

# 4G

## LTE / LTE-Advanced for Mobile Broadband

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# Preface

During the past years, there has been a quickly rising interest in radio access technologies for providing mobile as well as nomadic and fixed services for voice, video, and data. The difference in design, implementation, and use between telecom and datacom technologies is also becoming more blurred. One example is cellular technologies from the telecom world being used for broadband data and wireless LAN from the datacom world being used for voice-over IP.

Today, the most widespread radio access technology for mobile communication is digital cellular, with the number of users passing 5 billion by 2010, which is more than half of the world's population. It has emerged from early deployments of an expensive voice service for a few car-borne users, to today's widespread use of mobile-communication devices that provide a range of mobile services and often include camera, MP3 player, and PDA functions. With this widespread use and increasing interest in mobile communication, a continuing evolution ahead is foreseen.

This book describes LTE, developed in 3GPP (*Third Generation Partnership Project*) and providing true 4G broadband mobile access, starting from the first version in release 8 and through the continuing evolution to release 10, the latest version of LTE. Release 10, also known as LTE-Advanced, is of particular interest as it is the major technology approved by the ITU as fulfilling the IMT-Advanced requirements. The description in this book is based on LTE release 10 and thus provides a complete description of the LTE-Advanced radio access from the bottom up.

Chapter 1 gives the background to LTE and its evolution, looking also at the different standards bodies and organizations involved in the process of defining 4G. It also gives a discussion of the reasons and driving forces behind the evolution.

Chapters 2–6 provide a deeper insight into some of the technologies that are part of LTE and its evolution. Because of its generic nature, these chapters can be used as a background not only for LTE as described in this book, but also for readers who want to understand the technology behind other systems, such as WCDMA/HSPA, WiMAX, and CDMA2000.

Chapters 7–17 constitute the main part of the book. As a start, an introductory technical overview of LTE is given, where the most important technology components are introduced based on the generic technologies described in previous chapters. The following chapters provide a detailed description of the protocol structure, the downlink and uplink transmission schemes, and the associated mechanisms for scheduling, retransmission and interference handling. Broadcast operation and relaying are also described. This is followed by a discussion of the spectrum flexibility and the associated requirements from an RF perspective.

Finally, in Chapters 18–20, an assessment is made on LTE. Through an overview of similar technologies developed in other standards bodies, it will be clear that the technologies adopted for the evolution in 3GPP are implemented in many other systems as well. Finally, looking into the future, it will be seen that the evolution does not stop with LTE-Advanced but that new features are continuously added to LTE in order to meet future requirements.

# Acknowledgements

We thank all our colleagues at Ericsson for assisting in this project by helping with contributions to the book, giving suggestions and comments on the contents, and taking part in the huge team effort of developing LTE.

The standardization process involves people from all parts of the world, and we acknowledge the efforts of our colleagues in the wireless industry in general and in 3GPP RAN in particular. Without their work and contributions to the standardization, this book would not have been possible.

Finally, we are immensely grateful to our families for bearing with us and supporting us during the long process of writing this book.





# Abbreviations and Acronyms

3GPP	Third Generation Partnership Project
3GPP2	Third Generation Partnership Project 2
ACIR	Adjacent Channel Interference Ratio
ACK	Acknowledgement (in ARQ protocols)
ACLR	Adjacent Channel Leakage Ratio
ACS	Adjacent Channel Selectivity
AM	Acknowledged Mode (RLC configuration)
AMC	Adaptive Modulation and Coding
A-MPR	Additional Maximum Power Reduction
AMPS	Advanced Mobile Phone System
AQPSK	Adaptive QPSK
ARI	Acknowledgement Resource Indicator
ARIB	Association of Radio Industries and Businesses
ARQ	Automatic Repeat-reQuest
AS	Access Stratum
ATIS	Alliance for Telecommunications Industry Solutions
AWGN	Additive White Gaussian Noise
BC	Band Category
BCCH	Broadcast Control Channel
BCH	Broadcast Channel
BER	Bit-Error Rate
BLER	Block-Error Rate
BM-SC	Broadcast Multicast Service Center
BPSK	Binary Phase-Shift Keying
BS	Base Station
BSC	Base Station Controller
BTS	Base Transceiver Station
CA	Carrier Aggregation
CC	Convolutional Code (in the context of coding), or Component Carrier (in the context of carrier aggregation)
CCCH	Common Control Channel
CCE	Control Channel Element
CCSA	China Communications Standards Association
CDD	Cyclic-Delay Diversity
CDF	Cumulative Density Function
CDM	Code-Division Multiplexing
CDMA	Code-Division Multiple Access

CEPT	European Conference of Postal and Telecommunications Administrations
CN	Core Network
CoMP	Coordinated Multi-Point transmission/reception
CP	Cyclic Prefix
CPC	Continuous Packet Connectivity
CQI	Channel-Quality Indicator
C-RAN	Centralized RAN
CRC	Cyclic Redundancy Check
C-RNTI	Cell Radio-Network Temporary Identifier
CRS	Cell-specific Reference Signal
CS	Circuit Switched (or Cyclic Shift)
CS	Capability Set (for MSR base stations)
CSA	Common Subframe Allocation
CSG	Closed Subscriber Group
CSI	Channel-State Information
CSI-RS	CSI reference signals
CW	Continuous Wave
DAI	Downlink Assignment Index
DCCH	Dedicated Control Channel
DCH	Dedicated Channel
DCI	Downlink Control Information
DFE	Decision-Feedback Equalization
DFT	Discrete Fourier Transform
DFTS-OFDM	DFT-Spread OFDM (DFT-precoded OFDM, see also SC-FDMA)
DL	Downlink
DL-SCH	Downlink Shared Channel
DM-RS	Demodulation Reference Signal
DRX	Discontinuous Reception
DTCH	Dedicated Traffic Channel
DTX	Discontinuous Transmission
DwPTS	The downlink part of the special subframe (for TDD operation).
EDGE	Enhanced Data rates for GSM Evolution, Enhanced Data rates for Global Evolution
EGPRS	Enhanced GPRS
eNB	eNodeB
eNodeB	E-UTRAN NodeB
EPC	Evolved Packet Core
EPS	Evolved Packet System
ETSI	European Telecommunications Standards Institute
E-UTRA	Evolved UTRA
E-UTRAN	Evolved UTRAN
EV-DO	Evolution-Data Only (of CDMA2000 1x)
EV-DV	Evolution-Data and Voice (of CDMA2000 1x)
EVM	Error Vector Magnitude

FACH	Forward Access Channel
FCC	Federal Communications Commission
FDD	Frequency Division Duplex
FDM	Frequency-Division Multiplex
FDMA	Frequency-Division Multiple Access
FEC	Forward Error Correction
FFT	Fast Fourier Transform
FIR	Finite Impulse Response
FPLMTS	Future Public Land Mobile Telecommunications Systems
FRAMES	Future Radio Wideband Multiple Access Systems
FSTD	Frequency Switched Transmit Diversity
GERAN	GSM/EDGE Radio Access Network
GGSN	Gateway GPRS Support Node
GP	Guard Period (for TDD operation)
GPRS	General Packet Radio Services
GPS	Global Positioning System
GSM	Global System for Mobile communications
HARQ	Hybrid ARQ
HII	High-Interference Indicator
HLR	Home Location Register
HRPD	High Rate Packet Data
HSDPA	High-Speed Downlink Packet Access
HSPA	High-Speed Packet Access
HSS	Home Subscriber Server
HS-SCCH	High-Speed Shared Control Channel
ICIC	Inter-Cell Interference Coordination
ICS	In-Channel Selectivity
ICT	Information and Communication Technologies
IDFT	Inverse DFT
IEEE	Institute of Electrical and Electronics Engineers
IFDMA	Interleaved FDMA
IFFT	Inverse Fast Fourier Transform
IMT-2000	International Mobile Telecommunications 2000 (ITU's name for the family of 3G standards)
IMT-Advanced	International Mobile Telecommunications Advanced (ITU's name for the family of 4G standards)
IP	Internet Protocol
IR	Incremental Redundancy
IRC	Interference Rejection Combining
ITU	International Telecommunications Union
ITU-R	International Telecommunications Union-Radiocommunications Sector

