit and receive to use one set of parameters.	Channel characteristics are different in the two directions as a result of the use of different frequencies.
UL/DL asymmetry	It is possible to dynamically change the UL and DL capacity ratio to match demand.	UL/DL capacity is determined by frequency allocation set out by the regulatory authorities. It is therefore not possible to make dynamic changes to match capacity. Regulatory changes would normally be required and capacity is normally allocated so that it is the same in either direction.
Guard period/guard band	Guard period required to ensure uplink and downlink transmissions do not clash. Large guard period will limit capacity. Larger guard period normally required if distances are increased to accommodate larger propagation times.	Guard band required to provide sufficient isolation between uplink and downlink. Large guard band does not impact capacity.

(*Continued*)

Table 14.4 (*Continued*)

Parameter	**LTE-THD**	**LTE-FDD**
Discontinuous transmission	Discontinuous transmission is required to allow both uplink and downlink transmissions. This can degrade the performance of the RF power amplifier in the transmitter.	Continuous transmission is required.
Cross slot interference	Base stations need to be synchronized with respect to the uplink and downlink transmission times. If neighboring base stations use different uplink and downlink assignments and share the same channel, then interference may occur between cells.	Not applicable.

a typical spectrum allocation in which user *i* is allocated a pair of channels *Ui* and *Di* with bandwidths W_U and W_D. The frequency offset, W_O, used to separate the pair of channels should be large enough for the user terminal to avoid self-interference among the links because both links are simultaneously active.

For TDD, the UL and DL transmissions operate in the same band but alternate in the time domain. Capacity can be allocated more flexibly than with FDD. It is a simple matter of changing the proportion of time devoted to UL and DL within a given channel.

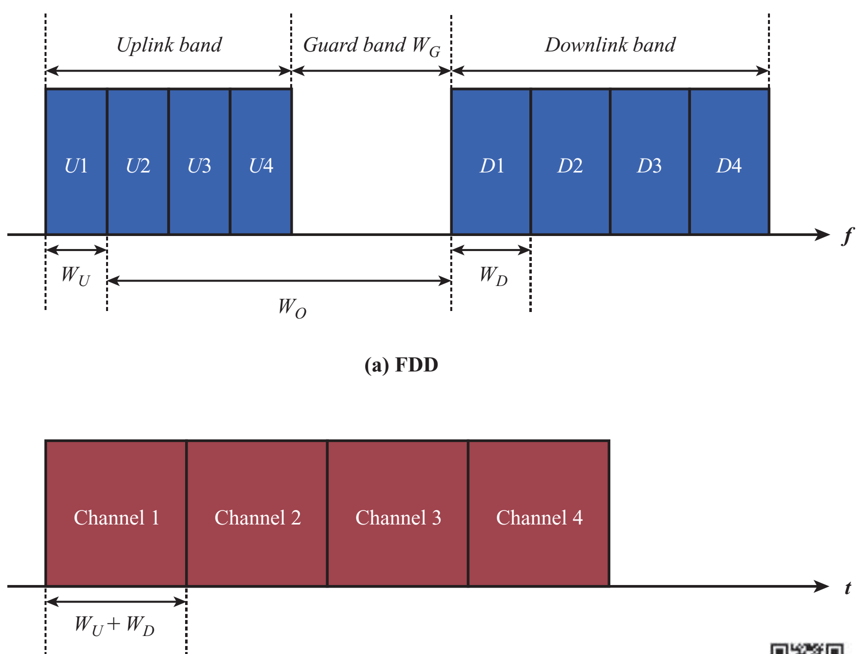


Figure 14.10 Spectrum Allocation for FDD and TDD

Virtually all physical layer processing in LTE is the same for FDD and TDD, so that there can be low-cost implementation of terminals that support TDD and FDD modes. The difference lies mainly in the frame structures.

In addition to the benefits of OFDM at combating multipath-induced frequency selective fading due to its long symbol times, the cyclic prefix (CP) adds extra time to overcome multipath effects. LTE uses a cyclic prefix of $144 \times T_s = 4.7\ \mu s$. For worse environments, a CP of $512 \times T_s = 16.7\ \mu s$ could instead be used. Using the speed of light, 4.7 μs corresponds to a maximum path length difference for multipath components of $(4.7 \times 10^{-6})(3 \times 10^8) = 1.41$ km. The 16.7 μs CP allows for 5.0 km.

Frame Structure Type 1, FDD For FDD, the frame structure is shown in Figure 14.11. Three different time units are applicable.

- The *slot* equals $T_{slot} = 15{,}360 \times T_s = 0.5$ ms.
- Two consecutive slots comprise a *subframe* of length 1 ms. Channel dependent scheduling and link adaptation (otherwise known as adaptive modulation and coding) occur on the time scale of a subframe (1000 times/second).
- 20 slots (10 subframes) equal a *radio frame* of 10 ms. Radio frames schedule distribution of more slowly changing information, such as system information and reference signals.

The ***normal CP*** fills 4.7 μs of the 500 μs frame, 144 of the 15,360 samples. An OFDM symbol is $1/15{,}000 = 66.67\ \mu s$, 2048 samples. Thus 7 OFDM symbols and 7 CPs will fit in a slot, with the first CP made slightly longer, 160 samples. This results in $160 + 6 \times 144 + 7 \times 2048 = 15{,}360$ samples per 0.5 ms. If the longer ***extended CP*** is used, only 6 OFDM symbols will fit. The CP is 512 samples, which results in $6 \times (512 + 2048) = 15{,}360$ samples per 0.5 ms. All else being equal, this means that ratio of extended CP throughput to normal CP throughput is 6/7, a 14.3% reduction.

