CHAPTER

RADIO-INTERFACE ARCHITECTURE

4

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

4.1 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 and the core network was revisited, including the split of functionality between the two networks. 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 are referred to as the *evolved packet system* (EPS).[1]

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 are discussed in detail in the subsequent chapters.

The EPC is responsible for functions not related to the radio access 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 CN.

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 [5].

4.1.1 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 in the following and illustrated in Figure 4.1.

[1]UTRAN, the WCDMA/HSPA RAN, is also part of the EPS.

4G, LTE-Advanced Pro and The Road to 5G. http://dx.doi.org/10.1016/B978-0-12-804575-6.00004-2

The *mobility management entity* (MME) is the control-plane node of the EPC. Its responsibilities include connection/release of bearers to a device, handling of IDLE to ACTIVE transitions, and handling of security keys. The functionality operating between the EPC and the device is sometimes referred to as the *non-access stratum* (NAS), to separate it from the *access stratum* (AS) which handles functionality operating between the device and the RAN.

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 devices 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 device is handled by the P-GW, as well as quality-of-service (QoS) enforcement according to the policy controlled by the PCRF (see later). 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 QoS handling and charging, and the *home subscriber service*

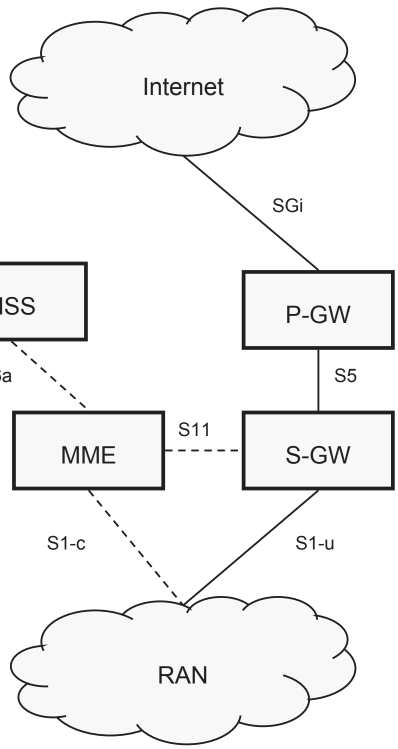

FIGURE 4.1

Core network architecture.

(HSS) node, a database containing subscriber information. There are also some additional nodes present with regard to network support of *multimedia broadcast multicast services* (MBMS) (see Chapter 19 for a more detailed description of MBMS, including the related architecture aspects).

It should be noted that the nodes discussed earlier 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.

4.1.2 RADIO-ACCESS NETWORK

The LTE RAN uses a flat architecture with a single type of node[2]—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 4.2, 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

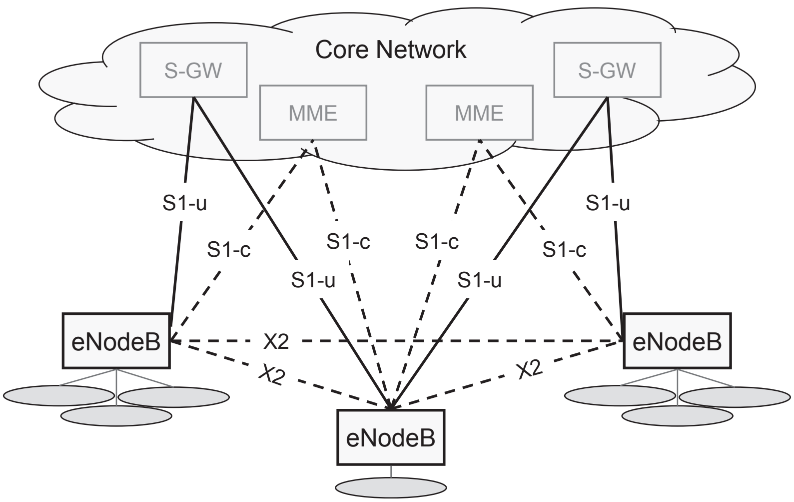

FIGURE 4.2

Radio-access network interfaces.

[2]The introduction of MBMS (see Chapter 19) in release 9 and relaying (see Chapter 18) in release 10 bring additional node types to the RAN.

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.