J-TACS	Japanese Total Access Communication System
LAN	Local Area Network
LCID	Logical Channel Index
LDPC	Low-Density Parity Check Code
LTE	Long-Term Evolution
MAC	Medium Access Control
MAN	Metropolitan Area Network
MBMS	Multimedia Broadcast/Multicast Service
MBMS-GW	MBMS gateway
MBS	Multicast and Broadcast Service
MBSFN	Multicast-Broadcast Single Frequency Network
MC	Multi-Carrier
MCCH	MBMS Control Channel
MCE	MBMS Coordination Entity
MCH	Multicast Channel
MCS	Modulation and Coding Scheme
MDHO	Macro-Diversity Handover
MIB	Master Information Block
MIMO	Multiple-Input Multiple-Output
ML	Maximum Likelihood
MLSE	Maximum-Likelihood Sequence Estimation
MME	Mobility Management Entity
MMS	Multimedia Messaging Service
MMSE	Minimum Mean Square Error
MPR	Maximum Power Reduction
MRC	Maximum Ratio Combining
MSA	MCH Subframe Allocation
MSC	Mobile Switching Center
MSI	MCH Scheduling Information
MSP	MCH Scheduling Period
MSR	Multi-Standard Radio
MSS	Mobile Satellite Service
MTCH	MBMS Traffic Channel
MU-MIMO	Multi-User MIMO
MUX	Multiplexer or Multiplexing
NAK, NACK	Negative Acknowledgement (in ARQ protocols)
NAS	Non-Access Stratum (a functional layer between the core network and the terminal that supports signaling and user data transfer)
NDI	New-data indicator
NSPS	National Security and Public Safety
NMT	Nordisk MobilTelefon (Nordic Mobile Telephony)

NodeB	NodeB, a logical node handling transmission/reception in multiple cells. Commonly, but not necessarily, corresponding to a base station.
NS	Network Signaling
OCC	Orthogonal Cover Code
OFDM	Orthogonal Frequency-Division Multiplexing
OFDMA	Orthogonal Frequency-Division Multiple Access
OI	Overload Indicator
OOB	Out-Of-Band (emissions)
PAPR	Peak-to-Average Power Ratio
PAR	Peak-to-Average Ratio (same as PAPR)
PARC	Per-Antenna Rate Control
PBCH	Physical Broadcast Channel
PCCH	Paging Control Channel
PCFICH	Physical Control Format Indicator Channel
PCG	Project Coordination Group (in 3GPP)
PCH	Paging Channel
PCRF	Policy and Charging Rules Function
PCS	Personal Communications Systems
PDA	Personal Digital Assistant
PDC	Personal Digital Cellular
PDCCH	Physical Downlink Control Channel
PDCP	Packet Data Convergence Protocol
PDSCH	Physical Downlink Shared Channel
PDN	Packet Data Network
PDU	Protocol Data Unit
PF	Proportional Fair (a type of scheduler)
P-GW	Packet-Data Network Gateway (also PDN-GW)
PHICH	Physical Hybrid-ARQ Indicator Channel
PHS	Personal Handy-phone System
PHY	Physical layer
PMCH	Physical Multicast Channel
PMI	Precoding-Matrix Indicator
POTS	Plain Old Telephony Services
PRACH	Physical Random Access Channel
PRB	Physical Resource Block
P-RNTI	Paging RNTI
PS	Packet Switched
PSK	Phase Shift Keying
PSS	Primary Synchronization Signal
PSTN	Public Switched Telephone Networks
PUCCH	Physical Uplink Control Channel

PUSC	Partially Used Subcarriers (for WiMAX)
PUSCH	Physical Uplink Shared Channel
QAM	Quadrature Amplitude Modulation
QoS	Quality-of-Service
QPP	Quadrature Permutation Polynomial
QPSK	Quadrature Phase-Shift Keying
RAB	Radio Access Bearer
RACH	Random Access Channel
RAN	Radio Access Network
RA-RNTI	Random Access RNTI
RAT	Radio Access Technology
RB	Resource Block
RE	Resource Element
RF	Radio Frequency
RI	Rank Indicator
RIT	Radio Interface Technology
RLC	Radio Link Control
RNC	Radio Network Controller
RNTI	Radio-Network Temporary Identifier
RNTP	Relative Narrowband Transmit Power
ROHC	Robust Header Compression
R-PDCCH	Relay Physical Downlink Control Channel
RR	Round-Robin (a type of scheduler)
RRC	Radio Resource Control
RRM	Radio Resource Management
RS	Reference Symbol
RSPC	IMT-2000 radio interface specifications
RSRP	Reference Signal Received Power
RSRQ	Reference Signal Received Quality
RTP	Real Time Protocol
RTT	Round-Trip Time
RV	Redundancy Version
RX	Receiver
S1	The interface between eNodeB and the Evolved Packet Core.
S1-c	The control-plane part of S1
S1-u	The user-plane part of S1
SAE	System Architecture Evolution
SCM	Spatial Channel Model
SDMA	Spatial Division Multiple Access
SDO	Standards Developing Organization
SDU	Service Data Unit
SEM	Spectrum Emissions Mask

SF	Spreading Factor
SFBC	Space-Frequency Block Coding
SFN	Single-Frequency Network (in general, see also MBSFN) or System Frame Number (in 3GPP)
SFTD	Space-Frequency Time Diversity
SGSN	Serving GPRS Support Node
S-GW	Serving Gateway
SI	System Information message
SIB	System Information Block
SIC	Successive Interference Combining
SIM	Subscriber Identity Module
SINR	Signal-to-Interference-and-Noise Ratio
SIR	Signal-to-Interference Ratio
SI-RNTI	System Information RNTI
SMS	Short Message Service
SNR	Signal-to-Noise Ratio
SOHO	Soft Handover
SORTD	Spatial Orthogonal-Resource Transmit Diversity
SR	Scheduling Request
SRS	Sounding Reference Signal
SSS	Secondary Synchronization Signal
STBC	Space-Time Block Coding
STC	Space-Time Coding
STTD	Space-Time Transmit Diversity
SU-MIMO	Single-User MIMO
TACS	Total Access Communication System
TCP	Transmission Control Protocol
TC-RNTI	Temporary C-RNTI
TD-CDMA	Time-Division Code-Division Multiple Access
TDD	Time-Division Duplex
TDM	Time-Division Multiplexing
TDMA	Time-Division Multiple Access
TD-SCDMA	Time-Division-Synchronous Code-Division Multiple Access
TF	Transport Format
TIA	Telecommunications Industry Association
TM	Transparent Mode (RLC configuration)
TR	Technical Report
TS	Technical Specification
TSG	Technical Specification Group
TTA	Telecommunications Technology Association
TTC	Telecommunications Technology Committee
TTI	Transmission Time Interval
TX	Transmitter

UCI	Uplink Control Information
UE	User Equipment, the 3GPP name for the mobile terminal
UL	Uplink
UL-SCH	Uplink Shared Channel
UM	Unacknowledged Mode (RLC configuration)
UMB	Ultra Mobile Broadband
UMTS	Universal Mobile Telecommunications System
UpPTS	The uplink part of the special subframe (for TDD operation).
US-TDMA	US Time-Division Multiple Access standard
UTRA	Universal Terrestrial Radio Access
UTRAN	Universal Terrestrial Radio Access Network
VAMOS	Voice services over Adaptive Multi-user channels
VoIP	Voice-over-IP
VRB	Virtual Resource Block
WAN	Wide Area Network
WARC	World Administrative Radio Congress
WCDMA	Wideband Code-Division Multiple Access
WG	Working Group
WiMAX	Worldwide Interoperability for Microwave Access
WLAN	Wireless Local Area Network
WMAN	Wireless Metropolitan Area Network
WP5D	Working Party 5D
WRC	World Radiocommunication Conference
X2	The interface between eNodeBs.
ZC	Zadoff-Chu
ZF	Zero Forcing



# Radio-Interface Architecture

# 8

This chapter contains a brief overview of the overall architecture of an LTE radio-access network and the associated core network, followed by descriptions of the radio-access network user-plane and control-plane protocols.

## 8.1 OVERALL SYSTEM ARCHITECTURE

In parallel to the work on the LTE radio-access technology in 3GPP, the overall system architecture of both the *Radio-Access Network* (RAN) and the *Core Network* (CN) was revisited, including the split of functionality between the two network parts. This work was known as the *System Architecture Evolution* (SAE) and resulted in a flat RAN architecture, as well as a new core network architecture referred to as the *Evolved Packet Core* (EPC). Together, the LTE RAN and the EPC can be referred to as the *Evolved Packet System* (EPS).<sup>1</sup>

The RAN is responsible for all radio-related functionality of the overall network including, for example, scheduling, radio-resource handling, retransmission protocols, coding and various multi-antenna schemes. These functions will be discussed in detail in the subsequent chapters.

