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Fundamentals of LTE

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Jeffrey G. Andrews • Rias Muhamed

Foreword by Rajiv Laroia

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Foreword

With the deployment of LTE, the wireless revolution will achieve an important milestone. For the first time, a wide-area wireless network will be universally deployed that has been primarily designed for IP-centric broadband data (rather than voice) from the very beginning. LTE also is rapidly becoming the dominant global standard for fourth generation cellular networks with nearly all the major cellular players behind it and working toward its success.

Having been personally involved in designing, developing, and promoting one of the first OFDM-based cellular systems since the late 1990s, back when such an approach was considered slightly eccentric, LTE's success is personally very satisfying for me to see. As with any standard, which by political necessity is "designed by committee," the LTE specification is not without flaws and there is room for progress and future evolution. The system architecture is not yet a fully flat IP platform, for example, and some interference issues are not fully addressed. But there can be no doubt that LTE is a giant step in the right direction and a necessary step to meet the anticipated growth in consumer and business mobile broadband applications and services. LTE provides a credible platform for wireless broadband access based on OFDMA, multiantenna technologies, and other cutting-edge techniques that provide improvements in spectral efficiency and significantly lower the cost of delivering mobile broadband. I expect the future evolution of LTE to continually improve the standard.

Fundamentals of LTE is an excellent introduction to the LTE standard and the various technologies that it incorporates, like OFDMA, SC-FDMA, and multiantenna transmission and reception. It is exceptionally well written, easy to understand, and concisely but completely covers the key aspects of the standard. Because of its diverse author team—including both LTE systems engineers as well as leading academic researchers who have worked extensively on the core underlying technologies—this book will be of use to a wide set of potential readers. I recommend it to folks in the industry who are involved with the development of LTE-based technology and products, as well as to students and faculty in academia who wish to understand the standard and participate in incorporating more advanced techniques into the future versions of the specification. The book also describes some of the "weak points" in the current specification of the standard. This helps ensure that these issues will be fixed as the specification evolves.

I hope you will enjoy reading the book and benefit from it, and am confident you will.

Rajiv Laroia
Senior vice president, Qualcomm Flarion Technologies

Preface

The Long-Term Evolution (LTE) is the next evolutionary step beyond 3G for mobile wireless communication. LTE brings together many technological innovations from different areas of research such as digital signal processing, Internet protocols, network architecture, and security, and is poised to dramatically change the way we use the worldwide mobile network in the future. Unlike 3G, LTE uses a clean-slate design approach for all the components of the network including the radio access network, the transport network, and the core network. This design approach, along with its built-in flexibility, allows LTE to be the first truly global wireless standard that can be deployed in a variety of spectrum and operating scenarios, and support a wide range of wireless applications. A large number of service providers around the world have already announced LTE as their preferred next generation technology.

Fundamentals of LTE is a comprehensive tutorial on the most innovative cellular standard since CDMA emerged in the early 1990s. The impending worldwide deployment of LTE (Long-Term Evolution, often called 4G cellular) will revolutionize the cellular networks by going to much larger bandwidths, data rates, and an all-IP framework. *Fundamentals of LTE* is the only book to provide an accessible but complete tutorial on the key enabling technologies behind LTE, such as OFDM, OFDMA, SC-FDMA, and MIMO, as well as provide a step-by-step breakdown of all the key aspects of the standard from the physical layer through the network stack. The book begins with a historical overview and the reasons for the radical departure from conventional voice-centric cellular systems that LTE represents. Following this, four tutorial chapters explain the essential underpinnings of LTE, which could also be used as the basis for an entry-level university course. Finally, five chapters on the LTE standard specifically attempt to illuminate its key aspects, explaining both how LTE works, and why certain choices were made by the LTE standards body. This collaboration between UT Austin and AT&T has resulted in a uniquely accessible and comprehensive book on LTE.

Chapter 1 provides an overview and history of the cellular wireless technologies, starting from first-generation systems such as AMPS to fourth-generation technologies such as LTE and WiMAX. This chapter provides a historical account of the mobile wireless networks and illustrates the key technological breakthroughs and market forces that drove the evolution of the mobile wireless network over the past two decades. This chapter also provides an executive summary of the LTE and some of its key technical enablers.

The balance of the book is organized into two parts, as noted. Part I consists of four tutorial chapters (Chapters 2–5) on the essential wireless networking and communications technologies underpinning LTE. Chapter 2 provides a tutorial introduction to broadband wireless channels and systems, and demonstrates the challenges inherent to the development of a broadband wireless system such as LTE. Chapter 3 provides a comprehensive tutorial on multicarrier modulation, detailing how it works in both theory and practice. This chapter emphasizes a practical understanding of OFDM system design, and discusses implementation issues, in particular the peak-to-average power ratio. An overview of single-carrier frequency domain equalization (SC-FDE), which overcomes the peak-to-average problem, is also provided. Chapter 4 extends Chapter 3 to provide an overview on the frequency domain multiple access techniques adopted in LTE: OFDMA in the downlink and SC-FDMA in the uplink. Resource allocation to the users, especially relevant opportunistic scheduling approaches, is discussed, along with important implementation issues pertinent to LTE. Chapter 5 provides a rigorous tutorial on multiple antenna techniques, covering techniques such as spatial diversity, interference cancellation, spatial multiplexing, and multiuser and networked MIMO. The inherent tradeoffs between different techniques and practical considerations for the deployment of MIMO in LTE are distinguishing features of this chapter.

Part II of the book, consisting of Chapters 6–10, provides a detailed description of the LTE standard with particular emphasis on the air-interface protocol. We begin this part in Chapter 6 with an introduction to the basic structure of the air-interface protocol and the channel structure utilized by LTE at different layers. This chapter also provides an overview of the physical layer and various OFDMA-related aspects of LTE. Chapters 7 and 8 provide a thorough description of the physical and MAC layer processing (at the transport channel level) for downlink (DL) and uplink (UL), respectively. Features such as channel encoding, modulation mapping, Hybrid-ARQ (H-ARQ), and multiantenna processing for the different DL and UL channels are discussed in detail. In Chapter 9 we discuss the various feedback mechanisms that are essential components of LTE and are needed to enable various features such as channel aware scheduling, closed-loop and open-loop multiantenna processing, adaptive modulation and coding, etc. These concepts are critical to a complete understanding of LTE and its operation. In this chapter we also discuss various MAC layer concepts related to scheduling, QoS, ARQ, etc. Finally, in Chapter 10 we discuss the higher layers of the LTE protocol stack, such as RLC, PDCP, and RRM, and the role of these in the overall operation of an LTE system. In this chapter we also provide an in-depth discussion on the mobility and handoff procedures in LTE from a radio access network point of view.

Chapter 6

Overview and Channel Structure of LTE

In Part I, we discussed the inherent challenges and associated technical solutions in designing a broadband wireless network. From here onward, we describe the technical details of the LTE specifications. As a starting point, in this chapter we provide an overview of the LTE radio interface. The 3rd Generation Partnership Project (3GPP) defines a separable network structure, that is, it divides the whole network into a radio access network (RAN) and a core network (CN), which makes it feasible to evolve each part independently. The *Long-Term Evolution (LTE)* project in 3GPP focuses on enhancing the UMTS Terrestrial Radio Access (UTRA)—the 3G RAN developed within 3GPP, and on optimizing 3GPP's overall radio access architecture. Another parallel project in 3GPP is the *Evolved Packet Core (EPC)*, which focuses on the CN evolution with a flatter all-IP, packet-based architecture. The complete packet system consisting of LTE and EPC is called the *Evolved Packet System (EPS)*. This book focuses on LTE, while EPC is discussed only when necessary. LTE is also referred to as *Evolved UMTS Terrestrial Radio Access (E-UTRA)*, and the RAN of LTE is also referred to as *Evolved UMTS Terrestrial Radio Access Network (E-UTRAN)*.

The radio interface of a wireless network is the interface between the mobile terminal and the base station, and thus in the case of LTE it is located between the RAN–E-UTRAN and the user equipment (UE, the name for the mobile terminal in 3GPP). Compared to the UMTS Terrestrial Radio Access Network (UTRAN) for 3G systems, which has two logical entities—the Node-B (the radio base station) and the radio network controller (RNC)—the E-UTRAN network architecture is simpler and flatter. It is composed of only one logical node—the evolved Node-B (eNode-B). The RAN architectures of UTRAN and E-UTRAN are shown in Figure 6.1. Compared to the traditional Node-B, the eNode-B supports additional features, such as radio resource control, admission control, and mobility management, which were originally contained in the RNC. This simpler structure simplifies the network operation and allows for higher throughput and lower latency over the radio interface.

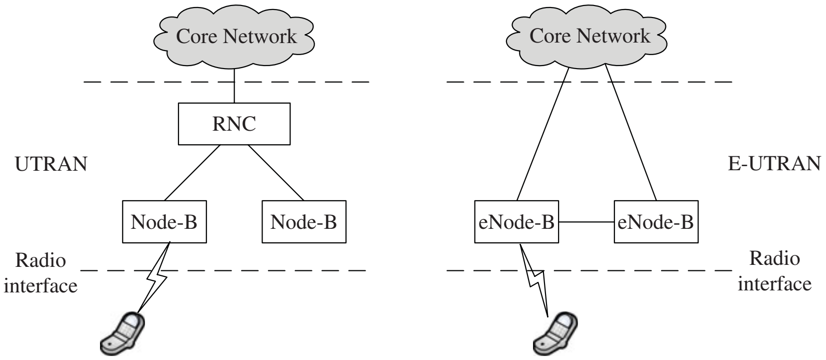

Figure 6.1 Radio interface architectures of UTRAN and E-UTRAN.