The interface between the eNodeB to the device is known as the *Uu interface*. Unless dual connectivity is used, see Chapter 16, a device is connected to a single eNodeB as a time. There is also a *PC5 interface* defined for direct device-to-device communication, see Chapter 21.

4.2 RADIO PROTOCOL ARCHITECTURE

With the overall network architecture in mind, the RAN protocol architecture for the user and control planes can be discussed. Figure 4.3 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 4.3.

The LTE RAN provides one or more *radio bearers* to which IP packets are mapped according to their QoS requirements. A general overview of the LTE (user-plane) protocol architecture for the downlink is illustrated in Figure 4.4. As will become clear in the subsequent discussion, not all the entities illustrated in Figure 4.4 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

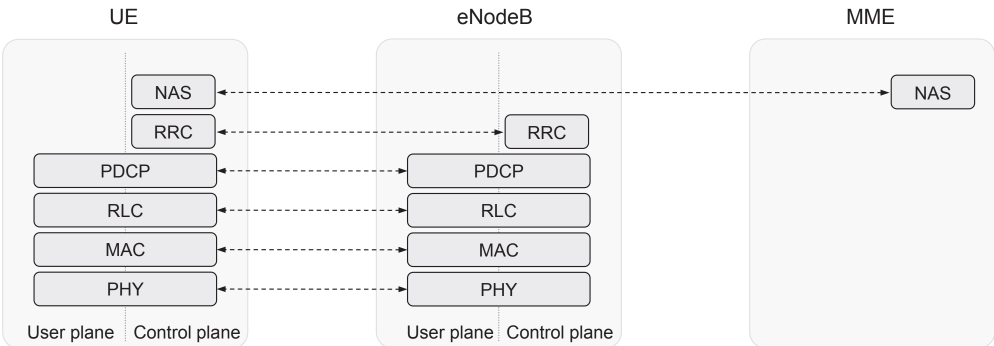

FIGURE 4.3

Overall RAN protocol architecture.