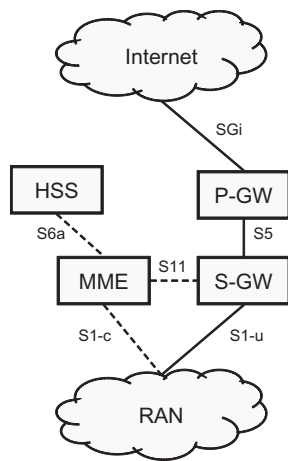
The EPC is responsible for functions not related to the radio interface but needed for providing a complete mobile-broadband network. This includes, for example, authentication, charging functionality, and setup of end-to-end connections. Handling these functions separately, instead of integrating them into the RAN, is beneficial as it allows for several radio-access technologies to be served by the same core network.

Although this book focuses on the LTE RAN, a brief overview of the EPC, as well as how it connects to the RAN, is useful. For an excellent in-depth discussion of EPC, the reader is referred to [9].

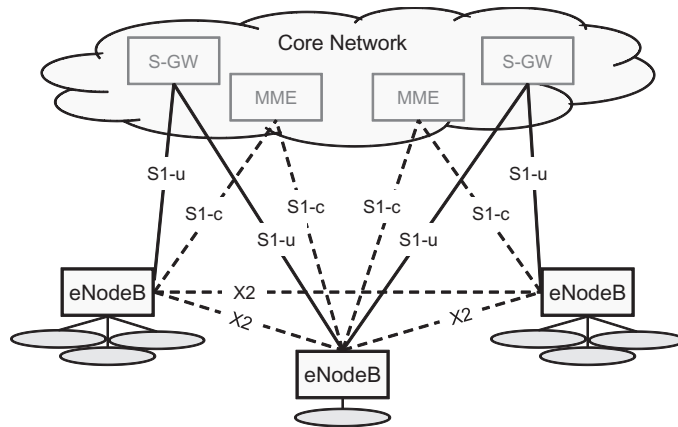
### 8.1.1 Core Network

The EPC is a radical evolution from the GSM/GPRS core network used for GSM and WCDMA/HSPA. EPC supports access to the *packet-switched domain* only, with no access to the *circuit-switched domain*. It consists of several different types of nodes, some of which are briefly described below and illustrated in [Figure 8.1](#).

<sup>1</sup>UTRAN, the WCDMA/HSPA radio-access network, is also part of the EPS.

**FIGURE 8.1**

Core-network (EPC) architecture.

**FIGURE 8.2**

Radio-access-network interfaces.

The *Mobility Management Entity* (MME) is the control-plane node of the EPC. Its responsibilities include connection/release of bearers to a terminal, handling of IDLE to ACTIVE transitions, and handling of security keys. The functionality operating between the EPC and the terminal is sometimes referred to as the *Non-Access Stratum* (NAS), to separate it from the *Access Stratum* (AS) which handles functionality operating between the terminal and the radio-access network.

The *Serving Gateway* (S-GW) is the user-plane node connecting the EPC to the LTE RAN. The S-GW acts as a mobility anchor when terminals move between eNodeBs (see next section), as well as a mobility anchor for other 3GPP technologies (GSM/GPRS and HSPA). Collection of information and statistics necessary for charging is also handled by the S-GW.

The *Packet Data Network Gateway* (PDN Gateway, P-GW) connects the EPC to the internet. Allocation of the IP address for a specific terminal is handled by the P-GW, as well as quality-of-service enforcement according to the policy controlled by the PCRF (see below). The P-GW is also the mobility anchor for non-3GPP radio-access technologies, such as CDMA2000, connected to the EPC.

In addition, the EPC also contains other types of nodes such as *Policy and Charging Rules Function* (PCRF) responsible for quality-of-service (QoS) handling and charging, and the *Home Subscriber Service* (HSS) node, a database containing subscriber information. There are also some additional nodes present as regards network support of *Multimedia Broadcast Multicast Services* (MBMS) (see Chapter 15 for a more detailed description of MBMS, including the related architecture aspects).

It should be noted that the nodes discussed above are *logical* nodes. In an actual physical implementation, several of them may very well be combined. For example, the MME, P-GW, and S-GW could very well be combined into a single physical node.

### 8.1.2 Radio-Access Network

The LTE radio-access network uses a flat architecture with a single type of node<sup>2</sup> – the *eNodeB*. The eNodeB is responsible for all radio-related functions in one or several cells. It is important to note that an eNodeB is a *logical* node and not a physical implementation. One common implementation of an eNodeB is a three-sector site, where a base station is handling transmissions in three cells, although other implementations can be found as well, such as one baseband processing unit to which a number of remote radio heads are connected. One example of the latter is a large number of indoor cells, or several cells along a highway, belonging to the same eNodeB. Thus, a base station is a *possible* implementation of, but not *the same* as, an eNodeB.

As can be seen in Figure 8.2, the eNodeB is connected to the EPC by means of the *S1 interface*, more specifically to the S-GW by means of the *S1 user-plane part*, S1-u, and to the MME by means of the *S1 control-plane part*, S1-c. One eNodeB can be connected to multiple MMEs/S-GWs for the purpose of load sharing and redundancy.

The *X2 interface*, connecting eNodeBs to each other, is mainly used to support active-mode mobility. This interface may also be used for multi-cell *Radio Resource Management* (RRM) functions such as *Inter-Cell Interference Coordination* (ICIC) discussed in Chapter 13. The X2 interface is also used to support lossless mobility between neighboring cells by means of packet forwarding.

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## 8.2 RADIO PROTOCOL ARCHITECTURE

With the overall network architecture in mind, the RAN protocol architecture for the user as well as the control planes can be discussed. Figure 8.3 illustrates the RAN protocol architecture (the MME is, as discussed in the previous section, not part of the RAN but is included in the figure for completeness). As seen in the figure, many of the protocol entities are common to the user and control planes. Therefore, although this section mainly describes the protocol architecture from a user-plane perspective, the description is in many respects also applicable to the control plane. Control-plane-specific aspects are discussed in Section 8.3.

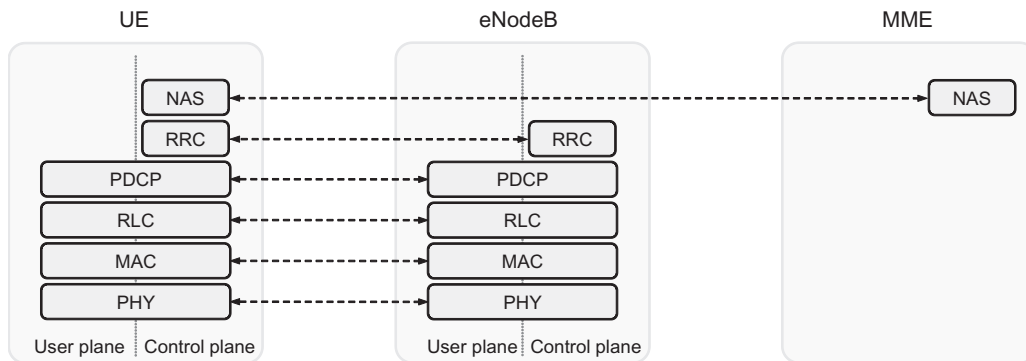
The LTE radio-access network provides one or more *Radio Bearers* to which IP packets are mapped according to their Quality-of-Service requirements. A general overview of the LTE (user-plane) protocol architecture for the downlink is illustrated in Figure 8.4. As will become clear in the subsequent discussion, not all the entities illustrated in Figure 8.4 are applicable in all situations. For example, neither MAC scheduling nor hybrid ARQ with soft combining is used for broadcast of the basic system information. The LTE protocol structure related to uplink transmissions is similar to the downlink structure in Figure 8.4, although there are some differences with respect to, for example, transport-format selection.

The different protocol entities of the radio-access network are summarized below and described in more detail in the following sections.