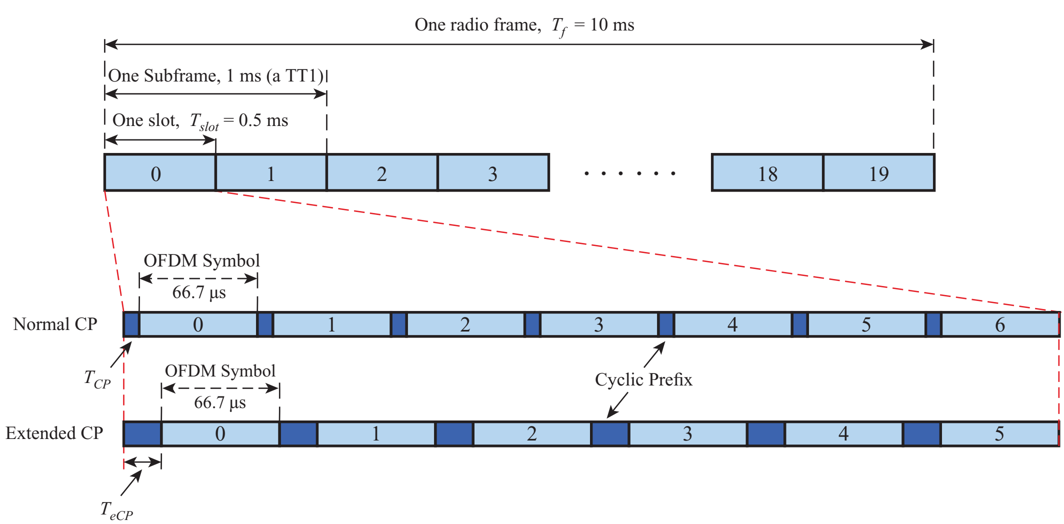


Figure 14.11 FDD Frame Structure, Type 1

For FDD, UL and DL use separate carrier frequencies, so each uses the same structure of 10 subframes and 20 slots per 10 ms.

Frame Structure Type 2, TDD For TDD, the frame structure is shown in Figure 14.12. All transmission occurs on a single carrier frequency. The frame structure is designed to be compatible with 3GPP legacy 3G systems. Each radio frame is again of length 10 ms, which has two half-frames of 5 ms each. There are special subframes to accommodate the switch downlink-to-uplink with the three following fields.

- **Downlink Pilot TimeSlot (DwPTS):** Ordinary but shorter DL subframe for data transmission. It can be 3 to 12 OFDM symbols.
- **Uplink Pilot TimeSlot (UpPTS):** Short duration of one or two OFDM symbols which can be used for sounding reference signals or random access preambles.
- **Guard Period (GP):** Remaining symbols in the special subframe in between to provide time to switch between DL and UL. This is used to overcome propagation delays and interference; LTE supports a guard period ranging from 140 to 667 μs (2 to 10 OFDM symbols), depending on the distance between UEs and eNodeBs.

The total length of these three fields together is 1 ms. Table 14.5 shows seven configurations for sharing of TDD uplink and downlink slots ("S" denotes the special frames). Downlink-to-uplink ratios vary from 2:3 to 9:1.

Resource Blocks

A time-frequency grid is used to illustrate the LTE allocation of OFDM physical resources. This is called a *resource grid* and the downlink structure is shown in Figure 14.13. Each column corresponds to the 6 or 7 OFDM symbols per slot.

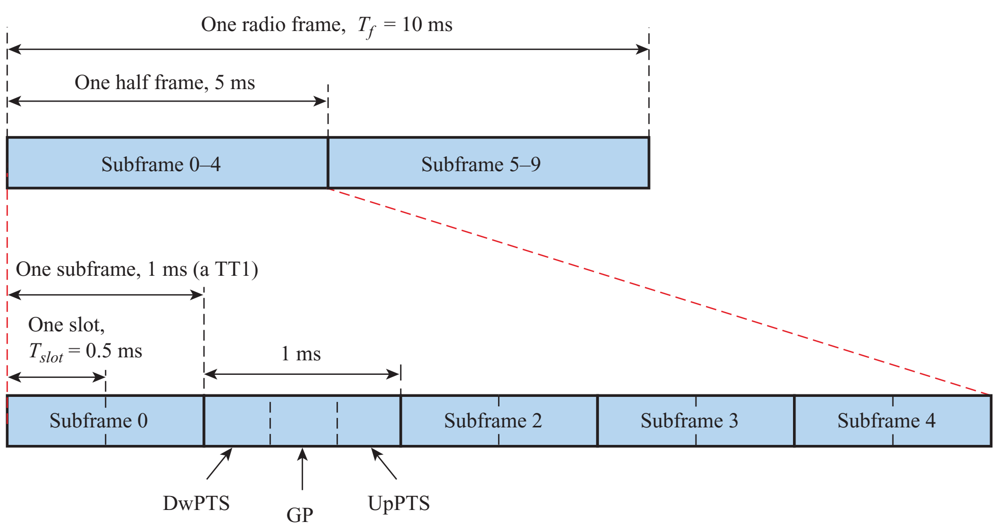


Figure 14.12 TDD Frame Structure, Type 2

Table 14.5 Uplink-Downlink Configurations for LTE TDD

Uplink-Downlink Configuration	Downlink-Uplink Switch-Point Periodicity	Subframe Number									
		0	1	2	3	4	5	6	7	8	9
0	5 ms	D	S	U	U	U	D	S	U	U	U
1	5 ms	D	S	U	U	D	D	S	U	U	D
2	5 ms	D	S	U	D	D	D	S	U	D	D
3	10 ms	D	S	U	U	U	D	D	D	D	D
4	10 ms	D	S	U	U	D	D	D	D	D	D
5	10 ms	D	S	U	D	D	D	D	D	D	D
6	5 ms	D	S	U	U	U	D	S	U	U	D