The LTE radio interface aims for a *long-term evolution*, so it is designed with a clean slate approach as opposed to High-Speed Packet Access (HSPA), which was designed as an add-on to UMTS in order to increase throughput of packet switched services. HSPA is a collection of *High-Speed Downlink Packet Access (HSDPA)* and *High-Speed Uplink Packet Access (HSUPA)*. The clean slate approach allows for a completely different air interface, which means that advanced techniques, including *Orthogonal Frequency Division Multiplexing (OFDM)* and *multiantenna transmission and reception (MIMO)*, could be included from the start of the standardization of LTE. For multiple access, it moves away from *Code Division Multiple Access (CDMA)* and instead uses *Orthogonal Frequency Division Multiple Access (OFDMA)* in the downlink and *Single-Carrier Frequency Division Multiple Access (SC-FDMA)* in the uplink. All these techniques were described in detail in Part I, so in Part II we assume a basic knowledge of a wireless system, antenna diversity, OFDMA, and other topics covered in Part I.

In this chapter, we provide an introduction to the LTE radio interface, and describe its hierarchical channel structure. First, an overview of the LTE standard is provided, including design principles, the network architecture, and radio interface protocols. We then describe the purpose of each channel type defined in LTE and the mapping between channels at various protocol layers. Next, the downlink OFDMA and uplink SC-FDMA aspects of the air interface are described, including frame structures, physical resource blocks, resource allocation, and the supported MIMO modes. This chapter serves as the foundation for understanding the physical layer procedures and higher layer protocols of LTE that are described in the chapters to follow.

6.1 Introduction to LTE

As mentioned previously, LTE is the next step in the evolution of mobile cellular systems and was standardized as part of the 3GPP Release 8 specifications. Unlike 2G and 3G cellular systems[1] that were designed mainly with voice services in mind, LTE was

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[1] Evolution of different 3GPP standards, including GPRS, UMTS, and HSPA, was discussed in Chapter 1.

designed primarily for high-speed data services, which is why LTE is a packet-switched network from end to end and has no support for circuit-switched services. However, the low latency of LTE and its sophisticated quality of service (QoS) architecture allow a network to emulate a circuit-switched connection on top of the packet-switched framework of LTE.

6.1.1 Design Principles

The LTE standard was designed as a completely new standard, with new numbering and new documentation, and it is not built on the previous versions of 3GPP standards. Earlier elements were brought in only if there was a compelling reason for them to exist in the new standard. The basic design principles that were agreed upon and followed in 3GPP while designing the LTE specifications include:[2]

- **Network Architecture**: Unlike 3G networks, LTE was designed to support packet-switched traffic with support for various QoS classes of services. Previous generations of networks such as UMTS/HSPA and 1xRTT/EvDO also support packet-switched traffic but this was achieved by subsequent add-ons to the initial version of the standards. For example, HSPA, which is a packet-switched protocol (packet-switched over the air), was built on top of the Release 99 UMTS network and as a result carried some of the unnecessary burdens of a circuit-switched network. LTE is different in the sense that it is a clean slate design and supports packet switching for high data rate services from the start. The LTE radio access network, E-UTRAN, was designed to have the minimum number of interfaces (i.e., the minimum number of network elements) while still being able to provide efficient packet-switched transport for traffic belonging to all the QoS classes such as conversational, streaming, real-time, non-real-time, and background classes.

- **Data Rate and Latency**: The design target for downlink and uplink peak data rates for LTE are 100 Mbps and 50 Mbps, respectively, when operating at the 20MHz frequency division duplex (FDD) channel size. The user-plane latency is defined in terms of the time it takes to transmit a small IP packet from the UE to the edge node of the radio access network or vice versa measured on the IP layer. The target for one-way latency in the user plane is 5 ms in an unloaded network, that is, if only a single UE is present in the cell. For the control-plane latency, the transition time from a camped state to an active state is less than 100 ms, while the transition time between a dormant state and an active state should be less than 50 ms.

- **Performance Requirements**: The target performance requirements for LTE are specified in terms of spectrum efficiency, mobility, and coverage, and they are in general expressed relative to the 3GPP Release 6 HSPA.
  - **Spectrum Efficiency** The average downlink user data rate and spectrum efficiency target is three to four times that of the baseline HSDPA network. Similarly, in the uplink the average user data rate and spectrum efficiency

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[2] See Section 1.2.4 for a comparison of different beyond-3G systems, including HSPA+, WiMAX, and LTE.

  target is two to three times that of the baseline HSUPA network. The cell edge throughput, measured as the 5th percentile throughput, should be two to three times that of the baseline HSDPA and HSUPA.
  - **Mobility** The mobility requirement for LTE is to be able to support handoff/mobility at different terminal speeds. Maximum performance is expected for the lower terminal speeds of 0 to 15 km/hr, with minor degradation in performance at higher mobile speeds up to 120 km/hr. LTE is also expected to be able to sustain a connection for terminal speeds up to 350 km/hr but with significant degradation in the system performance.
  - **Coverage** For the cell coverage, the above performance targets should be met up to 5 km. For cell ranges up to 30 km, a slight degradation of the user throughput is tolerated and a more significant degradation for spectrum efficiency is acceptable, but the mobility requirements should be met. Cell ranges up to 100 km should not be precluded by the specifications.
  - **MBMS Service** LTE should also provide enhanced support for the Multimedia Broadcast and Multicast Service (MBMS) compared to UTRA operation.

- **Radio Resource Management**: The radio resource management requirements cover various aspects such as enhanced support for end-to-end QoS, efficient support for transmission of higher layers, and support for load sharing/balancing and policy management/enforcement across different radio access technologies.

- **Deployment Scenario and Co-existence with 3G**: At a high level, LTE shall support the following two deployment scenarios:
  - Standalone deployment scenario, where the operator deploys LTE either with no previous network deployed in the area or with no requirement for interworking with the existing UTRAN/GERAN (GSM EDGE radio access network) networks.
  - Integrating with existing UTRAN and/or GERAN deployment scenario, where the operator already has either a UTRAN and/or a GERAN network deployed with full or partial coverage in the same geographical area.

- **Flexibility of Spectrum and Deployment**: In order to become a truly global standard, LTE was designed to be operable under a wide variety of spectrum scenarios, including its ability to coexist and share spectrum with existing 3G technologies. Service providers in different geographical regions often have different spectrums in terms of the carrier frequency and total available bandwidth, which is why LTE was designed to have a scalable bandwidth from 1.4MHz to 20MHz. In order to accommodate flexible duplexing options, LTE was designed to operate in both frequency division duplex (FDD) and time division duplex (TDD) modes.

- **Interoperability with 3G and 2G Networks**: Multimode LTE terminals, which support UTRAN and/or GERAN operation, should be able to support measurement of, and handover from and to, both 3GPP UTRAN and 3GPP GERAN systems with acceptable terminal complexity and network performance.

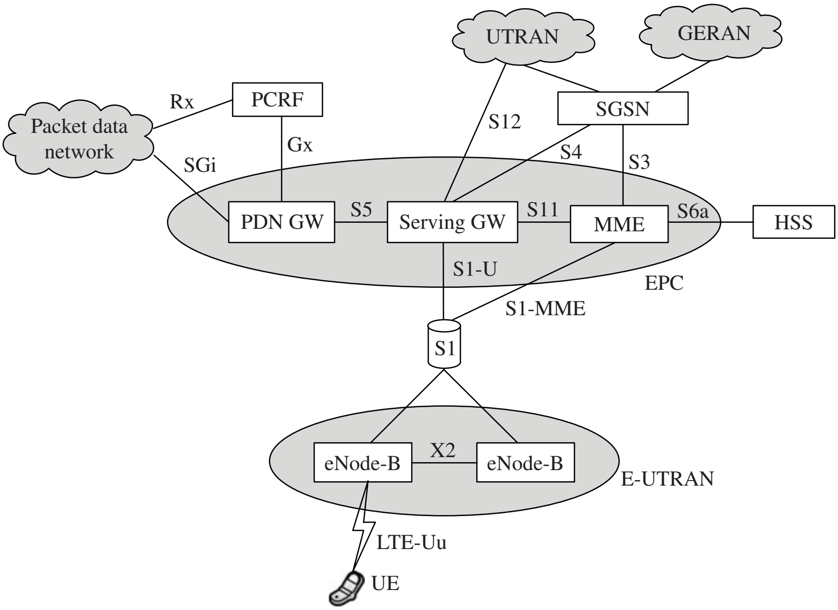

Figure 6.2 LTE end-to-end network architecture.

6.1.2 Network Architecture

Figure 6.2 shows the end-to-end network architecture of LTE and the various components of the network. The entire network is composed of the radio access network (E-UTRAN) and the core network (EPC), both of which have been defined as new components of the end-to-end network in Release 8 of the 3GPP specifications. In this sense, LTE is different from UMTS since UMTS defined a new radio access network but used the same core network as the previous-generation Enhanced GPRS (EDGE) network. This obviously has some implications for the service providers who are upgrading from a UMTS network to LTE. The main components of the E-UTRAN and EPC are

- **UE:** The mobile terminal.
- **eNode-B:** The eNode-B (also called the base station) terminates the air interface protocol and is the first point of contact for the UE. As already shown in Figure 6.1, the eNode-B is the only logical node in the E-UTRAN, so it includes some functions previously defined in the RNC of the UTRAN, such as radio bearer management, uplink and downlink dynamic radio resource management and data packet scheduling, and mobility management.
- **Mobility Management Entity (MME):** MME is similar in function to the control plane of legacy Serving GPRS Support Node (SGSN). It manages mobility aspects in 3GPP access such as gateway selection and tracking area list management.

- **Serving Gateway (Serving GW):** The Serving GW terminates the interface toward E-UTRAN, and routes data packets between E-UTRAN and EPC. In addition, it is the local mobility anchor point for inter-eNode-B handovers and also provides an anchor for inter-3GPP mobility. Other responsibilities include lawful intercept, charging, and some policy enforcement. The Serving GW and the MME may be implemented in one physical node or separate physical nodes.

- **Packet Data Network Gateway (PDN GW):** The PDN GW terminates the SGi interface toward the Packet Data Network (PDN). It routes data packets between the EPC and the external PDN, and is the key node for policy enforcement and charging data collection. It also provides the anchor point for mobility with non-3GPP accesses. The external PDN can be any kind of IP network as well as the IP Multimedia Subsystem (IMS) domain. The PDN GW and the Serving GW may be implemented in one physical node or separated physical nodes.