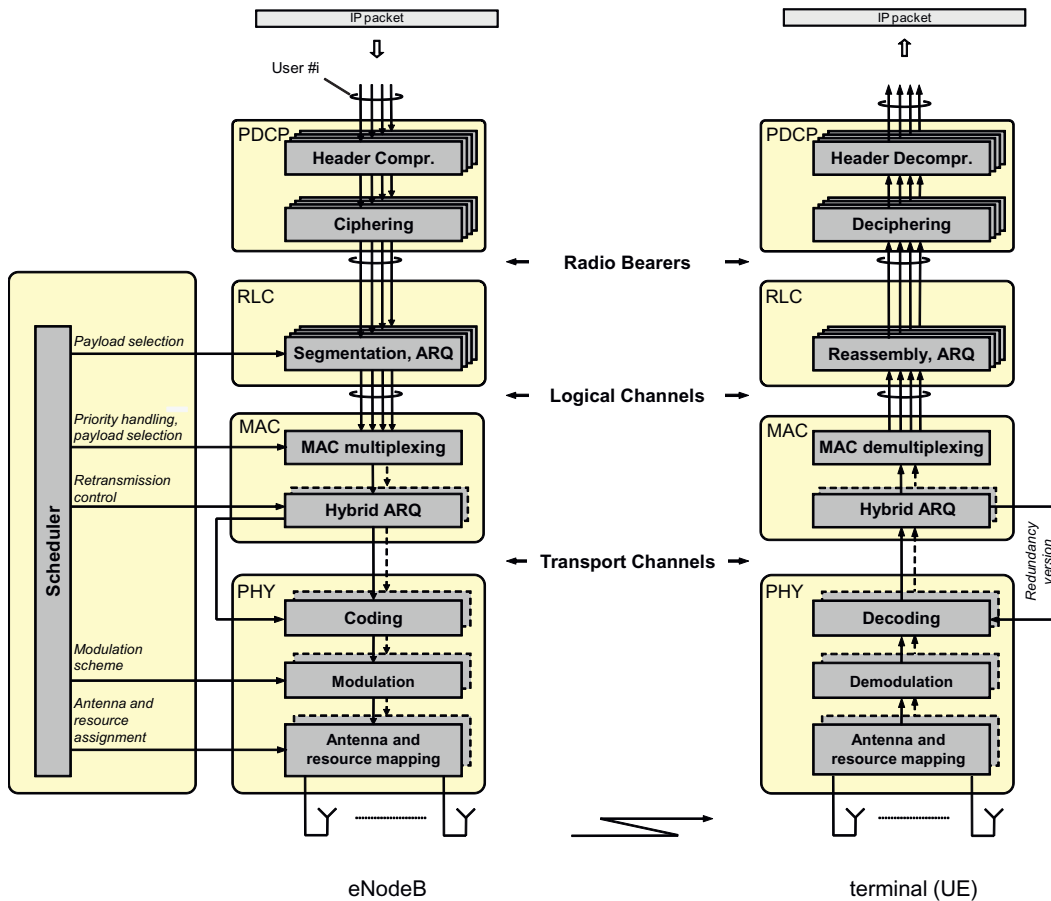
- *Packet Data Convergence Protocol* (PDCP) performs IP header compression to reduce the number of bits to transmit over the radio interface. The header-compression mechanism is based

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<sup>2</sup>The introduction of MBMS (see Chapter 15) in release 9 and relaying (see Chapter 16) in release 10 brings additional node types to the RAN.

**FIGURE 8.3**

Overall RAN protocol architecture.

**FIGURE 8.4**

LTE protocol architecture (downlink).

on Robust Header Compression (ROHC) [68], a standardized header-compression algorithm also used for several mobile-communication technologies. PDCP is also responsible for ciphering and, for the control plane, integrity protection of the transmitted data, as well as in-sequence delivery and duplicate removal for handover. At the receiver side, the PDCP protocol performs the corresponding deciphering and decompression operations. There is one PDCP entity per radio bearer configured for a terminal.

- *Radio-Link Control* (RLC) is responsible for segmentation/concatenation, retransmission handling, duplicate detection, and in-sequence delivery to higher layers. The RLC provides services to the PDCP in the form of *radio bearers*. There is one RLC entity per radio bearer configured for a terminal.
- *Medium-Access Control* (MAC) handles multiplexing of logical channels, hybrid-ARQ retransmissions, and uplink and downlink scheduling. The scheduling functionality is located in the eNodeB for both uplink and downlink. The hybrid-ARQ protocol part is present in both the transmitting and receiving ends of the MAC protocol. The MAC provides services to the RLC in the form of *logical channels*.
- *Physical Layer* (PHY) handles coding/decoding, modulation/demodulation, multi-antenna mapping, and other typical physical-layer functions. The physical layer offers services to the MAC layer in the form of *transport channels*.

To summarize the flow of downlink data through all the protocol layers, an example illustration for a case with three IP packets, two on one radio bearer and one on another radio bearer, is given in [Figure 8.5](#). The data flow in the case of uplink transmission is similar. The PDCP performs (optional) IP-header compression, followed by ciphering. A PDCP header is added, carrying information required for deciphering in the terminal. The output from the PDCP is forwarded to the RLC.

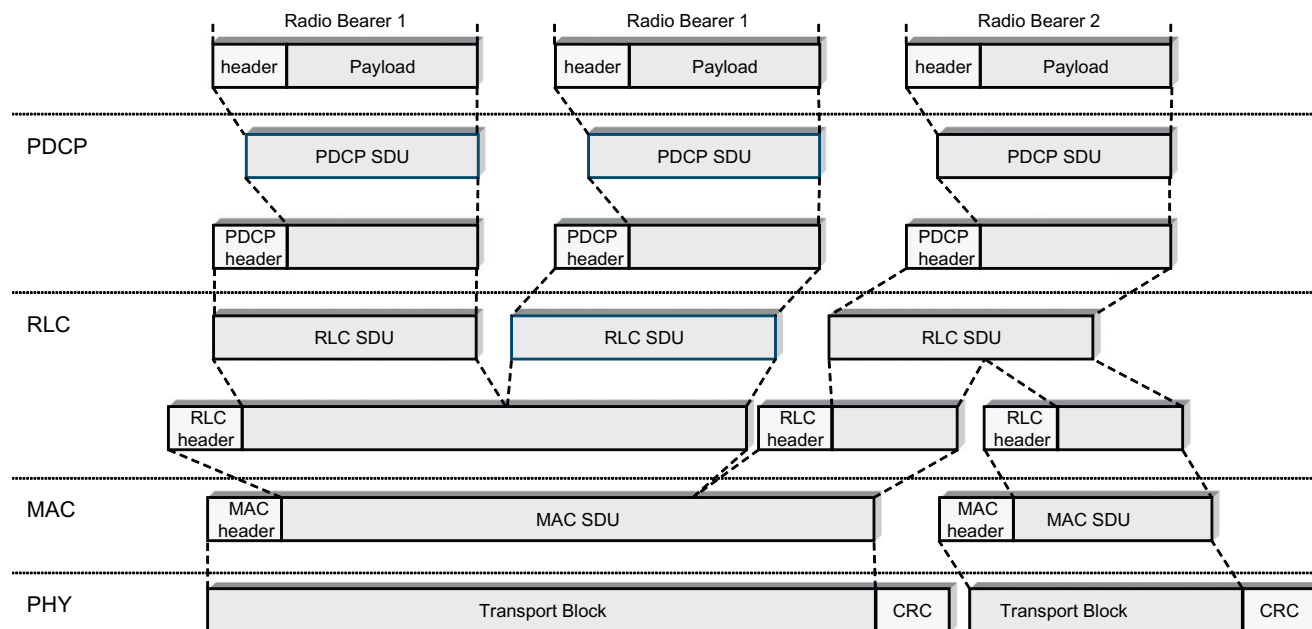
The RLC protocol performs concatenation and/or segmentation of the PDCP SDUs<sup>3</sup> and adds an RLC header. The header is used for in-sequence delivery (per logical channel) in the terminal and for identification of RLC PDUs in the case of retransmissions. The RLC PDUs are forwarded to the MAC layer, which multiplexes a number of RLC PDUs and attaches a MAC header to form a transport block. The transport-block size depends on the instantaneous data rate selected by the link-adaptation mechanism. Thus, the link adaptation affects both the MAC and RLC processing. Finally, the physical layer attaches a CRC to the transport block for error-detection purposes, performs coding and modulation, and transmits the resulting signal, possibly using multiple transmit antennas.

The remainder of the chapter contains an overview of the RLC, MAC, and physical layers. A more detailed description of the LTE physical-layer processing is given in Chapters 10 (downlink) and 11 (uplink), followed by descriptions of some specific uplink and downlink radio-interface functions and procedures in the subsequent chapters.

### 8.2.1 Radio-Link Control

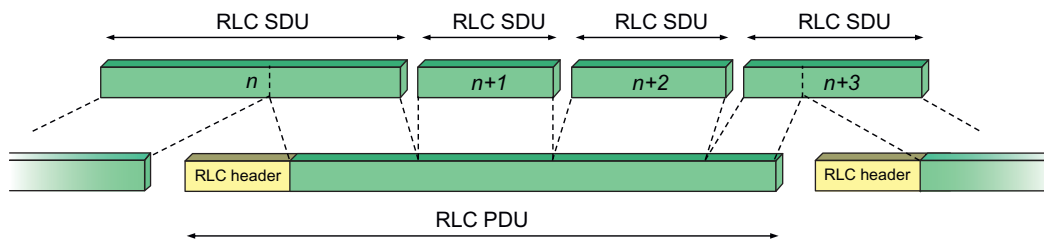
The RLC protocol is responsible for segmentation/concatenation of (header-compressed) IP packets, also known as RLC SDUs, from the PDCP into suitably sized RLC PDUs. It also handles

<sup>3</sup>In general, the data entity from/to a higher protocol layer is known as a Service Data Unit (SDU) and the corresponding entity to/from a lower protocol layer entity is called a Protocol Data Unit (PDU).