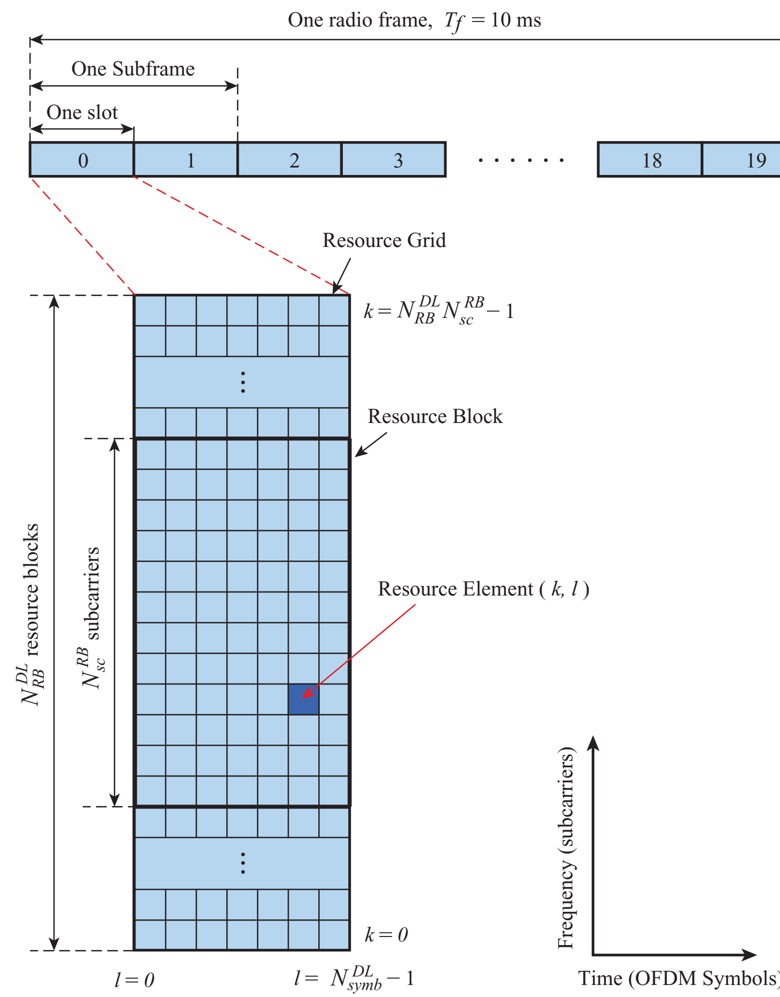


Figure 14.13 LTE Resource Grid

Each row corresponds to the allocated subcarriers. LTE uses 15 kHz subcarriers and allocates blocks of 12 subcarriers, a total of 180 kHz per allocation. The combination of 6 or 7 OFDM symbols over 12 subcarriers results in an allocation of 72 or 84 **resource elements** (i.e., OFDM symbols) over a **resource block.**

Table 14.6 shows the possible channel bandwidths and the number of resource blocks for each. For the larger bandwidth 3 MHz and above, 10% of the bandwidth is used for guard band, leaving 90% for resource blocks. For a 20 MHz channel, therefore, 18.0 MHz is available for 1200 15 MHz subcarriers. This corresponds to 100 resource blocks.

For the UL, carrier frequencies must be contiguously allocated because single-carrier OFDM is used. SC-OFDM is discussed in Chapter 8. Therefore, this contiguous block of 180 MHz for the resource block is also called the ***physical resource block (PRB)*** because it corresponds to a set of contiguous frequencies.

For the DL, however, frequencies are not required to be contiguous. As a matter of fact, the option to not be contiguous provides the potential for frequency diversity. Therefore, a resource block allocated for a DL connection is called a ***virtual resource block (VRB)*** for a set of subcarriers, but the subcarriers need not be consecutive.

MIMO is described in Chapter 5 and in more detail in Chapter 6. LTE Release 8 supports up to four transmit and four receive antennas. LTE-Advanced in Release 10 supports up to eight transmit and eight receive antennas. In such cases, there is one resource grid per antenna port. An antenna port is defined by a reference signal, not necessarily a physical antenna.

For both the DL and UL, the eNodeB decides on the resource blocks and uses the PDCCH to communicate these decisions to the UEs. In the UL case, the eNodeB will also communicate different timing advances to be used by the UEs so the signals will be synchronized when they reach the eNodeB. This synchronization preserves the orthogonality of OFDM.

The eNodeB dynamically assigns resources based on channel-dependent scheduling. *Multiuser diversity* can be exploited to increase bandwidth usage

Table 14.6 Typical Parameters for Downlink Transmission

Transmission bandwidth (MHz)	1.4	3	5	10	15	20
Occupied bandwidth (MHz)	1.08	2.7	4.5	9.0	13.5	18.0
Guardband (MHz)	0.32	0.3	0.5	1.0	1.5	2.0
Guardband, % of total	23	10	10	10	10	10
Sampling Frequncy (MHz)	1.92 $1/2 \times 3.84$	3.84	7.08 2×3.84	15.36 4×3.84	23.04 6×3.84	30.72 8×3.84
FFT size	128	256	512	1024	1536	2048
Number of occupied subcarriers	72	180	300	600	900	1200
Number of resource blocks	6	15	25	50	75	100
Number of CP samples (normal)	9×6 10×1	18×6 20×1	36×6 40×1	72×6 80×1	108×6 120×1	144×6 160×1
Number of CP samples (extended)	32	64	128	256	384	512

efficiency by assigning resource blocks for UEs with favorable qualities on certain time slots and subcarriers. These decisions can also include fairness considerations, understanding of UE locations, and typical channel conditions versus fading, and other user and QoS priorities.

Physical Transmission Formats

LTE uses the following physical transmission formats.

- **Channel coding:** For transport blocks, LTE first adds CRC codes of 8, 16, or 24 parity bits. Blocks larger than 6144 bits are then segmented into smaller blocks and CRC is added to each one. These segmented blocks are encoded using either 1/3 rate tail-biting convolutional codes or 1/3 rate convolutional turbo codes. Tail-biting convolutional coding is a special approach for the starting state of the convolutional encoder.
- **Modulation:** LTE supports downlink and uplink QPSK, 16QAM, and 64QAM, depending on channel conditions and UE capabilities. Choices are based on CQI and various other parameters. Of course, both transmitter and receiver need to use the same format, so this is communicated in the Downlink Control Information (DCI). The UE determines a CQI index that will provide the highest throughput while maintaining at most a 10% block error rate on the first H-ARQ transmission. The LTE CQI table is provided in Table 14.7. Then a modulation and coding scheme along with block size is chosen to meet packet error rate targets. H-ARQ will then correct errors. The efficiency

Table 14.7 4-Bit CQI Table

CQI Index	Modulation	Code Rate × 1024	Efficiency
0	Out of Range		
1	QPSK	78	0.1523
2	QPSK	120	0.2344
3	QPSK	193	0.3770
4	QPSK	308	0.6016
5	QPSK	449	0.8770
6	QPSK	602	1.1758
7	16QAM	378	1.4766
8	16QAM	490	1.9141
9	16QAM	616	2.4063
10	64QAM	466	2.7305
11	64QAM	567	3.3223
12	64QAM	666	3.9023
13	64QAM	772	4.5234
14	64QAM	873	5.1152
15	64QAM	948	5.5547

column shows the number of bps/Hz that can be achieved. For example, on a 20 MHz channel with CQI 14:

$$\text{Total bit rate} = (20\text{ MHz}) \times (5.1152\text{ bps/Hz}) = 102.3\text{ Mbps}$$