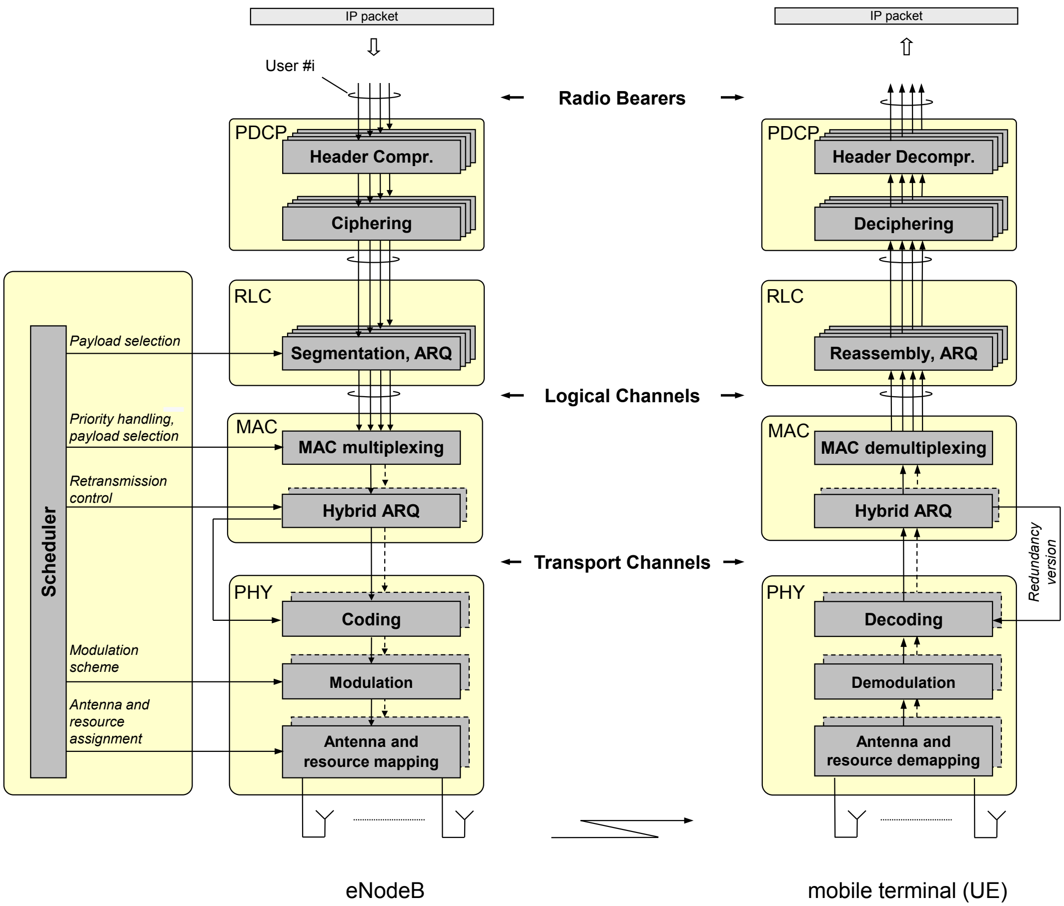

FIGURE 4.4

LTE protocol architecture (downlink).

transmissions is similar to the downlink structure in Figure 4.4, although there are some differences with respect to, for example, transport-format selection.

The different protocol entities of the RAN are summarized and described in more detail in the following sections:

- *Packet data convergence protocol* (PDCP) performs IP header compression, ciphering, and integrity protection. It also handles in-sequence delivery and duplicate removal in case of handover. There is one PDCP entity per radio bearer configured for a device.
- *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. There is one RLC entity per radio bearer configured for a device.

- *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 4.5. 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 device. The output from the PDCP is forwarded to the RLC. 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).

The RLC protocol performs concatenation and/or segmentation of the PDCP SDUs and adds an RLC header. The header is used for in-sequence delivery (per logical channel) in the device 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

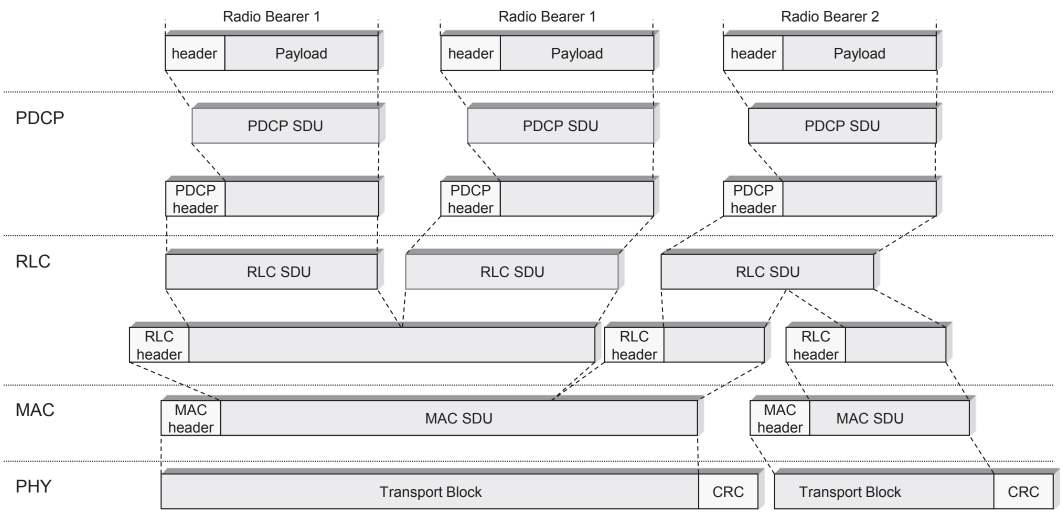

FIGURE 4.5

Example of LTE data flow.

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 Chapter 6 (downlink) and Chapter 7 (uplink), followed by descriptions of some specific uplink and downlink radio-interface functions and procedures in the subsequent chapters as well as some enhancements introduced after release 8/9.

4.2.1 PACKET-DATA CONVERGENCE PROTOCOL

The PDCP performs IP header compression to reduce the number of bits to transmit over the radio interface. The header-compression mechanism is based on robust header compression (ROHC) [31], a standardized header-compression algorithm also used for several other mobile-communication technologies. PDCP is also responsible for ciphering to protect against eavesdropping and, for the control plane, integrity protection to ensure that control messages originate from the correct source. At the receiver side, the PDCP performs the corresponding deciphering and decompression operations.