**FIGURE 8.5**

Example of LTE data flow.

**FIGURE 8.6**

RLC segmentation and concatenation.

retransmission of erroneously received PDUs, as well as removal of duplicated PDUs. Finally, the RLC ensures in-sequence delivery of SDUs to upper layers. Depending on the type of service, the RLC can be configured in different modes to perform some or all of these functions.

Segmentation and concatenation, one of the main RLC functions, is illustrated in Figure 8.6. Depending on the scheduler decision, a certain amount of data is selected for transmission from the RLC SDU buffer and the SDUs are segmented/concatenated to create the RLC PDU. Thus, for LTE the RLC PDU size varies *dynamically*. For high data rates, a large PDU size results in a smaller relative overhead, while for low data rates, a small PDU size is required as the payload would otherwise be too large. Hence, as the LTE data rates may range from a few kbit/s up to 3 Gbit/s, dynamic PDU sizes are motivated for LTE in contrast to earlier mobile-communication technologies, which typically use a fixed PDU size. Since the RLC, scheduler, and rate adaptation mechanisms are all located in the eNodeB, dynamic PDU sizes are easily supported for LTE. In each RLC PDU, a header is included, containing, among other things, a sequence number used for in-sequence delivery and by the retransmission mechanism.

The RLC retransmission mechanism is also responsible for providing error-free delivery of data to higher layers. To accomplish this, a retransmission protocol operates between the RLC entities in the receiver and transmitter. By monitoring the sequence numbers of the incoming PDUs, the receiving RLC can identify missing PDUs. Status reports are then fed back to the transmitting RLC entity, requesting retransmission of missing PDUs. Based on the received status report, the RLC entity at the transmitter can take the appropriate action and retransmit the missing PDUs if needed.

Although the RLC is capable of handling transmission errors due to noise, unpredictable channel variations, etc., error-free delivery is in most cases handled by the MAC-based hybrid-ARQ protocol. The use of a retransmission mechanism in the RLC may therefore seem superfluous at first. However, as will be discussed in Section 8.2.2.3, this is not the case and the use of both RLC- and MAC-based retransmission mechanisms is in fact well motivated by the differences in the feedback signaling.

The details of RLC are further described in Chapter 12.

### 8.2.2 Medium-Access Control

The MAC layer handles logical-channel multiplexing, hybrid-ARQ retransmissions, and uplink and downlink scheduling. It is also responsible for multiplexing/demultiplexing data across multiple component carriers when carrier aggregation is used.

### 8.2.2.1 Logical Channels and Transport Channels

The MAC provides services to the RLC in the form of *logical channels*. A logical channel is defined by the *type* of information it carries and is generally classified as a *control channel*, used for transmission of control and configuration information necessary for operating an LTE system, or as a *traffic channel*, used for the user data. The set of logical-channel types specified for LTE includes:

- The *Broadcast Control Channel* (BCCH), used for transmission of *system information* from the network to all terminals in a cell. Prior to accessing the system, a terminal needs to acquire the system information to find out how the system is configured and, in general, how to behave properly within a cell.
- The *Paging Control Channel* (PCCH), used for paging of terminals whose location on a cell level is not known to the network. The paging message therefore needs to be transmitted in multiple cells.
- The *Common Control Channel* (CCCH), used for transmission of control information in conjunction with random access.
- The *Dedicated Control Channel* (DCCH), used for transmission of control information to/from a terminal. This channel is used for individual configuration of terminals such as different handover messages.
- The *Multicast Control Channel* (MCCH), used for transmission of control information required for reception of the MTCH (see below).
- The *Dedicated Traffic Channel* (DTCH), used for transmission of user data to/from a terminal. This is the logical channel type used for transmission of all uplink and non-MBSFN downlink user data.
- The *Multicast Traffic Channel* (MTCH), used for downlink transmission of MBMS services.

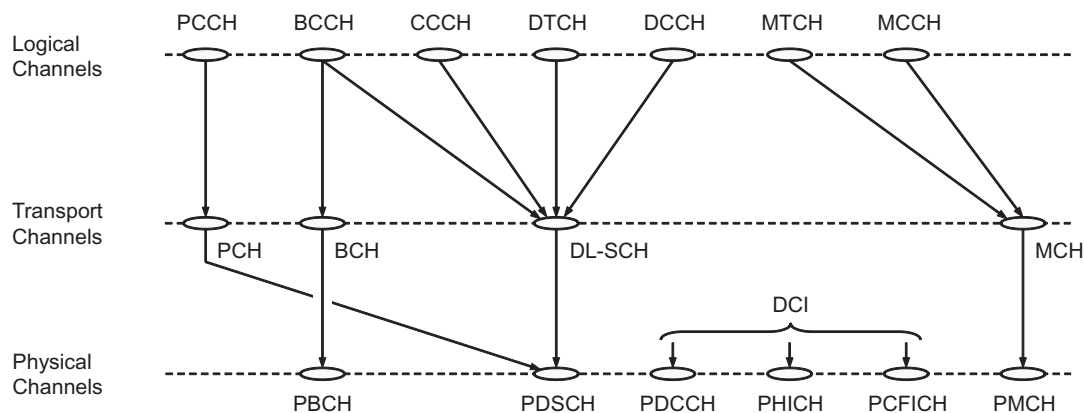
From the physical layer, the MAC layer uses services in the form of *transport channels*. A transport channel is defined by *how* and *with what characteristics* the information is transmitted over the radio interface. Data on a transport channel is organized into *transport blocks*. In each *Transmission Time Interval* (TTI), at most one transport block of dynamic size is transmitted over the radio interface to/from a terminal in the absence of spatial multiplexing. In the case of spatial multiplexing (MIMO), there can be up to two transport blocks per TTI.

Associated with each transport block is a *Transport Format* (TF), specifying *how* the transport block is to be transmitted over the radio interface. The transport format includes information about the transport-block size, the modulation-and-coding scheme, and the antenna mapping. By varying the transport format, the MAC layer can thus realize different data rates. Rate control is therefore also known as *transport-format selection*.

The following transport-channel types are defined for LTE:

- The *Broadcast Channel* (BCH) has a fixed transport format, provided by the specifications. It is used for transmission of parts of the BCCH system information, more specifically the so-called *Master Information Block* (MIB), as described in Chapter 14.
- The *Paging Channel* (PCH) is used for transmission of paging information from the PCCH logical channel. The PCH supports *discontinuous reception* (DRX) to allow the terminal to save battery power by waking up to receive the PCH only at predefined time instants. The LTE paging mechanism is also described in Chapter 14.



**FIGURE 8.7**

Downlink channel mapping.

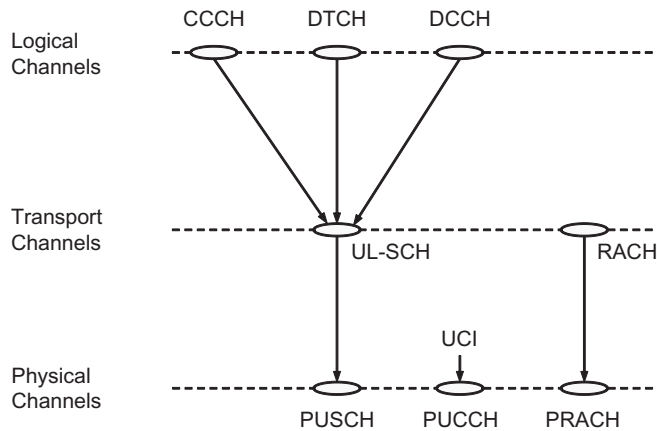
- The *Downlink Shared Channel* (DL-SCH) is the main transport channel used for transmission of downlink data in LTE. It supports key LTE features such as dynamic rate adaptation and channel-dependent scheduling in the time and frequency domains, hybrid ARQ with soft combining, and spatial multiplexing. It also supports DRX to reduce terminal power consumption while still providing an always-on experience. The DL-SCH is also used for transmission of the parts of the BCCH system information not mapped to the BCH. There can be multiple DL-SCHs in a cell, one per terminal<sup>4</sup> scheduled in this TTI, and, in some subframes, one DL-SCH carrying system information.
- The *Multicast Channel* (MCH) is used to support MBMS. It is characterized by a semi-static transport format and semi-static scheduling. In the case of multi-cell transmission using MBSFN, the scheduling and transport format configuration is coordinated among the transmission points involved in the MBSFN transmission. MBSFN transmission is described in Chapter 15.
- The Uplink Shared Channel (UL-SCH) is the uplink counterpart to the DL-SCH – that is, the uplink transport channel used for transmission of uplink data.