- **Scrambling:** Each codeword is mixed with a pseudo-random code that depends on physical cell ID and the mobile's radio network temporary identifier. This reduces interference with transmissions in nearby cells using the same resource block.
- **Reference Signals:** Reference signals are used to measure channel conditions. It is not practical to measure every frequency at every time slot, nor is it necessary because coherence times and coherence bandwidths dictate that there will be similarities in closely spaced times and frequencies. Reference signals are inserted at scattered points in the time, frequency, and antenna resources to achieve a balance of overhead and estimation accuracy. They are used to perform coherent demodulation and channel measurement. Later releases of LTE increase the types and usefulness of these reference signals, especially to enhance MIMO and expand to 8×8 MIMO and multiuser-MIMO.
- **H-ARQ:** Turbo coding is first applied to the code block. If there is a retransmission, Hybrid ARQ at the receiver will combine the new data with the previously received block. If no error, an ACK is sent on the PUCCH physical channel. For each retransmission, the same turbo-encoded block is sent by H-ARQ, but with different puncturing. There is typically an 8 ms delay for a retransmission, so LTE allows other blocks to be transmitted in the meantime with an N-channel Stop-and-Wait protocol. The maximum number of retransmissions of each transport block is determined by the RRC layer.

Power-On Procedures

Now that full descriptions of LTE Release 8 have been provided, it is helpful to consider how everything works together to create a communication session for a UE [COX14]. This is commonly considered the power-on sequence, because it involves all activities from the time a UE is completely disconnected until it is successfully communicating. Here is the sequence.

1. Power on the UE.
2. **Network selection:** The UE selects a public land mobile network (PLMN). It first attempts to register with the PLMN to which it was previously registered. If the UE cannot find this PLMN, it scans all of its known LTE carrier frequencies to find another network. If the mobile supports legacy technologies such as UMTS, GSM, or CDMA2000, it will try those as well.
3. **Cell selection:** The UE selects a suitable cell that belongs to the PLMN. It can scan its last known set of potential LTE frequencies or scan all frequencies it supports. For a cell to be suitable, the UE must be able to successfully hear downlink transmissions, the base station must be able to successfully hear the UE on the uplink, and interference levels must not be high.

4. **Contention-based random access:**
   a. The mobile transmits a random access preamble on the physical random access channel (PRACH). If it receives no response, it will keep retransmitting with increasing power until it receives a response or reaches a maximum number of retransmissions.
   b. The base station will provide a random access response. There may be contention with other mobiles and the base station may tell the mobile to randomly back off and try again later. The base station provides a C-RNTI (cell radio network temporary identifier), timing advance, and resources on the PUSCH.
5. **RRC connection establishment:** The mobile then sends an RRC Connection Request to move to RRC_CONNECTED state. The eNodeB responds with an RRC connection setup that configures the mobile's physical layer, MAC protocols, and signaling radio bearer. The mobile responds with the confirmation message *RRC Connection Setup Complete* that is also forwarded to the MME to serve as an EPS mobility management exchange with the MME.
6. **Attach procedure:** Four main objectives are accomplished. The UE registers its location with the MME, the network configures a radio bearer for non-access stratum signaling messages, the network gives an IP address, and the network sets up a default EPS bearer.
7. **Packet Transmission:** Then the UE transmits and receives data. It is now in EMM-REGISTERED, ECM-CONNECTED, and RRC_CONNECTED states and will stay there as long as it is communicating.

   For downlink transmission:
   a. The base station begins by sending a *scheduling command* that uses the DCI on the PDCCH. The scheduling command specifies parameters such as the amount of data, resource block allocation, and modulation scheme. This is repeated for each packet to be sent, unless *semi-persistent scheduling* is used, which allows the BS only to send one scheduling command for a set of messages. This is useful to reduce overhead for services like VoIP.
   b. Then the base station uses the downlink shared channel (DL-SCH) and the PDSCH to send the data.
   c. In response, the mobile sends a hybrid ARQ acknowledgment on the PUCCH. Alternatively, it may use the PUSCH if it is also transmitting uplink data on the same subframe.

   For uplink transmission, the mobile must first indicate to the BS that it wishes to send. If in RRC_IDLE mode, it can use the random access procedure above in Step 4. If RRC_CONNECTED, it can send a scheduling request on the PUCCH. If already transmitting other packets, the mobile can keep the BS updated about its buffer status (i.e., letting the BS know it has other packets to send) using buffer status reports.
   a. The base station begins by sending a *scheduling grant* that uses the DCI on the PDCCH. The scheduling grant specifies parameters such as the amount of data, resource block allocation, and modulation scheme.
   b. The mobile sends data on the UL-SCH and the PUSCH.
   c. If unsuccessful, the base station can respond either on the PHICH for a simple NACK to request a retransmission in the same format, or the BS

can respond on the PDCCH. A NACK on the PDCCH can include a new scheduling grant for resource block allocation or modulation.

8. **Improve quality of service:** If the user needs better QoS than the default bearer can provide, it sends an *ESM Bearer Resource Allocation Request* to the MME. It requests parameters such as QCI, guaranteed and maximum bit rates. It can also give further information about service data flows with IP addresses and TCP/UDP port numbers. The SGW, MME, and PGW share messages, and the PGW usually establishes a dedicated bearer. If the user already has a suitable dedicated EPS bearer, it may modify that bearer.

More details on these procedures are provided in the 3GPP standards and in [COX14].

14.7 LTE-ADVANCED

Since 3GPP LTE Release 8, Releases 9–11 have subsequently been issued and, at the time of this writing, Release 12 is close to being finalized. With Release 10, LTE was able to meet the requirements of IMT-Advanced for true 4G and took on the name LTE-Advanced. Many important technology advances have been published in these releases, but we will focus on those that have had the greatest impact on capacity and quality improvements for LTE-Advanced. These are the following:

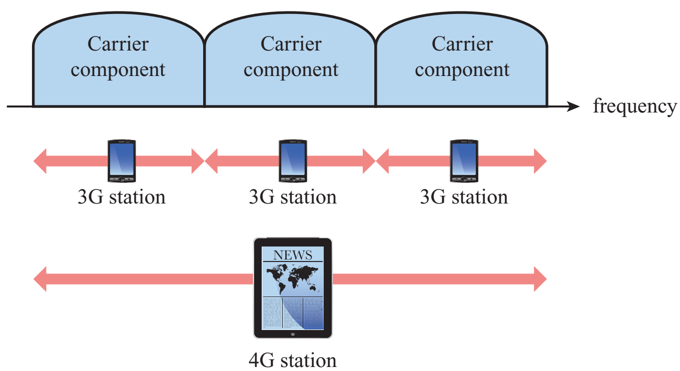
- carrier aggregation
- MIMO enhancements to support higher dimensional MIMO
- relay nodes
- heterogeneous networks involving small cells such as femtocells, picocells, and relays
- cooperative multipoint transmission and enhanced intercell interference coordination
- voice over LTE

Carrier Aggregation

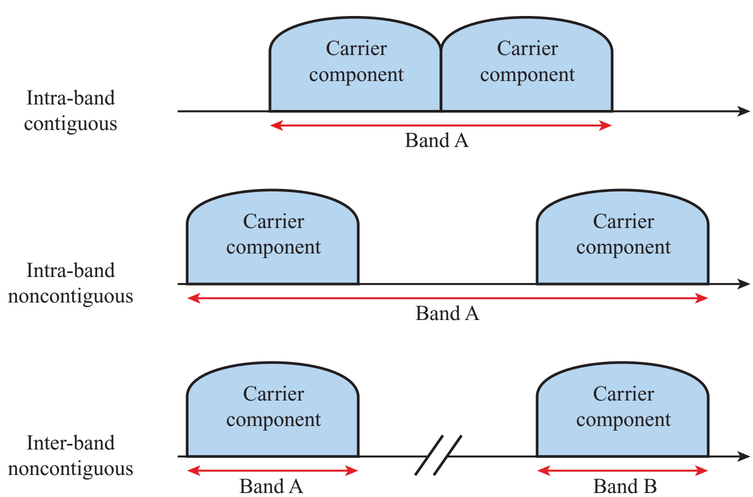
The ultimate goal of LTE-Advanced is to increase bandwidth to 100 MHz. **Carrier aggregation (CA)** is used in LTE-Advanced to increase the bandwidth, and thereby increase the bit rates. Because it is important to keep backward compatibility with LTE, the aggregation is of LTE carriers. Carrier aggregation can be used for both FDD and TDD. Each aggregated carrier is referred to as a component carrier, CC. The CC can have a bandwidth of 1.4, 3, 5, 10, 15, or 20 MHz and a maximum of five component carriers can be aggregated, hence the maximum aggregated bandwidth is 100 MHz. These CCs can come from multiple cells, for example, two different macro cells and maybe one small cell. One is named the primary cell and others the secondary cells. In FDD the number of aggregated carriers can be different in DL and UL. However, in FDD the number of UL component carriers is always equal to or lower than the number of DL component carriers. The individual component carriers can also be of different bandwidths. When TDD is used the number of CCs and the bandwidth of each CC are the same for DL and UL. Up through Release 11, the CCs need to have the same mode of operation (FDD or TDD), but in Release 12 this restriction is removed.

Figure 14.14a illustrates how three carriers, each of which is suitable for a Release 8 station, are aggregated to form a wider bandwidth suitable for a 4G LTE-Advanced station. As Figure 14.14b suggests, there are three approaches used in LTE-Advanced for aggregation:

- **Intra-band Contiguous:** This is the easiest form of LTE carrier aggregation to implement. Here, the carriers are adjacent to each other. The aggregated channel can be considered by the terminal as a single enlarged channel from



(a) Logical view of carrier aggregation



(b) Types of carrier aggregation

Figure 14.14 Carrier Aggregation

the RF viewpoint. In this instance, only one transceiver is required within the subscriber station. The drawback of this method is the need to have a contiguous spectrum band allocation.

- **Intra-band noncontiguous:** Multiple CCs belonging to the same band are used in a noncontiguous manner. In this approach, the multicarrier signal cannot be treated as a single signal and therefore multiple transceivers are required. This adds significant complexity, particularly to the UE where space, power, and cost are prime considerations. This approach is likely to be used in countries where spectrum allocation is noncontiguous within a single band or when the middle carriers are in use by other subscribers.
- **Inter-band noncontiguous:** This form of carrier aggregation uses different bands. It will be of particular use because of the fragmentation of bands—some of which are only 10 MHz wide. For the UE it requires the use of multiple transceivers within the single item, with the usual impact on cost, performance, and power.

Physical and MAC layer protocols are affected by carrier aggregation, so this involves the RRC, S1-AP, and X2-AP signaling protocols. There is no impact, however, on the RLC, PDCP, or data transport on the fixed network. Of the different types of UEs, category 8 UEs support CA with a peak data rate of 3 Gbps on the downlink and 1.5 Gbps on the downlink. But not all mobiles support every category 8 feature so they can limit cost and complexity. For example, they may only support two downlink CCs rather than five (Releases 10 and 11) and only a limited number of frequency bands. A mobile advertises as part of its radio access capabilities the bands and band combinations that it supports. It also declares its *bandwidth class* that states the number of CCs and resource blocks it can handle. Bandwidth classes A, B, C, and D have 1, 2, 2, or 3 CCs, respectively and 100, 100, 200, or 300 maximum RBs.

Each CC is independently scheduled. Downlink transmission is not affected by CA, but changes were necessary for the uplink, because the SC-FDMA format required a contiguous set of subcarriers. Release 10 specified a more general approach known at *Discrete Fourier Transform Spread Orthogonal Frequency Division Multiple Access* (DFT-S-OFDMA), which is the same as SC-FDMA, except it can use noncontiguous subcarriers.

Enhanced MIMO

LTE-Advanced extends support for downlink antenna transmission using what is known as *eight layer multiplexing*. LTE Release 8 supported four layer single-user MIMO. For LTE-Advanced single-user MIMO, up to eight separate transmissions can be sent on the downlink to the same UE, effectively increasing throughput eight times. In a downlink scenario where two component carriers are used with eight transmission layers apiece, Release 10 can support the following.

$$(75 \text{ Mbps per 20 MHz carrier}) \times (2 \text{ CCs}) \times (8 \text{ layers}) = 1200 \text{ Mbps}$$

If 5 CCs are used in later releases, 3000 Mbps is possible in ideal conditions.

If multiuser MIMO is used instead, up to four mobiles can receive signals simultaneously. And the eNodeB can switch between single-user and multiuser techniques every subframe without needing more RRC signaling.