In addition, the PDCP also plays an important role for intra-eNodeB handover, handling in-sequence delivery and duplicate removal.[3] Upon handover, undelivered downlink data packets will be forwarded by the PDCP from the old eNodeB to the new eNodeB. The PDCP entity in the device will also handle retransmission of all uplink packets not yet delivered to the eNodeB as the hybrid-ARQ buffers are flushed upon handover.

4.2.2 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 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 4.6. 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

[3]Reordering is done in a similar way as the RLC reordering handling out-of-sequence PDUs from the hybrid-ARQ entity, see Chapter 8.

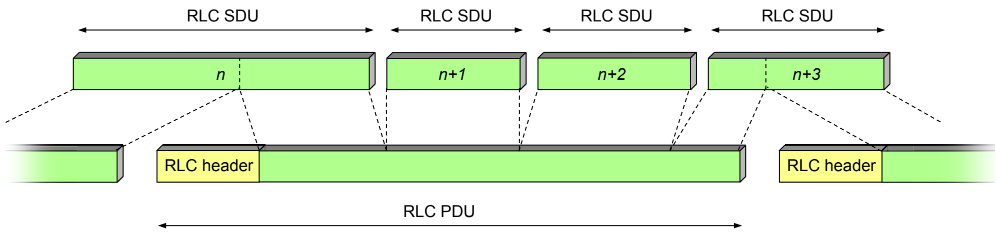

FIGURE 4.6

RLC segmentation and concatenation.

range from a few kbit/s up to several Gbit/s, dynamic PDU sizes are motivated for LTE in contrast to earlier mobile-communication technologies, which typically used 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 retransmission handling.

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 appropriate action and retransmit the missing PDUs if needed.

Although the RLC is capable of handling transmission errors due to noise, unpredictable channel variations, and so on, 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 is discussed in Section 4.2.3.3, 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 8.

4.2.3 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, see Chapter 12, and clear-channel assessment for license-assisted access, see Chapter 17.

4.2.3.1 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 devices in a cell. Prior to accessing the system, a device 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 devices 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 device. This channel is used for individual configuration of devices such as different handover messages.
- The *dedicated traffic channel* (DTCH), used for transmission of user data to/from a device. This is the logical channel type used for transmission of all uplink and non-MBSFN downlink user data.
- The *multicast control channel* (MCCH), used for transmission of control information required for reception of the MTCH (see later).
- The *single-cell multicast control channel* (SC-MCCH), used for transmission of control information for single-cell MTCH reception (see later).
- The *multicast traffic channel* (MTCH), used for downlink transmission of MBMS across multiple cells.
- The *single-cell multicast traffic channel* (SC-MTCH), used for downlink transmission of MBMS in a single cell.
- The *sidelink broadcast control channel* (SBCCH), used for sidelink synchronization.
- The *sidelink traffic channel* (STCH), used for sidelink communication (sidelink is the link for direct device-to-device communication, compare uplink and downlink for communication between a device and an eNodeB), see Chapter 21 for a description of device-to-device communication.

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 device 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 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 11.
- 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 device 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 11.
- 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 device 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 device[4] 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 are coordinated among the transmission points involved in the MBSFN transmission. MBSFN transmission is described in Chapter 19.
- 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.
- The *sidelink shared channel* (SL-SCH) is the transport channel used for sidelink communication as described in Chapter 21.
- The *sidelink broadcast channel* (SL-BCH) is used for sidelink synchronization, see Chapter 21.
- The *sidelink discovery channel* (SL-DCH) is used in the sidelink discovery process as described in Chapter 21.

In addition, the *random-access channel* (RACH) is also defined as a transport channel, although it does not carry transport blocks. Furthermore, the introduction of NB-IoT in release 13, see Chapter 20, resulted in a set of channels optimized for narrowband operation.

Part of the MAC functionality is multiplexing of different logical channels and mapping of the logical channels to the appropriate transport channels. The mapping between logical-

[4] For carrier aggregation, a device may receive multiple DL-SCHs, one per component carrier.