In addition, the *Random-Access Channel* (RACH) is also defined as a transport channel, although it does not carry transport blocks.

Part of the MAC functionality is multiplexing of different logical channels and mapping of the logical channels to the appropriate transport channels. The supported mappings between logical-channel types and transport-channel types are given in Figure 8.7 for the downlink and Figure 8.8 for the uplink. The figures clearly indicate how DL-SCH and UL-SCH are the main downlink and uplink transport channels respectively. In the figures, the corresponding physical channels, described further below, are also included and the mapping between transport channels and physical channels is illustrated.

To support priority handling, multiple logical channels, where each logical channel has its own RLC entity, can be multiplexed into one transport channel by the MAC layer. At the receiver, the

<sup>4</sup>For carrier aggregation, a UE may receive multiple DL-SCHs, one per component carrier.

**FIGURE 8.8**

Uplink channel mapping.

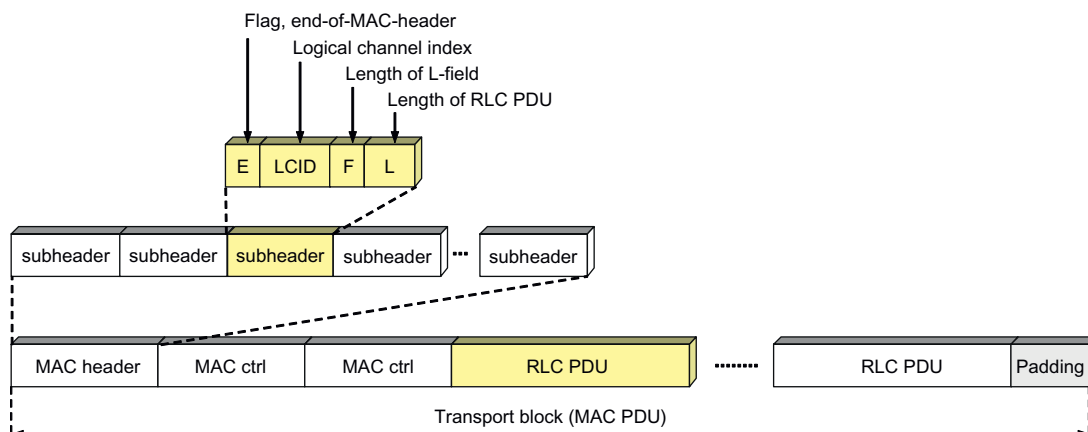
MAC layer handles the corresponding demultiplexing and forwards the RLC PDUs to their respective RLC entity for in-sequence delivery and the other functions handled by the RLC. To support the demultiplexing at the receiver, a MAC header, shown in Figure 8.9, is used. To each RLC PDU, there is an associated sub-header in the MAC header. The sub-header contains the identity of the logical channel (LCID) from which the RLC PDU originated and the length of the PDU in bytes. There is also a flag indicating whether this is the last sub-header or not. One or several RLC PDUs, together with the MAC header and, if necessary, padding to meet the scheduled transport-block size, form one transport block which is forwarded to the physical layer.

In addition to multiplexing of different logical channels, the MAC layer can also insert the so-called *MAC control elements* into the transport blocks to be transmitted over the transport channels. A MAC control element is used for inband control signaling – for example, timing-advance commands and random-access response, as described in Sections 11.5 and 14.3 respectively. Control elements are identified with reserved values in the LCID field, where the LCID value indicates the type of control information. Furthermore, the length field in the sub-header is removed for control elements with a fixed length.

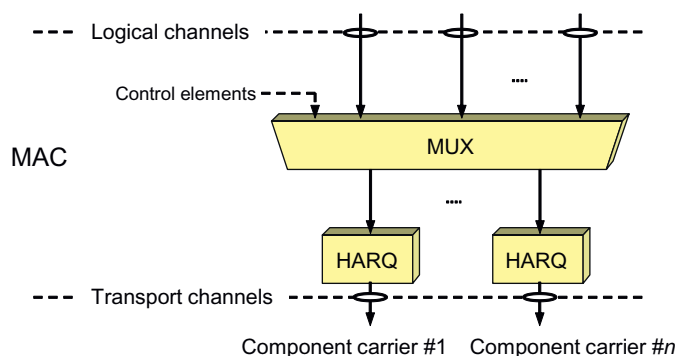
The MAC multiplexing functionality is also responsible for handling of multiple component carriers in the case of carrier aggregation. The basic principle for carrier aggregation is independent processing of the component carriers in the physical layer, including control signaling, scheduling and hybrid-ARQ retransmissions, while carrier aggregation is invisible to RLC and PDCP. Carrier aggregation is therefore mainly seen in the MAC layer, as illustrated in Figure 8.10, where logical channels, including any MAC control elements, are multiplexed to form one (two in the case of spatial multiplexing) transport block(s) per component carrier with each component carrier having its own hybrid-ARQ entity.

### 8.2.2.2 Scheduling

One of the basic principles of LTE radio access is shared-channel transmission – that is, time-frequency resources are dynamically shared between users. The *scheduler* is part of the MAC layer

**FIGURE 8.9**

MAC header and SDU multiplexing.

**FIGURE 8.10**

MAC operation in the case of multiple component carriers.

(although often better viewed as a separate entity as illustrated in Figure 8.4) and controls the assignment of uplink and downlink resources in terms of so-called *resource-block pairs*. Resource blocks correspond to a time–frequency unit of 1 ms times 180 kHz, as described in more detail in Chapter 9.

The basic operation of the scheduler is so-called *dynamic* scheduling, where the eNodeB in each 1 ms interval takes a scheduling decision and sends scheduling information to the selected set of terminals. However, there is also a possibility for semi-persistent scheduling where a semi-static scheduling pattern is signaled in advance to reduce the control-signaling overhead. Coordination of scheduling decisions across multiple cells residing in different eNodeBs is supported using signaling over the X2 interface.

Uplink and downlink scheduling are separated in LTE, and uplink and downlink scheduling decisions can be taken independently of each other (within the limits set by the uplink/downlink split in the case of half-duplex FDD operation).

The downlink scheduler is responsible for (dynamically) controlling which terminal(s) to transmit to and, for each of these terminals, the set of resource blocks upon which the terminal's DL-SCH should be transmitted. Transport-format selection (selection of transport-block size, modulation scheme, and antenna mapping) and logical-channel multiplexing for downlink transmissions are controlled by the eNodeB, as illustrated in the left part of Figure 8.11. As a consequence of the scheduler controlling the data rate, the RLC segmentation and MAC multiplexing will also be affected by the scheduling decision. The outputs from the downlink scheduler can be seen in Figure 8.4.

The uplink scheduler serves a similar purpose, namely to (dynamically) control which terminals are to transmit on their respective UL-SCH and on which uplink time–frequency resources (including component carrier). Despite the fact that the eNodeB scheduler determines the transport format for the terminal, it is important to point out that the uplink scheduling decision is taken *per terminal* and not per radio bearer. Thus, although the eNodeB scheduler controls the payload of a scheduled terminal, the terminal is still responsible for selecting *from which radio bearer(s)* the data is taken. The terminal autonomously handles logical-channel multiplexing according to rules, the parameters of which can be configured by the eNodeB. This is illustrated in the right part of Figure 8.11, where the eNodeB scheduler controls the transport format and the terminal controls the logical-channel multiplexing.

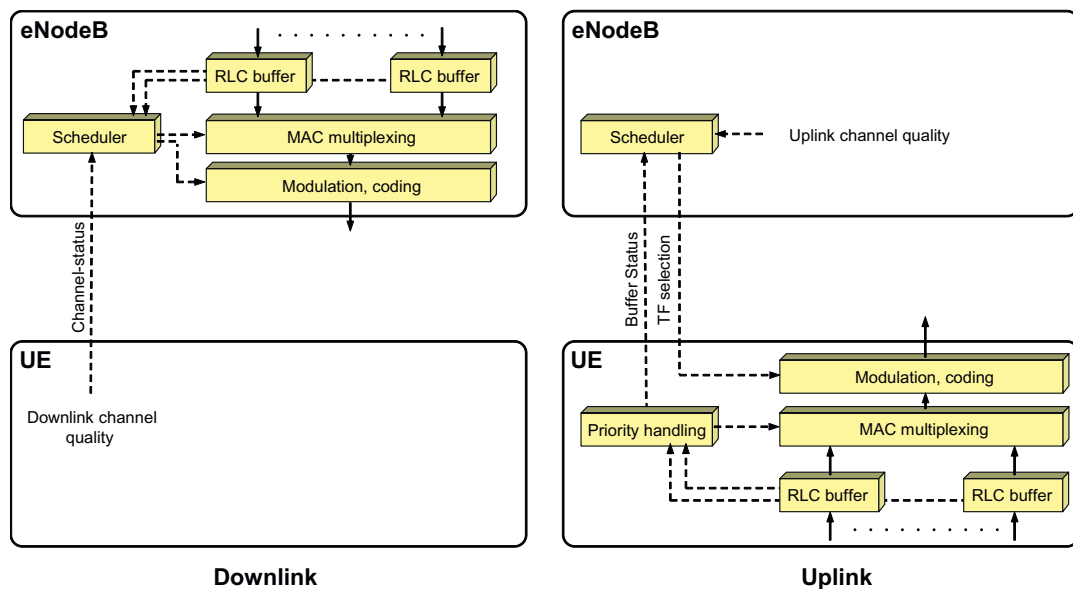


FIGURE 8.11

Transport-format selection in downlink and uplink.