Downlink references signals are keys to MIMO functionality. Reference signals are used widely within 3GPP releases. The UE measures the downlink channel using measurement reference signals, prepares recommendations for the eNodeB, and sends back the following recommendations in channel state information (CSI).

- **Rank Indicator (RI):** Recommended number of layers for SU-MIMO transmission.
- **Precoding matrix indicator (PMI):** Index into a codebook of matrices used at the eNodeB.
- **Channel Quality Indicator (CQI):** Index to table of recommended modulation and coding schemes.

LTE Release 8 uses the common reference signal (CRS) for data demodulation. LTE Release 10 adds the CSI-RS reference signal. These signals are sent on dynamically assigned subframes and resource blocks. The measurement interval can be 5 to 80 ms, depending on the mobile's speed. This reduces overhead by not using resource blocks for channel measurements unless they are needed.

LTE-Advanced uplink MIMO supports multiple antennas. In Release 8, MU-MIMO was supported, because it only required a single antenna on a mobile. This allowed the eNodeB to simultaneously send signals to multiple mobiles. With multiple antenna support on the UE in LTE-Advanced, SU-MIMO is also supported, so that up to four transmission layers are supported between a single UE and an eNodeB. By also adding the ability to use two component carriers on the uplink, the uplink maximum throughput was increased by a factor of 8 from 75 to 600 Mbps.

Relaying

Another key element of an LTE-Advanced cellular network is the use of **Relay Nodes (RNs)**. As with any cellular system, an LTE-Advanced base station experiences reduced data rates near the edge of its cell, due to lower signal levels and higher interference levels. Rather than use smaller cells, it is more efficient to use small relay nodes, which have a reduced radius of operation compared to an eNodeB, distributed around the periphery of the cell. A UE near an RN communicates with the RN, which in turn communicates with the eNodeB.

An RN is not simply a signal repeater that amplifies a received signal, amplifying both the signal and noise. Instead the RN receives, demodulates, and decodes the data and applies error correction as needed, and then transmits a new signal to the base station, referred to in this context as a **donor eNodeB**. See Figure 14.15. The RN functions as a base station with respect to its communication with the UE and as a UE with respect to its communication with the eNodeB.

- The eNodeB → RN transmissions and RN → eNodeB transmissions are carried out in the DL frequency band and UL frequency band, respectively, for FDD systems.
- The eNodeB → RN transmissions and RN → eNodeB transmissions are carried out in the DL subframes of the eNodeB and RN and UL subframes of the eNodeB and RN, respectively, for TDD systems.

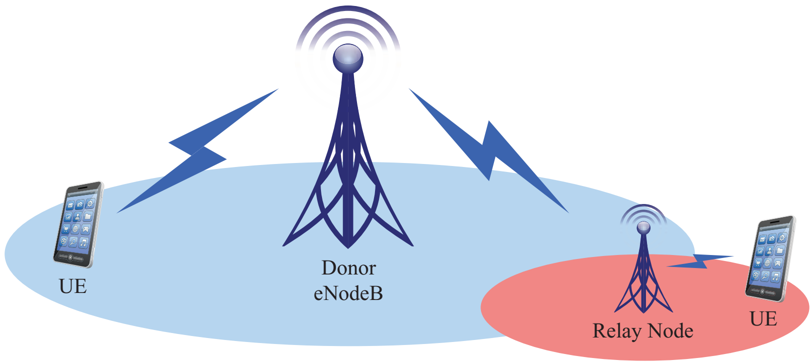


Figure 14.15 Relay Nodes

RNs can use out-of-band communication using microwave links or inband communication. Inband communication means that the RN–eNodeB interface uses the same carrier frequency as the RN–UE interface. This creates an interference issue that can be described as follows. If the RN receives from the eNodeB and transmits to the UE at the same time, it is both transmitting and receiving on the downlink channel. The RN's transmission will have a much greater signal strength than the DL signal arriving from the eNodeB, making it very difficult to recover the incoming DL signal. The same problem occurs in the uplink direction. To overcome this difficulty frequency resources are partitioned as follows:

- eNodeB → RN and RN → UE links are time division multiplexed in a single frequency band and only one is active at any one time.
- RN → eNodeB and UE → RN links are time division multiplexed in a single frequency band and only one is active at any one time.

The relay's non-access stratum in controlled by the MME, and its access stratum is controlled by the eNodeB. In this sense, the relay acts as a mobile to the eNodeB and EPC. But it also acts as a base station to a mobile node. It handles the access stratum for the mobile and can interact with other base stations using the X2 interface for handovers.

Release 10 assumes relays to be stationary, so they cannot be handed over to other eNodeBs. Multihop **relaying** is also not supported.

Heterogeneous Networks

Industry has responded to the increasing data transmission demands from smartphones, tablets, and similar devices by the introduction of 3G and now 4G cellular networks. As demand continues to increase, it becomes increasingly difficult to satisfy this requirement, particularly in densely populated areas and remote rural areas. An essential component of the 4G strategy for satisfying demand is the use of **picocells** and femtocells.

A **femtocell** is a low-power, short range, self-contained base station. Initially used to describe consumer units intended for residential homes, the term has expanded to encompass higher capacity units for enterprise, rural, and metropolitan areas. Key attributes include IP backhaul, self-optimization, low power consumption, and ease of deployment. Femtocells are by far the most numerous types of small cells.

The term *small cell* is an umbrella term for low-powered radio access nodes that operate in licensed and unlicensed spectrum that have a range of 10 m to several hundred meters indoors or outdoors. These contrast with a typical mobile **macrocell**, which might have a range of up to several tens of kilometers. Macrocells would best be used for highly mobile users, and small cells for low speed or stationary users. Femtocells now outnumber macrocells, and the proportion of femtocells in 4G networks is expected to rise dramatically. Deployment of these cells is called **network densification** and the result is a heterogeneous network of large and small cells called a ***HetNet***.

Figure 14.16 shows the typical elements in a network that uses femtocells. The femtocell access point is a small base station, much like a Wi-Fi hotspot base station, placed in a residential, business, or public setting. It operates in the same frequency band and with the same protocols as an ordinary cellular network base station. Thus, a 4G smartphone or tablet can connect wirelessly with a 4G femtocell with no change. The femtocell connects to the Internet, typically over a DSL, fiber, or cable landline. Packetized traffic to and from the femtocell connects to the cellular operator's core packet network via a femtocell gateway.