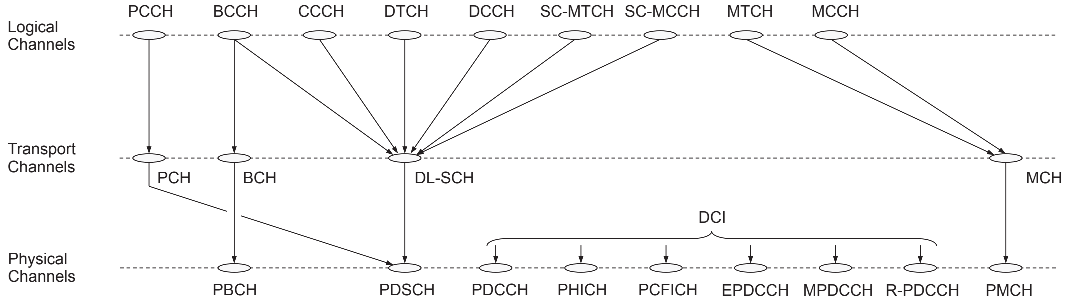

FIGURE 4.7

Downlink channel mapping.

channel types and transport channel types is given in Figure 4.7 for the downlink and Figure 4.8 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 later, are also included and the mapping between transport channels and physical channels is illustrated. For details on the mapping of sidelink channels see Chapter 21.

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 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, as shown in

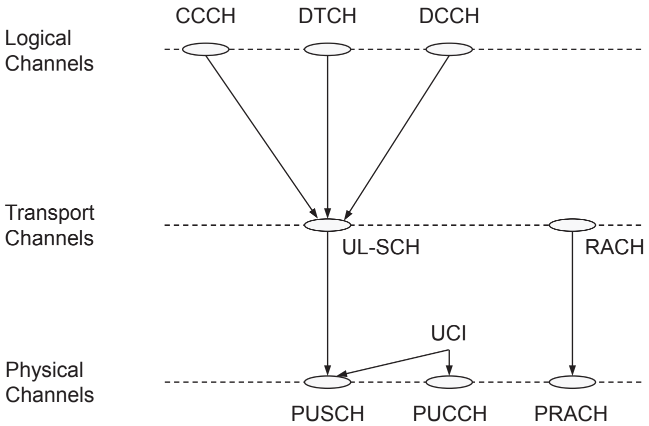

FIGURE 4.8

Uplink channel mapping.

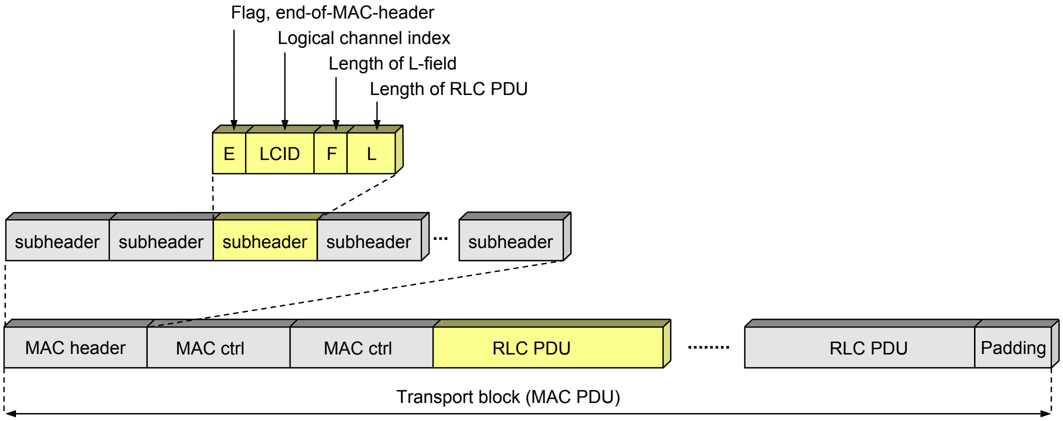

FIGURE 4.9

MAC header and SDU multiplexing.

Figure 4.9, is used. To each RLC PDU, there is an associated subheader in the MAC header. The subheader 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 subheader 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 7.6 and 11.3, 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 subheader is removed for control elements with a fixed length.