Although the scheduling strategy is implementation specific and not specified by 3GPP, the overall goal of most schedulers is to take advantage of the channel variations between terminals and preferably schedule transmissions to a terminal on resources with advantageous channel conditions. A benefit of the use of OFDM in LTE is the possibility to exploit channel variations in both time and frequency domains through channel-dependent scheduling. This was mentioned earlier in Chapter 7 and illustrated in Figure 7.2. For the larger bandwidths supported by LTE, where a significant amount of frequency-selective fading will often be experienced, the possibility for the scheduler to also exploit frequency-domain channel variations becomes increasingly important compared to exploiting time-domain variations only. The possibility to also exploit frequency-domain variations is beneficial especially at low speeds, where the variations in the time domain are relatively slow compared to the delay requirements set by many services.

Downlink channel-dependent scheduling is supported through *channel-state reports*, transmitted by the UE and reflecting the instantaneous channel quality in the time and frequency domains, as well as information necessary to determine the appropriate antenna processing in the case of spatial multiplexing. In the uplink, the channel-state information necessary for uplink channel-dependent scheduling can be based on a *sounding reference signal* transmitted from each terminal for which the eNodeB wants to estimate the uplink channel quality. To aid the uplink scheduler in its decisions, the terminal can transmit buffer-status information to the eNodeB using a MAC message. Obviously, this information can only be transmitted if the terminal has been given a valid scheduling grant. For situations when this is not the case, an indicator that the terminal needs uplink resources is provided as part of the uplink L1/L2 control-signaling structure (see Chapter 11).

Interference coordination, which tries to control the inter-cell interference on a slow basis, as mentioned in Chapter 7, is also part of the scheduler. As the scheduling strategy is not mandated by the specifications, the interference-coordination scheme (if used) is vendor specific and may range from simple higher-order reuse deployments to more advanced schemes. The mechanisms supporting inter-cell interference coordination are discussed in Chapter 13.

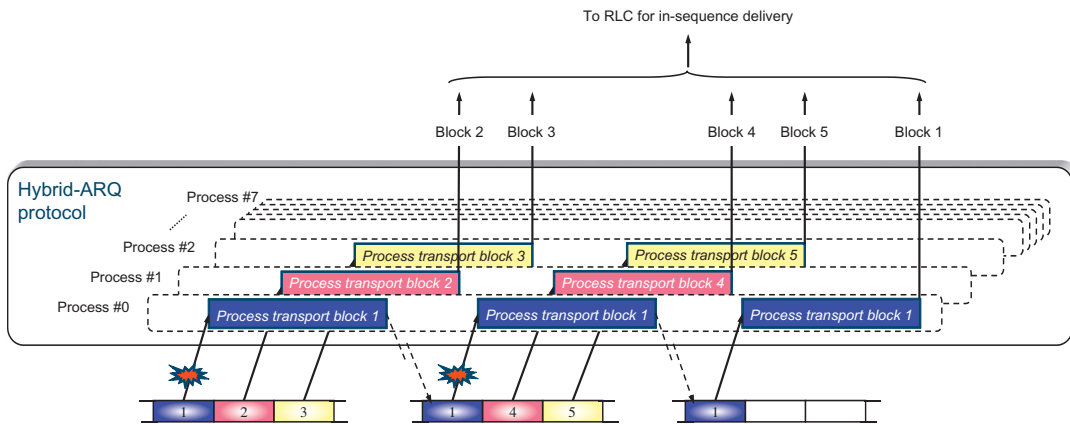
### 8.2.2.3 Hybrid ARQ with Soft Combining

Hybrid ARQ with soft combining provides robustness against transmission errors. As hybrid-ARQ retransmissions are fast, many services allow for one or multiple retransmissions, thereby forming an implicit (closed loop) rate-control mechanism. The hybrid-ARQ protocol is part of the MAC layer, while the actual soft combining is handled by the physical layer.<sup>5</sup>

Obviously, hybrid ARQ is not applicable for all types of traffic. For example, broadcast transmissions, where the same information is intended for multiple terminals, typically do not rely on hybrid ARQ. Hence, hybrid ARQ is only supported for the DL-SCH and the UL-SCH, although its usage is optional.

The LTE hybrid-ARQ protocol uses multiple parallel stop-and-wait processes. Upon reception of a transport block, the receiver makes an attempt to decode the transport block and informs the transmitter about the outcome of the decoding operation through a single acknowledgement bit indicating whether the decoding was successful or if a retransmission of the transport block is required. Further details on transmission of hybrid-ARQ acknowledgements are found in Chapters 10–12. Clearly, the receiver must know to which hybrid-ARQ process a received acknowledgement is associated. This is

<sup>5</sup>The soft combining is done before or as part of the channel decoding, which clearly is a physical-layer functionality.

**FIGURE 8.12**

Multiple parallel hybrid-ARQ processes.

solved by using the timing of the acknowledgement for association with a certain hybrid-ARQ process. Note that, in the case of TDD operation, the time relation between the reception of data in a certain hybrid-ARQ process and the transmission of the acknowledgement is also affected by the uplink/downlink allocation.

The use of multiple parallel hybrid-ARQ processes, illustrated in Figure 8.12, for each user can result in data being delivered from the hybrid-ARQ mechanism out of sequence. For example, transport block 5 in the figure was successfully decoded before transport block 1 which required retransmissions. In-sequence delivery of data is therefore ensured by the RLC layer. The same reordering mechanism in the RLC is also used to handle in-sequence delivery across multiple component carriers in the case of carrier aggregation. As mentioned above, the hybrid-ARQ retransmissions are handled independently per component carrier, which may result in out-of-sequence delivery in a similar way as within a component carrier.

Downlink retransmissions may occur at any time after the initial transmission – that is, the protocol is asynchronous – and an explicit hybrid-ARQ process number is used to indicate which process is being addressed. In an asynchronous hybrid-ARQ protocol, the retransmissions are in principle scheduled similarly to the initial transmissions. Uplink retransmissions, on the other hand, are based on a synchronous protocol, the retransmission occurs at a predefined time after the initial transmission and the process number can be implicitly derived. In a synchronous protocol the time instant for the retransmissions is fixed once the initial transmission has been scheduled, which must be accounted for in the scheduling operation. However, note that the scheduler knows from the hybrid-ARQ entity in the eNodeB whether a terminal will perform a retransmission or not.

The hybrid-ARQ mechanism will rapidly correct transmission errors due to noise or unpredictable channel variations. As discussed above, the RLC is also capable of requesting retransmissions, which at first sight may seem unnecessary. However, the reason for having two retransmission mechanisms on top of each other can be seen in the feedback signaling – hybrid ARQ provides fast retransmissions but due to errors in the feedback the residual error rate is typically too high for, for example,

good TCP performance, while RLC ensures (almost) error-free data delivery but slower retransmissions than the hybrid-ARQ protocol. Hence, the combination of hybrid ARQ and RLC provides an attractive combination of small round-trip time and reliable data delivery. Furthermore, as the RLC and hybrid ARQ are located in the same node, tight interaction between the two is possible, as discussed in Chapter 12.

### 8.2.3 Physical Layer

The physical layer is responsible for coding, physical-layer hybrid-ARQ processing, modulation, multi-antenna processing, and mapping of the signal to the appropriate physical time–frequency resources. It also handles mapping of transport channels to physical channels, as shown in Figures 8.7 and 8.8.

As mentioned in the introduction, the physical layer provides services to the MAC layer in the form of transport channels. Data transmission in downlink and uplink use the DL-SCH and UL-SCH transport-channel types respectively. There is at most one or, in the case of spatial multiplexing, two transport blocks per TTI on a DL-SCH or UL-SCH. In the case of carrier aggregation, there is one DL-SCH (or UL-SCH) per component carrier.