- **S1 Interface:** The S1 interface is the interface that separates the E-UTRAN and the EPC. It is split into two parts: the S1-U, which carries traffic data between the eNode-B and the Serving GW, and the S1-MME, which is a signaling-only interface between the eNode-B and the MME.

- **X2 Interface:** The X2 interface is the interface between eNode-Bs, consisting of two parts: the X2-C is the control plane interface between eNode-Bs, while the X2-U is the user plane interface between eNode-Bs. It is assumed that there always exists an X2 interface between eNode-Bs that need to communicate with each other, for example, for support of handover.

The specific functions supported by each component and the details about reference points (S1-MME, S1-U, S3, etc.) can be found in [1]. For other nodes in Figure 6.2, the Policy and Charging Rules Function (PCRF) is for policy and charging control, the Home Subscriber Server (HSS) is responsible for the service authorization and user authentication, and the Serving GPRS Support Node (SGSN) is for controlling packet sessions and managing the mobility of the UE for GPRS networks. The topics in this book mainly focus on the E-UTRAN and the LTE radio interface.

6.1.3 Radio Interface Protocols

As in other communication standards, the LTE radio interface is designed based on a layered protocol stack, which can be divided into control plane and user plane protocol stacks and is shown in Figure 6.3. The packet flow in the user plane is shown in Figure 6.4. The LTE radio interface protocol is composed of the following layers:

- **Radio Resource Control (RRC):** The RRC layer performs the control plane functions including paging, maintenance and release of an RRC connection-security handling-mobility management, and QoS management.

- **Packet Data Convergence Protocol (PDCP):** The main functions of the PDCP sublayer include IP packet header compression and decompression based

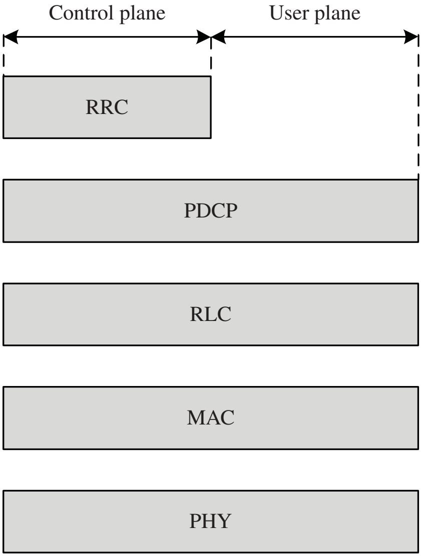

Figure 6.3 The LTE radio interface protocol stack.

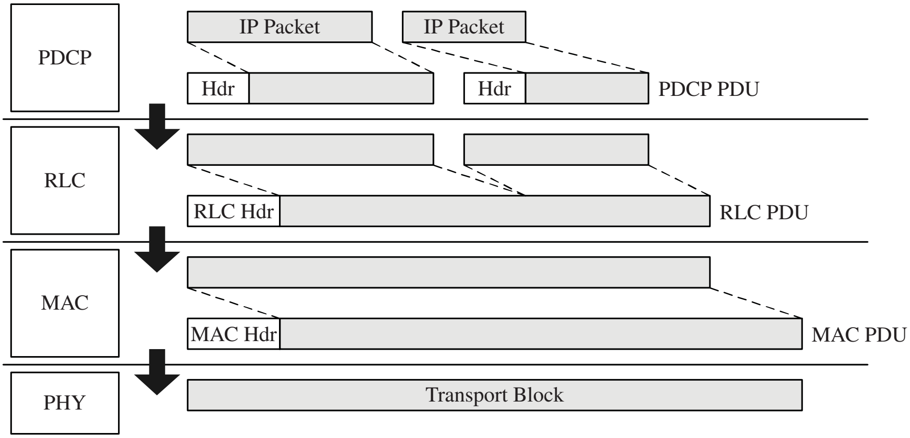

Figure 6.4 The packet flow in the user plane.

on the RObust Header Compression (ROHC) protocol, ciphering of data and signaling, and integrity protection for signaling. There is only one PDCP entity at the eNode-B and the UE per bearer.[3]

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[3] A bearer is an IP packet flow with a defined QoS between the PDN GW and the UE. It will be discussed in more detail in Chapter 10.

- **Radio Link Control (RLC):** The main functions of the RLC sublayer are segmentation and concatenation of data units, error correction through the Automatic Repeat reQuest (ARQ) protocol, and in-sequence delivery of packets to the higher layers. It operates in three modes:
  - **The Transparent Mode (TM):** The TM mode is the simplest one, without RLC header addition, data segmentation, or concatenation, and it is used for specific purposes such as random access.
  - **The Unacknowledged Mode (UM):** The UM mode allows the detection of packet loss and provides packet reordering and reassembly, but does not require retransmission of the missing protocol data units (PDUs).
  - **The Acknowledged Mode (AM):** The AM mode is the most complex one, and it is configured to request retransmission of the missing PDUs in addition to the features supported by the UM mode.

  There is only one RLC entity at the eNode-B and the UE per bearer.

- **Medium Access Control (MAC):** The main functions of the MAC sublayer include error correction through the Hybrid-ARQ (H-ARQ) mechanism, mapping between logical channels and transport channels, multiplexing/demultiplexing of RLC PDUs on to transport blocks, priority handling between logical channels of one UE, and priority handling between UEs by means of dynamic scheduling. The MAC sublayer is also responsible for transport format selection of scheduled UEs, which includes selection of modulation format, code rate, MIMO rank, and power level. There is only one MAC entity at the eNode-B and one MAC entity at the UE.

- **Physical Layer (PHY):** The main function of PHY is the actual transmission and reception of data in forms of transport blocks. The PHY is also responsible for various control mechanisms such as signaling of H-ARQ feedback, signaling of scheduled allocations, and channel measurements.

In Chapter 7 to Chapter 9, we focus on the PHY layer, also referred to as layer 1 of the Open Systems Interconnection (OSI) reference model. Higher layer processing is described in Chapter 10.

6.2 Hierarchical Channel Structure of LTE

To efficiently support various QoS classes of services, LTE adopts a hierarchical channel structure. There are three different channel types defined in LTE — logical channels, transport channels, and physical channels, each associated with a service access point (SAP) between different layers. These channels are used by the lower layers of the protocol stack to provide services to the higher layers. The radio interface protocol architecture and the SAPs between different layers are shown in Figure 6.5. Logical channels provide services at the SAP between MAC and RLC layers, while transport channels provide services at the SAP between MAC and PHY layers. Physical channels are the actual implementation of transport channels over the radio interface.

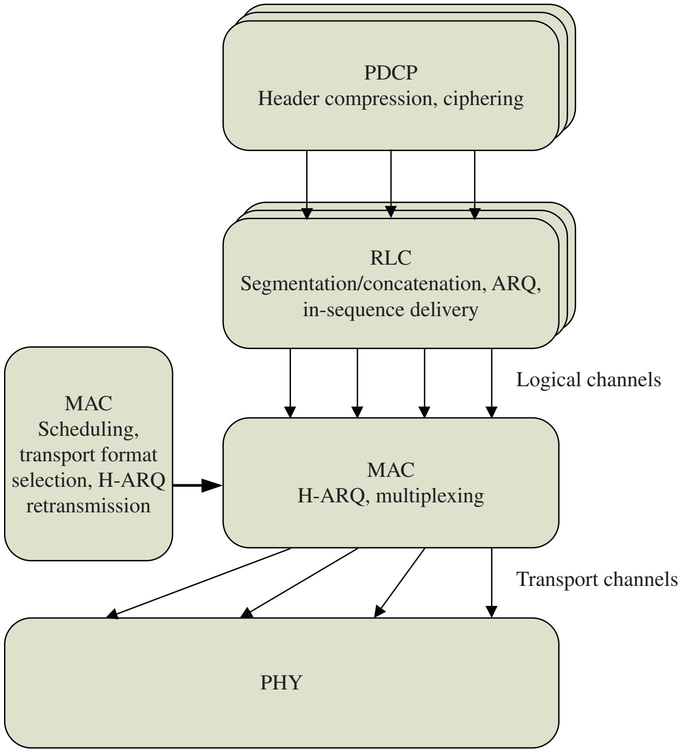

Figure 6.5 The radio interface protocol architecture and the SAPs between different layers.

The channels defined in LTE follow a similar hierarchical structure to UTRA/HSPA. However, in the case of LTE, the transport and logical channel structures are much more simplified and fewer in number compared to UTRA/HSPA. Unlike UTRA/HSPA, LTE is based entirely on shared and broadcast channels and contains no dedicated channels carrying data to specific UEs. This improves the efficiency of the radio interface and can support dynamic resource allocation between different UEs depending on their traffic/QoS requirements and their respective channel conditions. In this section, we describe in detail the various logical, transport, and physical channels that are defined in LTE. The description of different channel types and the channel mapping between different protocol layers provides an intuitive manner to understand the data flow of different services in LTE, which builds the foundation to understand the detail processing procedures in later chapters.

6.2.1 Logical Channels: What to Transmit

Logical channels are used by the MAC to provide services to the RLC. Each logical channel is defined based on the type of information it carries. In LTE, there are two categories of logical channels depending on the service they provide: *logical control channels* and *logical traffic channels*.

The logical control channels, which are used to transfer control plane information, include the following types:

- **Broadcast Control Channel (BCCH):** A downlink common channel used to broadcast system control information to the mobile terminals in the cell, including downlink system bandwidth, antenna configuration, and reference signal power. Due to the large amount of information carried on the BCCH, it is mapped to two different transport channels: the Broadcast Channel (BCH) and the Downlink Shared Channel (DL-SCH).
- **Multicast Control Channel (MCCH):** A point-to-multipoint downlink channel used for transmitting control information to UEs in the cell. It is only used by UEs that receive multicast/broadcast services.
- **Paging Control Channel (PCCH):** A downlink channel that transfers paging information to registered UEs in the cell, for example, in case of a mobile-terminated communication session. The paging process is discussed in Chapter 10.
- **Common Control Channel (CCCH):** A bi-directional channel for transmitting control information between the network and UEs when no RRC connection is available, implying the UE is not attached to the network such as in the idle state. Most commonly the CCCH is used during the random access procedure.
- **Dedicated Control Channel (DCCH):** A point-to-point, bi-directional channel that transmits dedicated control information between a UE and the network. This channel is used when the RRC connection is available, that is, the UE is attached to the network.