4.2.3.2 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 (although often better viewed as a separate entity as illustrated in Figure 4.4) and controls the assignment of uplink and downlink resources in terms of so-called *resource-block pairs*. Resource-block pairs 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 devices. However, there is also a possibility for semi-persistent scheduling

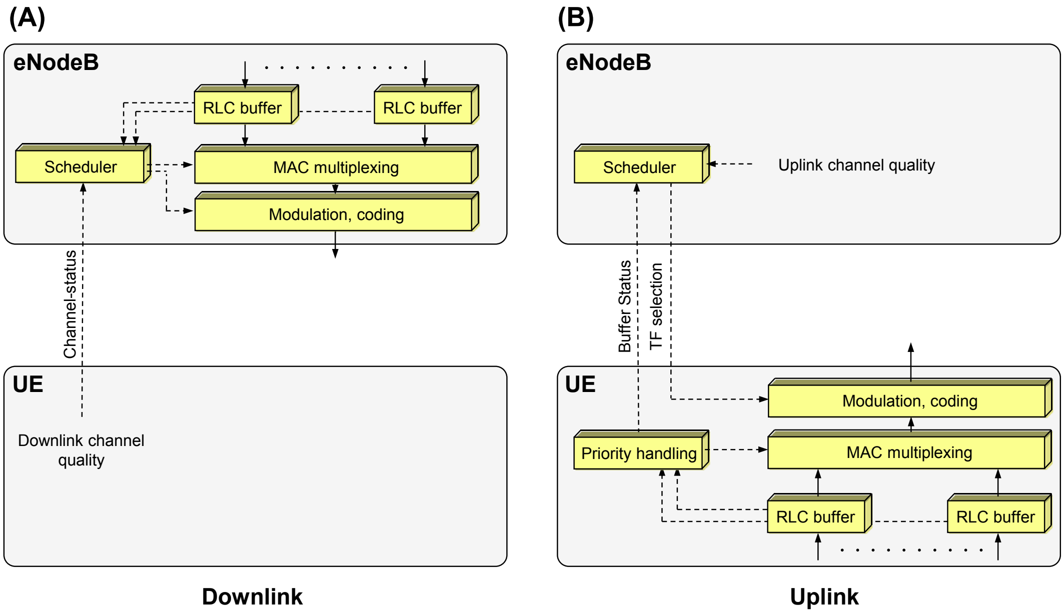

FIGURE 4.10

TF selection in (A) downlink and (B) uplink.

where a semi-static scheduling pattern is signaled in advance to reduce the control-signaling overhead.

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 device(s) to transmit to and, for each of these devices, the set of resource blocks upon which the device'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 4.10. 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 4.4.

The uplink scheduler serves a similar purpose, namely to (dynamically) control which devices 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 TF for the device, it is important to point out that the uplink scheduling decision is taken *per device* and not per radio bearer. Thus, although the eNodeB scheduler controls the payload of a scheduled device, the device is still responsible for selecting *from which radio bearer(s)* the data is taken. The device 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 4.10, where the eNodeB scheduler controls the TF and the device controls the logical-channel multiplexing.

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 devices and preferably schedule transmissions to a device 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 9, and illustrated in Figure 3.2. For the larger bandwidths supported by LTE, where a significant amount of frequency-selective fading may occur, the possibility for the scheduler to also exploit frequency-domain channel variations becomes increasingly important compared to exploiting time-domain variations only. This 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 information* (CSI), reported by the device to the eNodeB and reflecting the instantaneous downlink 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 device for which the eNodeB wants to estimate the uplink channel quality. To aid the uplink scheduler in its decisions, the device can transmit buffer-status information to the eNodeB using a MAC message. This information can only be transmitted if the device has been given a valid scheduling grant. For situations when this is not the case, an indicator that the device needs uplink resources is provided as part of the uplink L1/L2 control-signaling structure (see Chapter 7).

4.2.3.3 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.[5]

Hybrid ARQ is not applicable for all types of traffic. For example, broadcast transmissions, where the same information is intended for multiple devices, typically do not rely on hybrid ARQ.[6] Hence, hybrid ARQ is only supported for the DL-SCH and the UL-SCH, although its usage is optional.

---

[5]The soft combining is done before or as part of the channel decoding, which clearly is a physical-layer functionality.