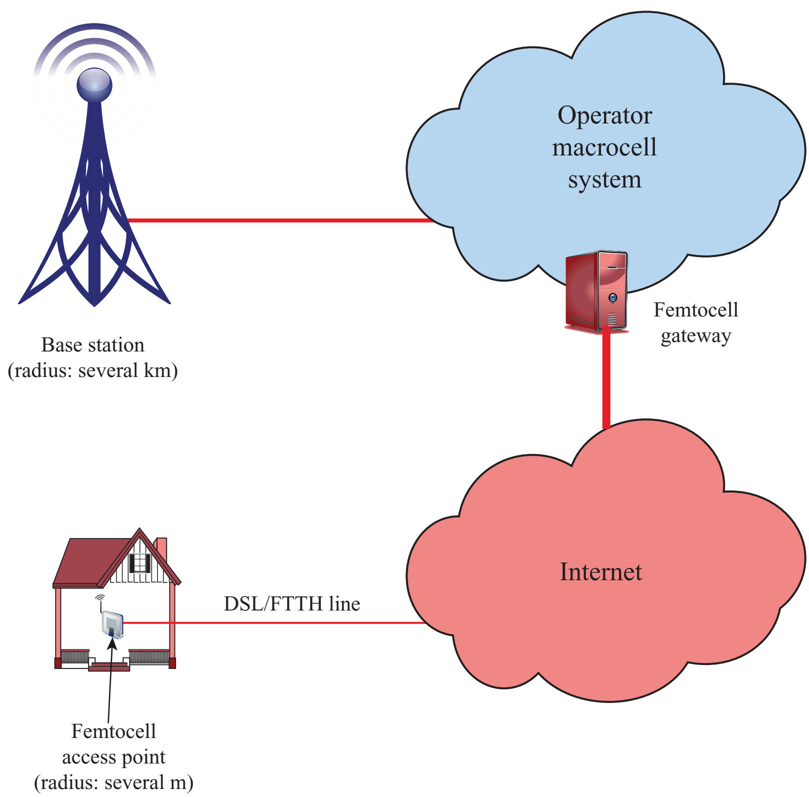


Figure 14.16 The Role of Femtocells

Coordinated Multipoint Transmission and Reception

Interference coordination between cells has been a topic for several LTE releases. Release 8 specified Inter-cell Interference Coordination (ICIC) as discussed in Section 14.4. LTE is designed for all cells to reuse all frequencies, but this can cause interference at cell edges. The X2 interface was enhanced so eNodeBs could coordinate their use of resource blocks. In one approach, cells could avoid using the same resource blocks, but this would reduce overall spectral efficiency. Cells could also reuse some RBs for UEs near the base stations, but avoid using the same RBs for mobiles near the cell edges. This could also be enhanced by also reducing power levels for mobiles near base stations. Release 8 introduced the RNTP indicator, HII, and OI for these purposes.

Interference between small cells and macrocells can be significant. Release 10 provided some solutions, called enhanced ICIC. On one hand, a deployment may expect that a mobile will connect with a nearby small cell, but the macrocell signal could be stronger and the mobile would attempt to connect to the macrocell instead. This effectively unnecessarily reduces the range of the small cell. Conversely, a small cell may implement a closed subscriber group. For example, a femtocell may be deployed in a business and only the employees are authorized to connect to it. An outside mobile would need to connect to a macrocell instead, but would be unable to do so because of the femtocell interference. This would effectively create a hole in the macrocell coverage area. As solution, LTE-Advanced introduces the *almost blank subframe*. Each cell has subframes where minimal information is transmitted (i.e., they are almost blank) so the other cell can be heard with reduced interference. These subframes are not reused between the cells, which means spectral efficiency is reduced, but this coexistence function allows both cells to operate effectively.

Release 11 implemented **Coordinated Multipoint Transmission and Reception (CoMP)**. In CoMP, antennas cooperate to increase power to mobiles at cell edges and reduce interference at cell edges. Antennas may come from those at the same eNodeB, those at separate eNodeBs, those between macro cells and small cells, and those between a cell and a **remote radio head (RRH)**, which is a simple set of antennas deployed away from a base station. CoMP may use techniques such as *coordinated scheduling/coordinated beamforming* (CS/CB) that steers antenna beam nulls and mainlobes, *joint transmission* (JT) that transmits data simultaneously from multiple transmission points to the same UE, and *dynamic point selection* (DPS) that transmits from multiple transmission points but only one at a time.

Release 11 supports these techniques (actually only a noncoherent form of JT) and defines the *CoMP measurement set* as a set of nodes participating in these techniques. The main LTE enhancement is to provide new channel state information to support CoMP. The channel state information provides the set of resource elements to be used for measurement of the signal power (as came from Release 10) and also an interference measurement configuration to measure interference, which is new to Release 11. Release 11 does not add RRC measurements to help determine eNodeBs for the measurement set, does not support coherent JT, and does not change S1 and X2 interfaces. Therefore, it is best to implement CoMP between antennas on the same eNodeB or between an eNodeB and remote radio head, because an RRH is under direct control of an eNodeB.

Other Enhancements

The following other enhancements are provided in LTE-Advanced Releases 10 and 11, and are also likely to be issued in Release 12.

- Traffic offload techniques to divert traffic onto non-LTE networks.
- Enhanced Physical Downlink Control Channel to enable adjustable capacity and interference coordination.
- Enhancements for machine-type communications–overload control, device triggering so an application service can call devices into action, a new device identity known as the external identifier to tackle number shortages, proximity services for device-to-device communications, and enhancements for machine-type data and mobile data.
- Support for dynamic adaptation of TDD configuration so traffic fluctuations can be accommodated, which are especially common in small cells.
- Release 12 also conducted studies for future requirements on enhancements to small cells and heterogeneous networks, such as higher order modulation like 256-QAM, a new mobile-specific reference signal, dual connectivity (for example, simultaneous connection with a macrocell and a picocell), and a lean carrier for use as a secondary cell.
- Also in Release 12, studies were conducted on two-dimensional arrays that could create beams on a horizontal plane and also at different elevations for user-specific elevation beamforming. This would be supported by ***massive MIMO*** or ***full dimension MIMO*** that is created by a two-dimensional array with many more antenna elements than previous deployments.