The logical traffic channels, which are to transfer user plane information, include:

- **Dedicated Traffic Channel (DTCH):** A point-to-point, bi-directional channel used between a given UE and the network. It can exist in both uplink and downlink.
- **Multicast Traffic Channel (MTCH):** A unidirectional, point-to-multipoint data channel that transmits traffic data from the network to UEs. It is associated with the multicast/broadcast service.

6.2.2 Transport Channels: How to Transmit

The transport channels are used by the PHY to offer services to the MAC. A transport channel is basically characterized by how and with what characteristics data is transferred over the radio interface, that is, the channel coding scheme, the modulation scheme, and antenna mapping. Compared to UTRA/HSPA, the number of transport channels in LTE is reduced since no dedicated channels are present.

LTE defines two MAC entities: one in the UE and one in the E-UTRAN, which handle the following downlink/uplink transport channels.

Downlink Transport Channels

- **Downlink Shared Channel (DL-SCH):** Used for transmitting the downlink data, including both control and traffic data, and thus it is associated with both logical control and logical traffic channels. It supports H-ARQ, dynamic link adaption, dynamic and semi-persistent resource allocation, UE discontinuous reception, and multicast/broadcast transmission. The concept of shared channel transmission originates from HSDPA, which uses the *High-Speed Downlink Shared Channel* (HS-DSCH) to multiplex traffic and control information among different UEs. By sharing the radio resource among different UEs the DL-SCH is able to maximize the throughput by allocating the resources to the optimum UEs. The processing of the DL-SCH is described in Section 7.2.
- **Broadcast Channel (BCH):** A downlink channel associated with the BCCH logical channel and is used to broadcast system information over the entire coverage area of the cell. It has a fixed transport format defined by the specifications. The processing of the BCH will be described in Section 7.4.
- **Multicast Channel (MCH):** Associated with MCCH and MTCH logical channels for the multicast/broadcast service. It supports *Multicast/Broadcast Single Frequency Network* (MBSFN) transmission, which transmits the same information on the same radio resource from multiple synchronized base stations to multiple UEs. The processing of the MCH is described in Section 7.5.
- **Paging Channel (PCH):** Associated with the PCCH logical channel. It is mapped to dynamically allocated physical resources, and is required for broadcast over the entire cell coverage area. It is transmitted on the Physical Downlink Shared Channel (PDSCH), and supports UE discontinuous reception.

Uplink Transport Channels

- **Uplink Shared Channel (UL-SCH):** The uplink counterpart of the DL-SCH. It can be associated to CCCH, DCCH, and DTCH logical channels. It supports H-ARQ, dynamic link adaption, and dynamic and semi-persistent resource allocation. The processing of the UL-SCH is described in Section 8.2.
- **Random Access Channel (RACH):** A specific transport channel that is not mapped to any logical channel. It transmits relatively small amounts of data for initial access or, in the case of RRC, state changes. The processing of the RACH is described in Section 8.5, while the random access procedure is described in Section 9.9.

The data on each transport channel is organized into *transport blocks*, and the transmission time of each transport block, also called Transmission Time Interval (TTI), is 1 ms in LTE. TTI is also the minimum interval for link adaptation and scheduling decision. Without spatial multiplexing, at most one transport block is transmitted to a UE in each TTI; with spatial multiplexing, up to two transport blocks can be transmitted in each TTI to a UE.

Besides transport channels, there are different types of control information defined in the MAC layer, which are important for various physical layer procedures. The defined control information includes

- **Downlink Control Information (DCI):** It carries information related to downlink/uplink scheduling assignment, modulation and coding scheme, and Transmit Power Control (TPC) command, and is sent over the Physical Downlink Control Channel (PDCCH). The DCI supports 10 different formats, listed in Table 6.1. Among them, Format 0 is for signaling uplink transmission allocation, Format 3 and 3A are for TPC, and the remaining formats are for signaling downlink transmission allocation. The detail content of each format can be found in [7], some of which is discussed in Section 7.3.
- **Control Format Indicator (CFI):** It indicates how many symbols the DCI spans in that subframe. It takes values CFI = 1, 2, or 3, and is sent over the Physical Control Format Indicator Channel (PCFICH).
- **H-ARQ Indicator (HI):** It carries H-ARQ acknowledgment in response to uplink transmissions, and is sent over the Physical Hybrid ARQ Indicator Channel (PHICH). HI = 1 for a positive acknowledgment (ACK) and HI = 0 for a negative acknowledgment (NAK).

Table 6.1 DCI Formats

Format	**Carried Information**
Format 0	Uplink scheduling assignment
Format 1	Downlink scheduling for one codeword
Format 1A	Compact downlink scheduling for one codeword and random access procedure
Format 1B	Compact downlink scheduling for one codeword with precoding information
Format 1C	Very compact downlink scheduling for one codeword
Format 1D	Compact downlink scheduling for one codeword with precoding and power offset information
Format 2	Downlink scheduling for UEs configured in closed-loop spatial multiplexing mode
Format 2A	Downlink scheduling for UEs configured in open-loop spatial multiplexing mode
Format 3	TPC commands for PUCCH and PUSCH with 2-bit power adjustments
Format 3A	TPC commands for PUCCH and PUSCH with 1-bit power adjustments

- **Uplink Control Information (UCI):** It is for measurement indication on the downlink transmission, scheduling request of uplink, and the H-ARQ acknowledgment of downlink transmissions. The UCI can be transmitted either on the Physical Uplink Control Channel (PUCCH) or the Physical Uplink Shared Channel (PUSCH). The detail transmission format is discussed in Section 8.3.

6.2.3 Physical Channels: Actual Transmission

Each physical channel corresponds to a set of resource elements in the time-frequency grid that carry information from higher layers. The basic entities that make a physical channel are resource elements and resource blocks. A resource element is a single subcarrier over one OFDM symbol, and typically this could carry one (or two with spatial multiplexing) modulated symbol(s). A resource block is a collection of resource elements and in the frequency domain this represents the smallest quanta of resources that can be allocated. The details of the time-frequency resource structures for downlink and uplink are described in Section 6.3 and Section 6.4, respectively.

Downlink Physical Channels

- **Physical Downlink Control Channel (PDCCH):** It carries information about the transport format and resource allocation related to the DL-SCH and PCH transport channels, and the H-ARQ information related to the DL-SCH. It also informs the UE about the transport format, resource allocation, and H-ARQ information related to UL-SCH. It is mapped from the DCI transport channel.

- **Physical Downlink Shared Channel (PDSCH):** This channel carries user data and higher-layer signaling. It is associated to DL-SCH and PCH.

- **Physical Broadcast Channel (PBCH):** It corresponds to the BCH transport channel and carries system information.

- **Physical Multicast Channel (PMCH):** It carriers multicast/broadcast information for the MBMS service.

- **Physical Hybrid-ARQ Indicator Channel (PHICH):** This channel carries H-ARQ ACK/NAKs associated with uplink data transmissions. It is mapped from the HI transport channel.

- **Physical Control Format Indicator Channel (PCFICH):** It informs the UE about the number of OFDM symbols used for the PDCCH. It is mapped from the CFI transport channel.

Uplink Physical Channels

- **Physical Uplink Control Channel (PUCCH):** It carries uplink control information including Channel Quality Indicators (CQI), ACK/NAKs for H-ARQ in response to downlink transmission, and uplink scheduling requests.

- **Physical Uplink Shared Channel (PUSCH):** It carries user data and higher-layer signaling. It corresponds to the UL-SCH transport channel.

- **Physical Random Access Channel (PRACH):** This channel carries the random access preamble sent by UEs.

Besides physical channels, there are signals embedded in the downlink and uplink physical layer, which do not carry information from higher layers. The physical signals defined in the LTE specifications are

- **Reference signal:** It is defined in both downlink and uplink for channel estimation that enables coherent demodulation and for channel quality measurement to assist user scheduling. There are three different reference signals in the downlink:
  - Cell-specific reference signals, associated with non-MBSFN transmission
  - MBSFN reference signals, associated with MBSFN transmission
  - UE-specific reference signals

  There are two types of uplink reference signals:
  - Demodulation reference signal, associated with transmission of PUSCH or PUCCH
  - Sounding reference signal, to support uplink channel-dependent scheduling

  The processing of reference signals in the downlink and uplink are treated in Section 7.6.1 and Section 8.4, respectively.
- **Synchronization signal:** It is split into a primary and a secondary synchronization signal, and is only defined in the downlink to enable acquisition of symbol timing and the precise frequency of the downlink signal. It is discussed further in Section 7.6.2.

6.2.4 Channel Mapping

From the description of different channel types, we see that there exists a good correlation based on the purpose and the content between channels in different layers. This requires a mapping between the logical channels and transport channels at the MAC SAP and a mapping between transport channels and physical channels at the PHY SAP. Such channel mapping is not arbitrary, and the allowed mapping between different channel types is shown in Figure 6.6,[4] while the mapping between control information and physical channels is shown in Figure 6.7. It is possible for multiple channels mapped to a single channel, for example, different logical control channels and logical traffic channels are mapped to the DL-SCH transport channel. The channel mapping in Figures 6.6 and 6.7 will reappear in different sections in Chapters 7 and 8 when we discuss downlink and uplink transport channel processing.

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[4] The mapping of multicast-related channels, that is, MCCH, MTCH, MCH, and PMCH, is not specified in Release 8 but in Release 9.