A *physical channel* corresponds to the set of time–frequency resources used for transmission of a particular transport channel and each transport channel is mapped to a corresponding physical channel, as shown in Figures 8.7 and 8.8. In addition to the physical channels with a corresponding transport channel, there are also physical channels without a corresponding transport channel. These channels, known as L1/L2 control channels, are used for *downlink control information* (DCI), providing the terminal with the necessary information for proper reception and decoding of the downlink data transmission, and *uplink control information* (UCI) used for providing the scheduler and the hybrid-ARQ protocol with information about the situation at the terminal.

The physical-channel types defined in LTE include the following:

- The *Physical Downlink Shared Channel* (PDSCH) is the main physical channel used for unicast data transmission, but also for transmission of paging information.
- The *Physical Broadcast Channel* (PBCH) carries part of the system information, required by the terminal in order to access the network.
- The *Physical Multicast Channel* (PMCH) is used for MBSFN operation.
- The *Physical Downlink Control Channel* (PDCCH) is used for downlink control information, mainly scheduling decisions, required for reception of PDSCH, and for scheduling grants enabling transmission on the PUSCH.
- The *Physical Hybrid-ARQ Indicator Channel* (PHICH) carries the hybrid-ARQ acknowledgement to indicate to the terminal whether a transport block should be retransmitted or not.
- The *Physical Control Format Indicator Channel* (PCFICH) is a channel providing the terminals with information necessary to decode the set of PDCCHs. There is only one PCFICH per component carrier.
- The *Physical Uplink Shared Channel* (PUSCH) is the uplink counterpart to the PDSCH. There is at most one PUSCH per uplink component carrier per terminal.
- The *Physical Uplink Control Channel* (PUCCH) is used by the terminal to send hybrid-ARQ acknowledgements, indicating to the eNodeB whether the downlink transport block(s) was successfully received or not, to send channel-state reports aiding downlink channel-dependent scheduling, and for requesting resources to transmit uplink data upon. There is at most one PUCCH per terminal.



- The *Physical Random-Access Channel* (PRACH) is used for random access, as described in Chapter 14.

Note that some of the physical channels, more specifically the channels used for downlink control information (PCFICH, PDCCH, PHICH) and uplink control information (PUCCH), do not have a corresponding transport channel.

The remaining downlink transport channels are based on the same general physical-layer processing as the DL-SCH, although with some restrictions in the set of features used. This is especially true for PCH and MCH transport channels. For the broadcast of system information on the BCH, a terminal must be able to receive this information channel as one of the first steps prior to accessing the system. Consequently, the transmission format must be known to the terminals a priori and there is no dynamic control of any of the transmission parameters from the MAC layer in this case. The BCH is also mapped to the physical resource (the OFDM time–frequency grid) in a different way, as described in more detail in Chapter 14.

For transmission of paging messages on the PCH, dynamic adaptation of the transmission parameters can, to some extent, be used. In general, the processing in this case is similar to the generic DL-SCH processing. The MAC can control modulation, the amount of resources, and the antenna mapping. However, as an uplink has not yet been established when a terminal is paged, hybrid ARQ cannot be used as there is no possibility for the terminal to transmit a hybrid-ARQ acknowledgement.

The MCH is used for MBMS transmissions, typically with single-frequency network operation, as described in Chapter 3, by transmitting from multiple cells on the same resources with the same format at the same time. Hence, the scheduling of MCH transmissions must be coordinated between the cells involved and dynamic selection of transmission parameters by the MAC is not possible.

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### 8.3 CONTROL-PLANE PROTOCOLS

The control-plane protocols are, among other things, responsible for connection setup, mobility, and security. Control messages transmitted from the network to the terminals can originate either from the MME, located in the core network, or from the *Radio Resource Control* (RRC), located in the eNodeB.

NAS control-plane functionality, handled by the MME, includes EPS bearer management, authentication, security, and different idle-mode procedures such as paging. It is also responsible for assigning an IP address to a terminal. For a detailed discussion about the NAS control-plane functionality, see [9].

The RRC is located in the eNodeB and is responsible for handling the RAN-related procedures, including:

- Broadcast of system information necessary for the terminal to be able to communicate with a cell. Acquisition of system information is described in Chapter 14.
- Transmission of paging messages originating from the MME to notify the terminal about incoming connection requests. Paging, discussed further in Chapter 14, is used in the RRC\_IDLE state (described further below) when the terminal is not connected to a particular cell. Indication of system-information update is another use of the paging mechanism, as is public warning systems.



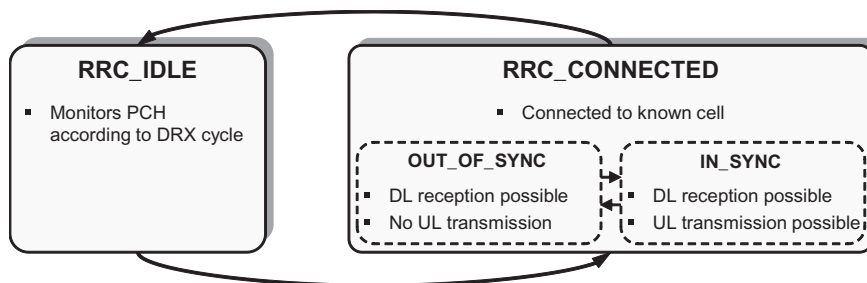
- Connection management, including setting up bearers and mobility within LTE. This includes establishing an RRC context – that is, configuring the parameters necessary for communication between the terminal and the radio-access network.
- Mobility functions such as cell (re)selection.
- Measurement configuration and reporting.
- Handling of UE capabilities; when connection is established the terminal will announce its capabilities as all terminals are not capable of supporting all the functionality described in the LTE specifications, as briefly discussed in Chapter 7.

RRC messages are transmitted to the terminal using *signaling radio bearers* (SRBs), using the same set of protocol layers (PDCP, RLC, MAC and PHY) as described in Section 8.2. The SRB is mapped to the common control channel (CCCH) during establishment of connection and, once a connection is established, to the dedicated control channel (DCCH). Control-plane and user-plane data can be multiplexed in the MAC layer and transmitted to the terminal in the same TTI. The aforementioned MAC control elements can also be used for control of radio resources in some specific cases where low latency is more important than ciphering, integrity protection, and reliable transfer.

### 8.3.1 State Machine

In LTE, a terminal can be in two different states, as illustrated in Figure 8.13, RRC\_CONNECTED and RRC\_IDLE.

In RRC\_CONNECTED, there is an RRC context established – that is, the parameters necessary for communication between the terminal and the radio-access network are known to both entities. The cell to which the terminal belongs is known and an identity of the terminal, the *Cell Radio-Network Temporary Identifier* (C-RNTI), used for signaling purposes between the terminal and the network, has been configured. RRC\_CONNECTED is intended for data transfer to/from the terminal, but *discontinuous reception* (DRX) can be configured in order to reduce terminal power consumption (DRX is described in further detail in Chapter 13). Since there is an RRC context established in the eNodeB in RRC\_CONNECTED, leaving DRX and starting to receive/transmit data is relatively fast as no connection with its associated signaling is needed.



**FIGURE 8.13**

LTE states.

Although expressed differently in the specifications, RRC\_CONNECTED can be thought of as having two substates, IN\_SYNC and OUT\_OF\_SYNC, depending on whether the uplink is synchronized to the network or not. Since LTE uses an orthogonal FDMA/TDMA-based uplink, it is necessary to synchronize the uplink transmission from different terminals such that they arrive at the receiver at (approximately) the same time. The procedure for obtaining and maintaining uplink synchronization is described in Chapter 11, but in short the receiver measures the arrival time of the transmissions from each actively transmitting terminal and sends timing-correction commands in the downlink. As long as the uplink is synchronized, uplink transmission of user data and L1/L2 control signaling is possible. If no uplink transmission has taken place within a configurable time window, timing alignment is obviously not possible and the uplink is declared to be non-synchronized. In this case, the terminal needs to perform a random-access procedure to restore uplink synchronization prior to transmission of uplink data or control information.

In RRC\_IDLE, there is no RRC context in the radio-access network and the terminal does not belong to a specific cell. No data transfer may take place as the terminal sleeps most of the time in order to reduce battery consumption. Uplink synchronization is not maintained and hence the only uplink transmission activity that may take place is random access, discussed in Chapter 14, to move to RRC\_CONNECTED. When moving to RRC\_CONNECTED the RRC context needs to be established in both the radio-access network and the terminal. Compared to leaving DRX this takes a somewhat longer time. In the downlink, terminals in RRC\_IDLE periodically wake up in order to receive paging messages, if any, from the network, as described in Chapter 14.