In addition to these enhancements, the cellular industry's main trade association, the **GSM Association**, has defined profiles and services for what is known as **Voice over LTE (VoLTE)**. The GSM Association documents provide additional specifications for issues that 3GPP specifications left as implementation options. The GSM Association also specifies services beyond voice, such as video calls, instant messaging, chat, and file transfer in what is known as the **Rich Communication Services (RCS)**. The IP Multimedia Subsystem (IMS) is used to control the delivery of VoIP streams. IMS is not part of LTE; it is a separate network, the same way the Internet is a separate network. IMS is mainly concerned with signaling. It provides a higher layer capability to use LTE for voice transport.

14.8 RECOMMENDED READING

[GHOS10] provides a thorough background to LTE. Worthwhile introductions to LTE-Advanced include [FREN13], [BAKE12], [PARK11]. [DAEW12], [LING12], and [IWAM10] provide introductions to CoMP, MIMO, and carrier aggregation in LTE-Advanced. [COX14] provides an excellent detailed coverage of LTE-Advanced and Releases 11 and 12.

BAKE12 Baker, M. "From LTE-Advanced to the Future." *IEEE Communications Magazine,* February 2012.

COX14 Cox, C. *An Introduction to LTE: LTE, LTE-Advanced, SAE, VoLTE, and 4G Communications,* Second Edition. United Kingdom: John Wiley & Sons, Ltd, 2014.

DAEW12 Daewon L., et al. "Coordinated multipoint transmission and reception in LTE-advanced: deployment scenarios and operational challenges." *Communications Magazine, IEEE,* vol. 50, no. 2, pp. 148, 155, February 2012.

FREN13 Frenzel, L. "An Introduction to LTE-Advanced: The Real 4G." *Electronic Design,* February 2013.

GHOS10 Ghosh, A., et al. "LTE-Advanced: Next-Generation Wireless Broadband Technology." *IEEE Wireless Communications,* June 2010.

IWAM10 Iwamura, M., et al. "Carrier Aggregation Framework in 3GPP LTE-Advanced." *IEEE Communications Magazine,* August 2010.

LING12 Lingjia Liu; Runhua Chen; Geirhofer, S.; Sayana, K.; Zhihua Shi; Yongxing Zhou. "Downlink MIMO in LTE-advanced: SU-MIMO vs. MU-MIMO." *Communications Magazine, IEEE,* vol. 50, no. 2, pp. 140, 147, February 2012.

PARK11 Parkvall, S.; Furuskar, A.; and Dahlman, E. "Evolution of LTE toward IMT-Advanced." *IEEE Communications Magazine,* February 2011.

14.9 KEY TERMS, REVIEW QUESTIONS, AND PROBLEMS

Key Terms

access stratum	femtocell	Packet Data Network Gateway (PGW)
base station	fourth-generation (4G) network	picocells
bearers	frequency division duplex (FDD)	QoS class identifier (QCI)
carrier aggregation (CA)	frequency reuse	radio link control
coordinated multipoint transmission and reception (CoMP)	GSM Association	radio resource control (RRC)
dedicated bearer	guaranteed bit rate (GBR) bearers	relay nodes (RNs)
default bearer	heterogeneous networks (HetNets)	relaying
donor eNodeB	home subscriber server (HSS)	remote radio head (RRH)
EPS mobility management (EMM)	Long Term Evolution (LTE)	resource block
EPS session management (ESM)	LTE-Advanced	resource elements
evolved NodeB (eNodeB)	macrocells	reuse factor
evolved packet core (EPC)	mobility management entity (MME)	rich communication services (RCS)
evolved packet system (EPS)	network densification	service data flows (SDFs)
evolved UMTS terrestrial radio access (E-UTRA)	non-guaranteed bit rate bearers	S1 interface
evolved UMTS terrestrial radio access network (E-UTRAN)	packet data convergence protocol (PDCP)	Serving Gateway (SGW)
		Time division duplex (TDD)
		user equipment (UE)
		voice over LTE (VoLTE)
		X2 interface

Review Questions

14.1 What are the major reasons for 4G?

14.2 Which 3GPP releases are related to LTE-Advanced?

14.3 What are the main components of the Evolved Packet Core (EPC)? What are their main functions?

14.4 What are the roles of the RRC, PDCP, and RLC protocols?

14.5 What are logical, transport, and physical channels?

14.6 What two types of cyclic prefixes are supported by LTE?

14.7 What is the difference between the LTE FDD and TDD frame structures?

14.8 What is a resource block? What does it consist of?

14.9 What types of modulation are supported by LTE?

14.10 List and describe the steps in the power-on procedure.

14.11 What is carrier aggregation? What are the different types of carrier aggregation?

14.12 How does LTE-Advanced enhance MIMO?

14.13 What is relaying?

14.14 What is a femtocell?

14.15 What is the difference between eICIC and CoMP?

Problems

14.1 For which generation of cellular wireless network was a >5 Mbps data rate achieved?

14.2 According to Table 14.2, if LTE-Advanced provides 1 Gbps for a 100 MHz channel whereas LTE provides 100 Mbps over a 20 MHz channel, by what factor has the channel efficiency (bps/Hz) improved?

14.3 Table 14.2 shows how LTE-Advanced can use 8×8 MIMO, or 8 parallel streams. By what factor is per-stream bandwidth efficiency higher for LTE-Advanced?

14.4 By what factor does Table 14.2 show that the uplink has lower channel efficiency than the downlink?

14.5 What would be the expected packet delay budget when a user is watching a movie from an online video service?

14.6 Why do conversational forms of voice and video have smaller packet delay budgets in LTE?

14.7 From Table 14.5, what are the maximum and minimum proportions of the subframe used for uplink traffic?

14.8 From Table 14.6, for 15 MHz transmission bandwidth, show how to compute the total occupied bandwidth of 13.5 MHz from the values in the table.

14.9 From Tables 14.6 and 14.7, show the expected data rate to be achieved for CQI 9 on a 15 MHz channel.

14.10 Based on Figure 14.11, show how 7 OFDM symbols fit within a slot time of 0.5 ms for the normal CP and only 6 OFDM symbols for the extended CP.

14.11 Based on Table 14.7, if a user is experiencing a CQI of index 6, how many resource blocks should be assigned if the user requires at least 3.0 Mbps?

14.12 From Problem 14.11, if the CQI index improves to 13, then how many resource blocks should be assigned?

14.13 Given LTE system parameters, what was likely assumed in the system design concerning the coherence time (see Chapter 6) of the environments in which LTE was designed to operate?