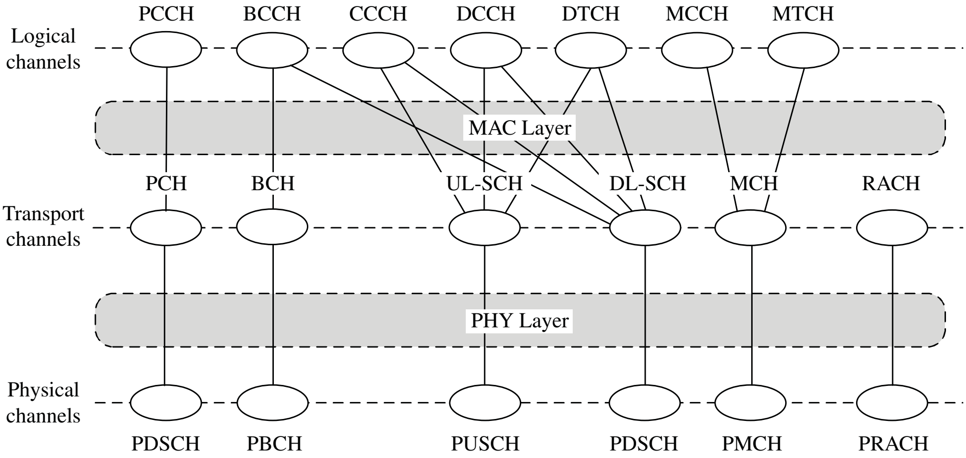

Figure 6.6 Mapping between different channel types.

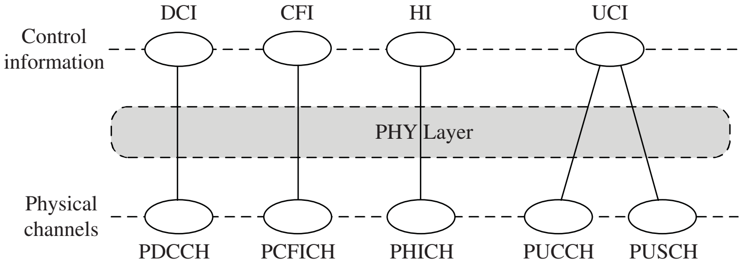

Figure 6.7 Mapping of control information to physical channels.

6.3 Downlink OFDMA Radio Resources

In LTE, the downlink and uplink use different transmission schemes due to different considerations. In this and the next section, we describe downlink and uplink radio transmission schemes, respectively. In the downlink, a scalable OFDM transmission/multiaccess technique is used that allows for high spectrum efficiency by utilizing multiuser diversity in a frequency selective channel. On the other hand, a scalable SC-FDMA transmission/ multiaccess technique is used in the uplink since this reduces the peak-to-average power ratio (PAPR) of the transmitted signal.

The downlink transmission is based on OFDM with a cyclic prefix (CP), which was described in Chapter 3 along with the associated multiple access scheme described in Chapter 4. We summarize some key advantages of OFDM that motivate using it in the LTE downlink:

- As shown in Chapter 3, OFDM is efficient in combating the frequency-selective fading channel with a simple frequency-domain equalizer, which makes it a suitable technique for wireless broadband systems such as LTE.

- As shown in Chapter 4, it is possible to exploit frequency-selective scheduling with OFDM-based multiple access (OFDMA), while HSPA only schedules in the time domain. This can make a big difference especially in slow time-varying channels.
- The transceiver structure of OFDM with FFT/IFFT enables scalable bandwidth operation with a low complexity, which is one of the major objectives of LTE.
- As each subcarrier becomes a flat fading channel, compared to single-carrier transmission OFDM makes it much easier to support multiantenna transmission, which is a key technique to enhance the spectrum efficiency.
- OFDM enables multicast/broadcast services on a synchronized single frequency network, that is, MBSFN, as it treats signals from different base stations as propagating through a multipath channel and can efficiently combine them.

The multiple access in the downlink is based on OFDMA. In each TTI, a scheduling decision is made where each scheduled UE is assigned a certain amount of radio resources in the time and frequency domain. The radio resources allocated to different UEs are orthogonal to each other, which means there is no intra-cell interference. In the remaining part of this section, we describe the frame structure and the radio resource block structure in the downlink, as well as the basic principles of resource allocation and the supported MIMO modes.

6.3.1 Frame Structure

Before going into details about the resource block structure for the downlink, we first describe the frame structure in the time domain, which is a common element shared by both downlink and uplink.

In LTE specifications, the size of elements in the time domain is expressed as a number of time units $T_s = 1/(15000 \times 2048)$ seconds. As the normal subcarrier spacing is defined to be $\Delta f = 15$kHz, T_s can be regarded as the sampling time of an FFT-based OFDM transmitter/receiver implementation with FFT size $N_{\mathrm{FFT}} = 2048$. Note that this is just for notation purpose, as different FFT sizes are supported depending on the transmission bandwidths. A set of parameters for typical transmission bandwidths for LTE in the downlink is shown in Table 6.2, where the subcarrier spacing is $\Delta f = 15$kHz. The FFT size increases with the transmission bandwidth, ranging from 128 to 2048. With $\Delta f =$ 15kHz, the sampling frequency, which equals $\Delta f \times N_{\mathrm{FFT}}$, is a multiple or sub-multiple of the UTRA/HSPA chip rate of 3.84MHz. In this way, multimode UTRA/HSPA/LTE terminals can be implemented with a single clock circuitry. In addition to the 15kHz subcarrier spacing, a *reduced subcarrier spacing* of 7.5kHz is defined for MBSFN cells, which provides a larger OFDM symbol duration that is able to combat the large delay spread associated with the MBSFN transmission. Unless otherwise stated, we will assume $\Delta f = 15$kHz in the following discussion.

In the time domain, the downlink and uplink multiple TTIs are organized into radio frames with duration $T_f = 307200 \cdot T_s = 10$ ms. For flexibility, LTE supports both FDD

Table 6.2 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 frequency [MHz]	1.92 $1/2 \times 3.84$	3.84	7.68 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

and TDD modes.[5] Most of the design parameters are common to FDD and TDD in order to reduce the terminal complexity and maximize reuse between the designs of FDD and TDD systems. Accordingly, LTE supports two kinds of frame structures: frame structure type 1 for the FDD mode and frame structure type 2 for the TDD mode.

Frame Structure Type 1

Frame structure type 1 is applicable to both full duplex and half duplex FDD. There are three different kinds of units specified for this frame structure, illustrated in Figure 6.8. The smallest one is called a *slot*, which is of length $T_{slot} = 15360 \cdot T_s = 0.5$ ms. Two consecutive slots are defined as a *subframe* of length 1 ms, and 20 slots, numbered from 0 to 19, constitute a *radio frame* of 10 ms. Channel-dependent scheduling and link adaptation operate on a subframe level. Therefore, the subframe duration corresponds to the minimum downlink TTI, which is of 1 ms duration, compared to a 2 ms TTI for the HSPA and a minimum 10 ms TTI for the UMTS. A shorter TTI is for fast link adaptation and is able to reduce delay and better exploit the time-varying channel through channel-dependent scheduling.

Each slot consists of a number of OFDM symbols including CPs. As shown in Chapter 3, CP is a kind of guard interval to combat inter-OFDM-symbol interference, which should be larger than the channel delay spread. Therefore, the length of CP depends on the environment where the network operates, and it should not be too large as it brings a bandwidth and power penalty. With a subcarrier spacing $\Delta f = 15$kHz, the OFDM symbol time is $1/\Delta f \approx 66.7\mu s$. As shown in Figure 6.8, LTE defines two different

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[5] The LTE TDD mode, also referred to as TD-LTE, provides the long-term evolution path for TD-SCDMA-based networks.

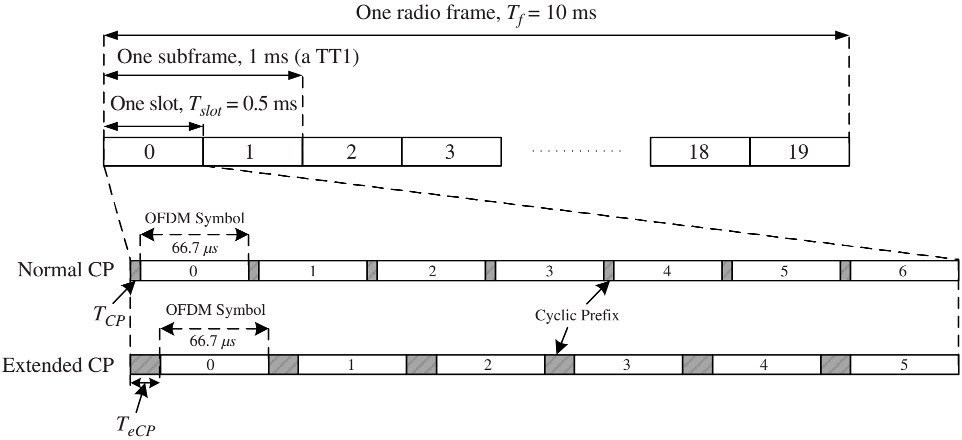

Figure 6.8 Frame structure type 1. For the normal CP, $T_{CP} = 160 \cdot T_s \approx 5.2\mu s$ for the first OFDM symbol, and $T_{CP} = 144 \cdot T_s \approx 4.7\mu s$ for the remaining OFDM symbols, which together fill the entire slot of 0.5 ms. For the extended CP, $T_{eCP} = 512 \cdot T_s \approx 16.7\mu s$.

CP lengths: a *normal CP* and an *extended CP*, corresponding to seven and six OFDM symbols per slot, respectively. The extended CP is for multicell multicast/broadcast and very-large-cell scenarios with large delay spread at a price of bandwidth efficiency, with length $T_{eCP} = 512 \cdot T_s \approx 16.7\mu s$. The normal CP is suitable for urban environment and high data rate applications. Note that the normal CP lengths are different for the first ($T_{CP} = 160 \cdot T_s \approx 5.2\mu s$) and subsequent OFDM symbols ($T_{CP} = 144 \cdot T_s \approx 4.7\mu s$), which is to fill the entire slot of 0.5 ms. The numbers of CP samples for different bandwidths are shown in Table 6.2. For example, with 10MHz bandwidth, the sampling time is $1/(15000 \times 1024)$ sec and the number of CP samples for the extended CP is 256, which provides the required CP length of $256/(15000 \times 1024) \approx 1.67\mu s$. In case of 7.5kHz subcarrier spacing, there is only a single CP length, corresponding to 3 OFDM symbols per slot.

For FDD, uplink and downlink transmissions are separated in the frequency domain, each with 10 subframes. In half-duplex FDD operation, the UE cannot transmit and receive at the same time while there are no such restrictions in full-duplex FDD. However, full-duplex FDD terminals need high quality and expensive RF duplex-filters to separate uplink and downlink channels, while half-duplex FDD allows hardware sharing between the uplink and downlink, which offers a cost saving at the expense of reducing data rates by half. Half-duplex FDD UEs are also considered a good solution if the duplex separation between the uplink and downlink transmissions is relatively small. In such cases, the half-duplex FDD is the preferable approach to mitigate the cross-interference between the transmit and receive chains.

Frame Structure Type 2

Frame structure type 2 is applicable to the TDD mode. It is designed for coexistence with legacy systems such as the 3GPP TD-SCDMA-based standard. As shown in Figure 6.9, each radio frame of frame structure type 2 is of length $T_f = 30720 \cdot T_s = 10$ ms, which

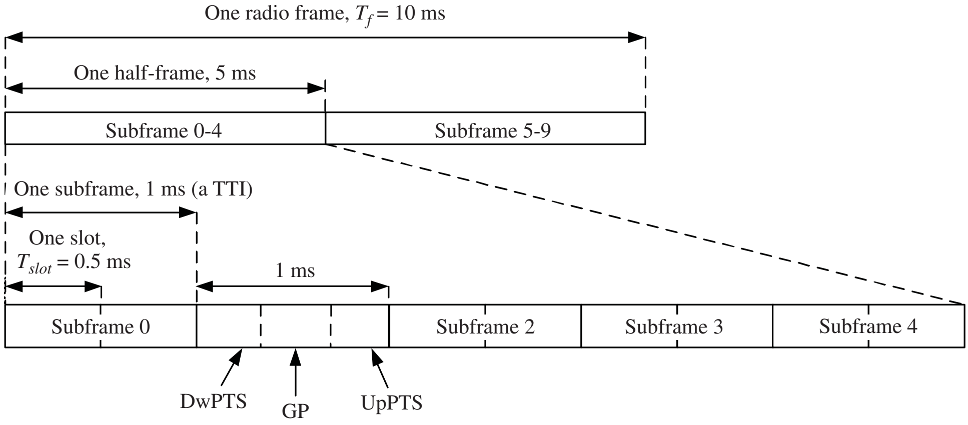

Figure 6.9 Frame structure type 2.

consists of two half-frames of length 5 ms each. Each half-frame is divided into five subframes with 1 ms duration. There are special subframes, which consist of three fields: Downlink Pilot TimeSlot (DwPTS), Guard Period (GP), and Uplink Pilot TimeSlot (UpPTS). These fields are already defined in TD-SCDMA and are maintained in the LTE TDD mode to provide sufficiently large guard periods for the equipment to switch between transmission and reception.

- **The DwPTS field:** This is the downlink part of the special subframe, and can be regarded as an ordinary but shorter downlink subframe for downlink data transmission. Its length can be varied from three up to twelve OFDM symbols.

- **The UpPTS field:** This is the uplink part of the special subframe, and has a short duration with one or two OFDM symbols. It can be used for transmission of uplink sounding reference signals and random access preambles.

- **The GP field:** The remaining symbols in the special subframe that have not been allocated to DwPTS or UpPTS are allocated to the GP field, which is used to provide the guard period for the downlink-to-uplink and the uplink-to-downlink switch.

The total length of these three special fields has a constraint of 1 ms. With the DwPTS and UpPTS durations mentioned above, LTE supports a guard period ranging from two to ten OFDM symbols, sufficient for cell size up to and beyond 100 km. All other subframes are defined as two slots, each with length $T_{slot} = 0.5$ ms.

Figure 6.9 only shows the detail structure of the first half-frame. The second half-frame has the similar structure, which depends on the uplink-downlink configuration. Seven uplink-downlink configurations with either 5 ms or 10 ms downlink-to-uplink switch-point periodicity are supported, as illustrated in Table 6.3, where “D” and “U” denote subframes reserved for downlink and uplink, respectively, and “S” denotes the special

Table 6.3 Uplink-Downlink Configurations for the LTE TDD Mode

Uplink-Downlink Configuration	Downlink-to-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

subframe. In the case of 5 ms switch-point periodicity, the special subframe exists in both half-frames, and the structure of the second half-frame is the same as the first one depicted in Figure 6.9. In the case of 10 ms switch-point periodicity, the special subframe exists in the first half-frame only. Subframes 0, 5, and the field DwPTS are always reserved for downlink transmission, while UpPTS and the subframe immediately following the special subframe are always reserved for uplink transmission.

6.3.2 Physical Resource Blocks for OFDMA

The physical resource in the downlink in each slot is described by a time-frequency grid, called a *resource grid*, as illustrated in Figure 6.10. Such a time-frequency plane representation is a common practice for OFDM systems, which makes it intuitive for radio resource allocation. Each column and each row of the resource grid correspond to one OFDM symbol and one OFDM subcarrier, respectively. The duration of the resource grid in the time domain corresponds to one slot in a radio frame. The smallest time-frequency unit in a resource grid is denoted as a *resource element*. Each resource grid consists of a number of *resource blocks*, which describe the mapping of certain physical channels to resource elements. The detail of these resource units is described as follows.

Resource Grid

The structure of each resource grid is characterized by the following three parameters:

- **The number of downlink resource blocks (N_{RB}^{DL}):** It depends on the transmission bandwidth and shall fulfill $N_{RB}^{min,DL} \leq N_{RB}^{DL} \leq N_{RB}^{max,DL}$, where $N_{RB}^{min,DL} = 6$ and $N_{RB}^{max,DL} = 110$ are for the smallest and largest downlink channel bandwidth, respectively. The values of N_{RB}^{DL} for several current specified bandwidths are listed in Table 6.2.
- **The number of subcarriers in each resource block (N_{sc}^{RB}):** It depends on the subcarrier spacing Δf, satisfying $N_{sc}^{RB}\Delta f = 180\text{kHz}$, that is, each resource block is

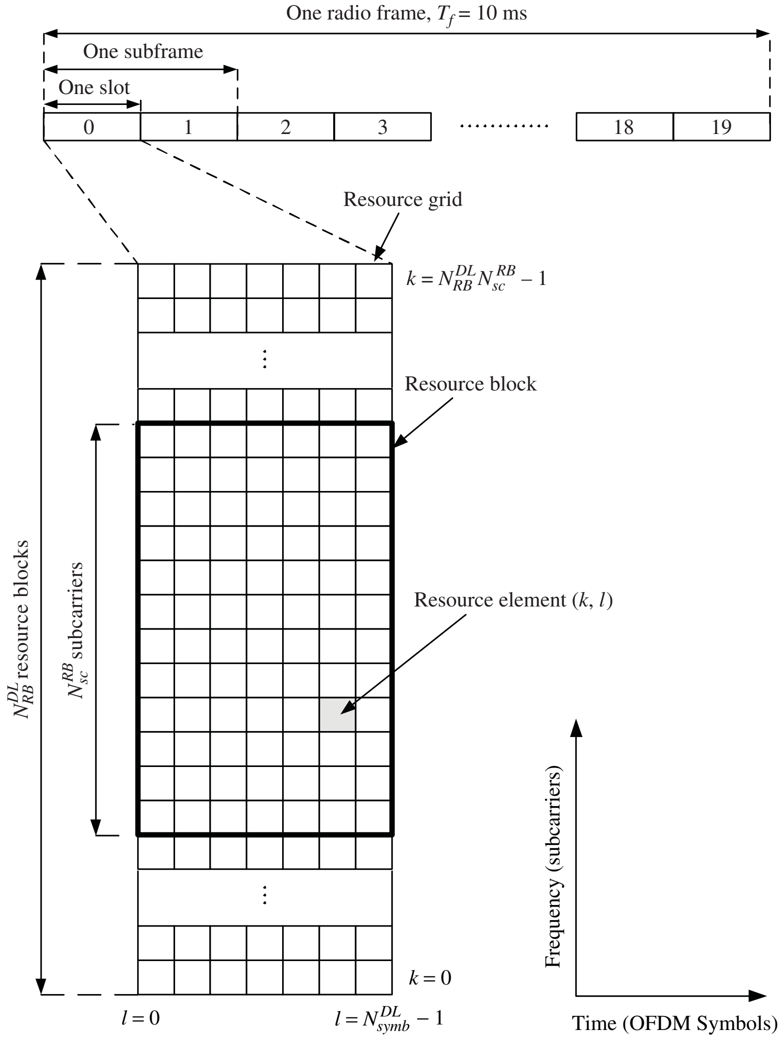

Figure 6.10 The structure of the downlink resource grid.

of 180kHz wide in the frequency domain. The values of N_{sc}^{RB} for different subcarrier spacings are shown in Table 6.4. There are a total of $N_{RB}^{DL} \times N_{sc}^{RB}$ subcarriers in each resource grid. For downlink transmission, the DC subcarrier is not used as it may be subject to a too high level of interference.

- **The number of OFDM symbols in each block (N_{symb}^{DL}):** It depends on both the CP length and the subcarrier spacing, specified in Table 6.4.

Therefore, each downlink resource grid has $N_{RB}^{DL} \times N_{RB}^{sc} \times N_{symb}^{DL}$ resource elements. For example, with 10MHz bandwidth, $\Delta f = 15$kHz, and normal CP, we get $N_{RB}^{DL} = 50$ from

Table 6.4 Physical Resource Block Parameters for the Downlink

Configuration		N_{sc}^{RB}	N_{symb}^{DL}
Normal CP	$\Delta f = 15\text{kHz}$	12	7
Extended CP	$\Delta f = 15\text{kHz}$	12	6
	$\Delta f = 7.5\text{kHz}$	24	3

Table 6.2, $N_{RB}^{sc} = 12$ and $N_{symb}^{DL} = 7$ from Table 6.4, so there are $50 \times 12 \times 7 = 4200$ resource elements in the downlink resource grid.

In case of multiantenna transmission, there is one resource grid defined per antenna port. An antenna port is defined by its associated reference signal, which may not correspond to a physical antenna. The set of antenna ports supported depends on the reference signal configuration in the cell. As discussed in Section 6.2.3, there are three different reference signals defined in the downlink, and the associated antenna ports are as follows:

- Cell-specific reference signals support a configuration of 1, 2, or 4 antenna ports and the antenna port number p shall fulfill $p = 0$, $p \in \{0, 1\}$, and $p \in \{0, 1, 2, 3\}$, respectively.
- MBSFN reference signals are transmitted on antenna port $p = 4$.
- UE-specific reference signals are transmitted on antenna port $p = 5$.

We will talk more about antenna ports when discussing MIMO transmission in the downlink in Section 7.2.2.

Resource Element

Each resource element in the resource grid is uniquely identified by the index pair (k, l) in a slot, where $k = 0, 1, \ldots, N_{RB}^{DL} N_{sc}^{RB} - 1$ and $l = 0, 1, \ldots, N_{symb}^{DL} - 1$ are indices in the frequency and time domains, respectively. The size of each resource element depends on the subcarrier spacing Δf and the CP length.

Resource Block

The resource block is the basic element for radio resource allocation. The minimum size of radio resource that can be allocated is the minimum TTI in the time domain, that is, one subframe of 1 ms, corresponding to two resource blocks. The size of each resource block is the same for all bandwidths, which is 180kHz in the frequency domain. There are two kinds of resource blocks defined for LTE: physical and virtual resource blocks, which are defined for different resource allocation schemes and are specified in the following section.

6.3.3 Resource Allocation

Resource allocation's role is to dynamically assign available time-frequency resource blocks to different UEs in an efficient way to provide good system performance. In LTE, channel-dependent scheduling is supported, and transmission is based on the shared channel structure where the radio resource is shared among different UEs. Therefore, with resource allocation techniques described in Chapter 4, *multiuser diversity* can be exploited by assigning resource blocks to the UEs with favorable channel qualities. Moreover, resource allocation in LTE is able to exploit the channel variations in both the time and frequency domain, which provides higher multiuser diversity gain than HSPA that can only exploit the time-domain variation. Given a wide bandwidth in LTE, this property is beneficial especially for slow-time varying channels, such as in the scenario with low mobility, where taking advantage of channel selectivity in the time domain is difficult.

With OFDMA, the downlink resource allocation is characterized by the fact that each scheduled UE occupies a number of resource blocks while each resource block is assigned exclusively to one UE at any time. Physical resource blocks (PRBs) and virtual resource blocks (VRBs) are defined to support different kinds of resource allocation types. The VRB is introduced to support both block-wise transmission (localized) and transmission on non-consecutive subcarriers (distributed) as a means to maximize frequency diversity. The LTE downlink supports three resource allocation types: type 0, 1, and 2 [8]. The downlink scheduling is performed at the eNode-B based on the channel quality information fed back from UEs, and then the downlink resource assignment information is sent to UEs on the PDCCH channel.

A PRB is defined as N_{symb}^{DL} consecutive OFDM symbols in the time domain and N_{sc}^{RB} consecutive subcarriers in the frequency domain, as demonstrated in Figure 6.10. Therefore, each PRB corresponds to one slot in the time domain (0.5 ms) and 180kHz in the frequency domain. PRBs are numbered from 0 to $N_{RB}^{DL} - 1$ in the frequency domain. The PRB number n_{PRB} of a resource element (k, l) in a slot is given by:

$$n_{PRB} = \left\lfloor \frac{k}{N_{sc}^{RB}} \right\rfloor.$$

The PRB is to support resource allocations of type 0 and type 1, which are defined for the DCI format 1, 2, and 2A.

- In **type 0 resource allocations**, several consecutive PRBs constitute a resource block group (RBG), and the resource allocation is done in units of RBGs. Therefore, a bitmap indicating the RBG is sufficient to carry the resource assignment. The allocated RBGs to a certain UE do not need to be adjacent to each other, which provides frequency diversity. The RBG size P, that is, the number of PRBs in each RBG, depends on the bandwidth and is specified in Table 6.5. An example of type 0

Table 6.5 Resource Allocation RBG Size vs. Downlink System Bandwidth

Downlink Resource Blocks $\left(N_{RB}^{DL}\right)$	**RBG Size** (P)
≤ 10	1
$11 - 26$	2
$27 - 63$	3
$64 - 110$	4

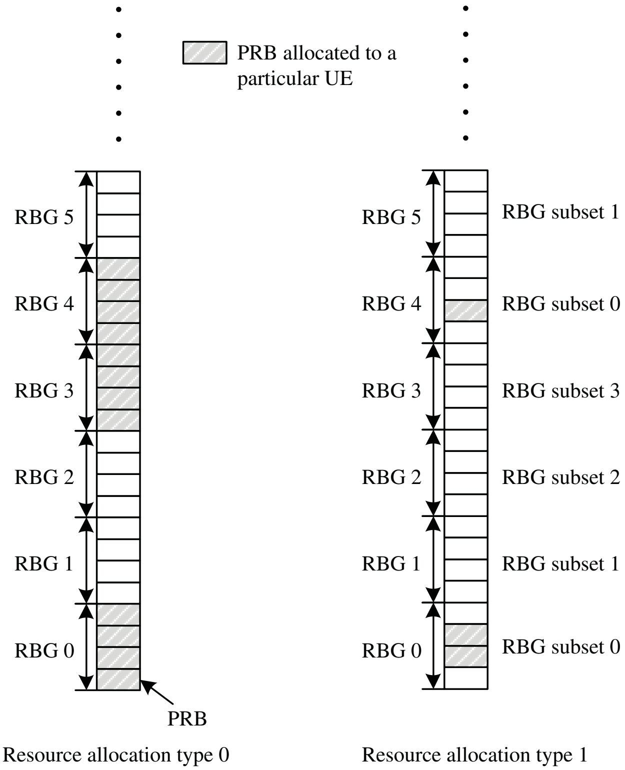

Figure 6.11 Examples of resource allocation type 0 and type 1, where the RBG size $P = 4$.

resource allocation is shown in Figure 6.11, where $P = 4$ and RBGs 0, 3, 4, ..., are allocated to a particular UE.

- In **type 1 resource allocations**, all the RBGs are grouped into a number of RBG subsets, and certain PRBs inside a selected RBG subset are allocated to the UE. There are a total of P RBG subsets, where P is the RBG size. An RBG subset p, where $0 \leq p < P$, consists of every P-th RBG starting from RBG p. Therefore, the resource assignment information consists of three fields: the first field indicates the selected RBG subset, the second field indicates whether an offset is applied, and the third field contains the bitmap indicating PRBs inside the selected RBG subset. This type of resource allocation is more flexible and is able to provide higher frequency diversity, but it also requires a larger overhead. An example of type 1 resource allocation is shown in Figure 6.11, where $P = 4$ and the RBG subset 0 is selected for the given UE.

In **type 2 resource allocations** that are defined for the DCI format 1A, 1B, 1C, and 1D, PRBs are not directly allocated. Instead, VRBs are allocated, which are then mapped onto PRBs. A VRB is of the same size as a PRB. There are two types of VRBs: VRBs of the localized type and VRBs of the distributed type.

For each type of VRB, a pair of VRBs over two slots in a subframe are assigned together with a single VRB number, n_{VRB}. VRBs of the localized type are mapped directly to physical resource blocks such that the VRB number n_{VRB} corresponds to the PRB number $n_{PRB} = n_{VRB}$. For VRBs of the distributed type, the VRB numbers are mapped to PRB numbers according to the rule specified in [6].

For resource allocations of type 2, the resource assignment information indicates a set of contiguously allocated localized VRBs or distributed VRBs. A one-bit flag indicates whether localized VRBs or distributed VRBs are assigned.

Details about the downlink resource allocation can be found in [8]. The feedback for channel quality information and the related signaling is discussed in Chapter 9.

6.3.4 Supported MIMO Modes

Multiantenna transmission and reception (MIMO), as described in Chapter 5, is a physical layer technique that can improve both the reliability and throughput of the communications over wireless channels. It is considered a key component of the LTE physical layer from the start. The baseline antenna configuration in LTE is two transmit antennas at the cell site and two receive antennas at the UE. The higher-order downlink MIMO is also supported with up to four transmit and four receive antennas.

The downlink transmission supports both single-user MIMO (SU-MIMO) and multiuser MIMO (MU-MIMO). For SU-MIMO, one or multiple data streams are transmitted to a single UE through space-time processing; for MU-MIMO, modulation data streams are transmitted to different UEs using the same time-frequency resource. The supported SU-MIMO modes are listed as follows:

- Transmit diversity with space frequency block codes (SFBC)
- Open-loop spatial multiplexing supporting four data streams
- Closed-loop spatial multiplexing, with closed-loop precoding as a special case when channel rank = 1
- Conventional direction of arrival (DOA)-based beamforming

The supported MIMO mode is restricted by the UE capability. The PDSCH physical channel supports all the MIMO modes, while other physical channels support transmit diversity except PMCH, which only supports single-antenna–port transmission. The details about MIMO transmission on each downlink physical channel are provided in Chapter 7, while the feedback to assist MIMO transmission is discussed in Chapter 9.

6.4 Uplink SC-FDMA Radio Resources

For the LTE uplink transmission, SC-FDMA with a CP is adopted. As discussed in Chapter 4, SC-FDMA possesses most of the merits of OFDM while enjoying a lower PAPR. A lower PAPR is highly desirable in the uplink as less expensive power amplifiers are needed at UEs and the coverage is improved. In LTE, the SC-FDMA signal is generated by the DFT-spread-OFDM. Compared to conventional OFDM, the SC-FDMA receiver has higher complexity, which, however, is not considered to be an issue in the uplink given the powerful computational capability at the base station.

An SC-FDMA transceiver has a similar structure as OFDM, so the parametrization of radio resource in the uplink enjoys similarities to that in the downlink described in Section 6.3. Nevertheless, the uplink transmission has its own properties. Different from the downlink, only localized resource allocation on consecutive subcarriers is allowed in the uplink. In addition, only limited MIMO modes are supported in the uplink. In this section, we focus on the differences in the uplink radio resource from that in the downlink.

6.4.1 Frame Structure

The uplink frame structure is similar to that for the downlink. The difference is that now we talk about *SC-FDMA symbols* and *SC-FDMA subcarriers*. In frame structure type 1, an uplink radio frame consists of 20 slots of 0.5 ms each, and one subframe consists of two slots, as in Figure 6.8. Frame structure type 2 consists of ten subframes, with one or two special subframes including DwPTS, GP, and UpPTS fields, as shown in Figure 6.9. A CP is inserted prior to each SC-FDMA symbol. Each slot carries seven SC-FDMA symbols in the case of normal CP, and six SC-FDMA symbols in the case of extended CP.

6.4.2 Physical Resource Blocks for SC-FDMA

As SC-FDMA can be regarded as conventional OFDM with a DFT-based precoder, the *resource grid* for the uplink is similar to the one for the downlink, illustrated in Figure 6.12, that is, it comprises a number of resource blocks in the time-frequency plane. The number of resource blocks in each resource grid, N_{RB}^{UL}, depends on the uplink transmission bandwidth configured in the cell and should satisfy

$$N_{RB}^{min,UL} \leq N_{RB}^{UL} \leq N_{RB}^{max,UL},$$

where $N_{RB}^{min,UL} = 6$ and $N_{RB}^{max,UL} = 110$ correspond to the smallest and largest uplink bandwidth, respectively. There are $N_{sc}^{RB} \times N_{symb}^{RB}$ resource elements in each resource block. The values of N_{sc}^{RB} and N_{symb}^{UL} for normal and extended CP are given in Table 6.6. There is only one subcarrier spacing supported in the uplink, which is $\Delta f = 15$kHz. Different from the downlink, the DC subcarrier is used in the uplink, as the DC interference is spread over the modulation symbols due to the DFT-based precoding.

As for the downlink, each *resource element* in the resource grid is uniquely defined by the index pair (k, l) in a slot, where $k = 0, \ldots, N_{RB}^{UL} N_{sc}^{RB} - 1$ and $l = 0, \ldots, N_{symb}^{UL} - 1$ are the indices in the frequency and time domain, respectively. For the uplink, no antenna port is defined, as only single antenna transmission is supported in the current specifications.

A PRB in the uplink is defined as N_{symb}^{UL} consecutive SC-FDMA symbols in the time domain and N_{sc}^{RB} consecutive subcarriers in the frequency domain, corresponding to one slot in the time domain and 180kHz in the frequency domain. The relation between the

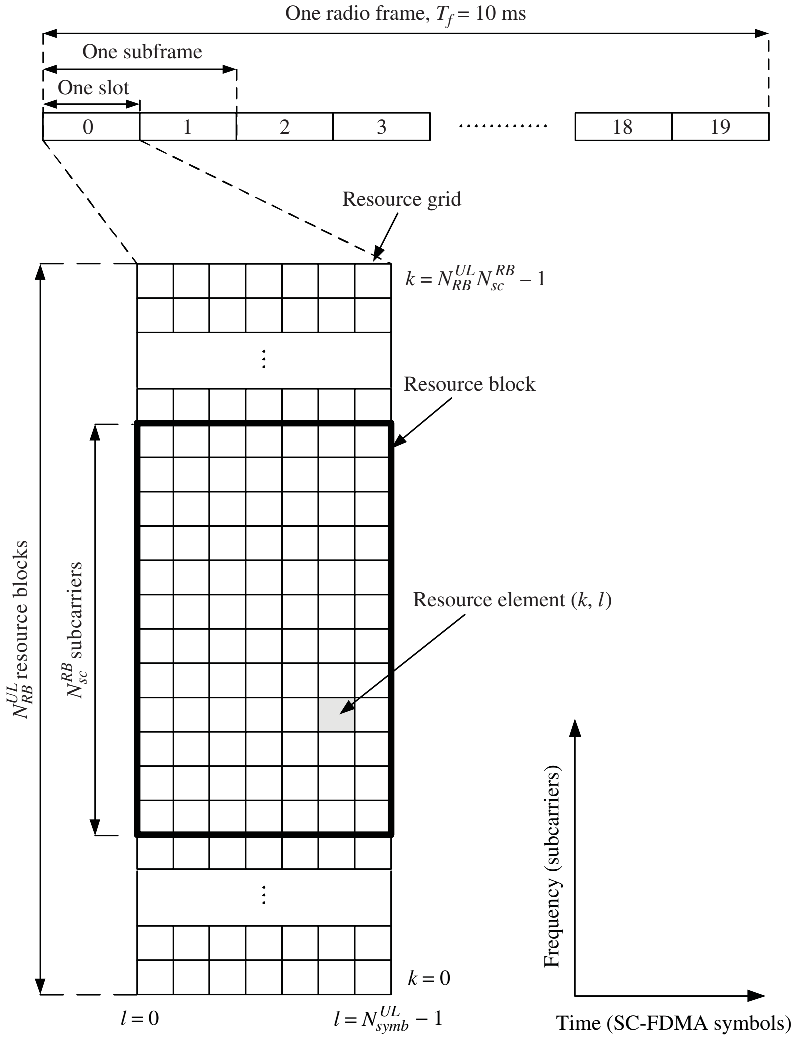

Figure 6.12 The structure of the uplink resource grid.

Table 6.6 Physical Resource Block Parameters for Uplink

Configuration	N_{sc}^{RB}	N_{symb}^{UL}
Normal CP	12	7
Extended CP	12	6

PRB number n_{PRB} in the frequency domain and resource elements (k, l) in a slot is given by:

$$n_{PRB} = \left\lfloor \frac{k}{N_{sc}^{RB}} \right\rfloor.$$

6.4.3 Resource Allocation

Similar to the downlink, shared-channel transmission and channel-dependent scheduling are supported in the uplink. Resource allocation in the uplink is also performed at the eNode-B. Based on the channel quality measured on the uplink sounding reference signals and the scheduling requests sent from UEs, the eNode-B assigns a unique time-frequency resource to a scheduled UE, which achieves orthogonal intra-cell transmission. Such intra-cell orthogonality in the uplink is preserved between UEs by using timing advance such that the transport blocks of different UEs are received synchronously at the eNode-B. This provides significant coverage and capacity gain in the uplink over UMTS, which employs non-orthogonal transmission in the uplink and the performance is limited by inter-channel interference. In general, SC-FDMA is able to support both localized and distributed resource allocation. In the current specification, only localized resource allocation is supported in the uplink, which preserves the single-carrier property and can better exploit the multiuser diversity gain in the frequency domain. Compared to distributed resource allocation, localized resource allocation is less sensitive to frequency offset and also requires fewer reference symbols.

The resource assignment information for the uplink transmission is carried on the PDCCH with DCI format 0, indicating a set of contiguously allocated resource blocks. However, not all integer multiples of one resource block are allowed to be assigned to a UE, which is to simplify the DFT design for the SC-FDMA transceiver. Only factors 2, 3, and 5 are allowed. The frequency hopping is supported to provide frequency diversity, with which the UEs can hop between frequencies within or between the allocated subframes. The resource mapping for different uplink channels is discussed in Chapter 8, and the uplink channel sounding and scheduling signaling is described in Chapter 9.

6.4.4 Supported MIMO Modes

For the MIMO modes supported in the uplink, the terminal complexity and cost are among the major concerns. MU-MIMO is supported, which allocates the same time and frequency resource to two UEs with each transmitting on a single antenna. This is also called Spatial Division Multiple Access (SDMA). The advantage is that only one transmit antenna per UE is required. To separate streams for different UEs, channel state information is required at the eNode-B, which is obtained through uplink reference signals that are orthogonal between UEs. Uplink MU-MIMO also requires power control, as the near-far problem arises when multiple UEs are multiplexed on the same radio resource.

For UEs with two or more transmit antennas, closed-loop adaptive antenna selection transmit diversity shall be supported. For this scenario, each UE only needs one transmit chain and amplifier. The antenna that provides the best channel to the eNode-B is selected based on the feedback from the eNode-B. The details of MIMO transmission in the uplink are described in Chapter 8.

6.5 Summary and Conclusions

This chapter provided an overview of the LTE radio interface, emphasizing the hierarchical channel structure and the radio resource in both downlink and uplink. The material covered should be adequate for the reader to get the unique characteristics of the LTE physical layer and understand the detailed physical layer procedures in the following chapters.

- LTE is the next step in the evolution of mobile cellular systems, and is a packet-switched network from end to end that is designed with a clean slate approach.
- LTE adopts the hierarchical channel structure from UTRA/HSPA. It simplifies the channel structure and is based totally on the shared channel transmission, which improves the efficiency of the air interface.
- LTE applies OFDMA in the downlink and SC-FDMA in the uplink, both of which have similar radio resource structures in the time-frequency plane. The capability of scheduling in both time and frequency domain provides a higher spectral efficiency in LTE than what is achieved in HSPA. Both localized and distributed resource allocations are supported in the downlink, while only localized resource allocation is supported in the uplink.
- MIMO transmission is a key component of LTE. In current specifications, downlink transmission supports a variety of MIMO modes, while uplink transmission has a limited MIMO support considering cost and complexity.

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