[6]Autonomous retransmissions, where the transmitter repeats the same information several times without the receivers transmitting an acknowledgment, is possible and sometimes used to obtain a soft combining gain.

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 acknowledgment bit indicating whether the decoding was successful or if a retransmission of the transport block is required. Clearly, the receiver must know to which hybrid-ARQ process a received acknowledgment is associated. This is solved by using the timing of the acknowledgment 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 acknowledgment is also affected by the uplink/downlink allocation.

The use of multiple parallel hybrid-ARQ processes, illustrated in Figure 4.11, 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.

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 retransmission needs to be scheduled or not.

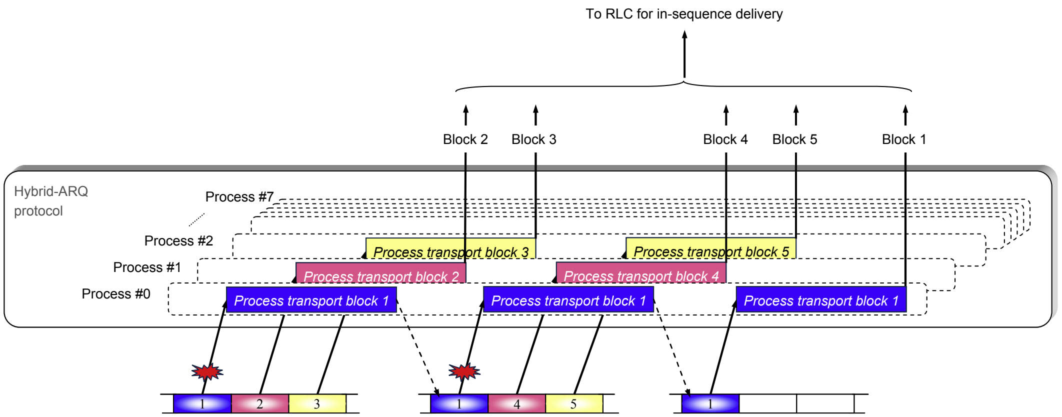

FIGURE 4.11

Multiple parallel hybrid-ARQ processes.

The hybrid-ARQ mechanism will rapidly correct transmission errors due to noise or unpredictable channel variations. As discussed earlier in this chapter, 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 example, for 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 8.

4.2.4 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 4.7 and 4.8.

As mentioned in the introduction, the physical layer provides services to the MAC layer in the form of transport channels. Data transmission in downlink, uplink, and sidelink use the DL-SCH, UL-SCH, and SL-SCH transport-channel types, respectively. There is at most one or, in the case of spatial multiplexing,[7] two transport blocks per TTI on a DL-SCH, UL-SCH, or SL-SCH. In the case of carrier aggregation, there is one DL-SCH (or UL-SCH) per component carrier seen by the device.

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 4.7 and 4.8 for the downlink and uplink (the sidelink is covered in Chapter 21). 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 device with the necessary information for proper reception and decoding of the downlink data transmission, *uplink control information* (UCI) used for providing the scheduler and the hybrid-ARQ protocol with information about the situation at the device, and *sidelink control information* (SCI) for handling sidelink transmissions.

The following physical-channel types are defined for LTE:

- 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 device in order to access the network.

[7] There is no spatial multiplexing defined for sidelink communication.

- The *physical multicast channel* (PMCH) is used for MBSFN transmission.
- 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 *enhanced physical downlink control channel* (EPDCCH) was introduced in release 11. It essentially serves the same purpose as the PDCCH but allows for transmission of the control information in a more flexible way.
- The *MTC physical downlink control channel* (MPDCCH) was introduced in release 13 as part of the improved support for massive machine-type communication, see Chapter 20. In essence it is a variant of the EPDCCH.
- The *relay physical downlink control channel* (R-PDCCH) was introduced in release 10 and is used to carry L1/L2 control signaling on the donor-eNodeB-to-relay link.
- The *physical hybrid-ARQ indicator channel* (PHICH) carries the hybrid-ARQ acknowledgment to indicate to the device whether a transport block should be retransmitted or not.
- The *physical control format indicator channel* (PCFICH) is a channel providing the devices 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 device.
- The *physical uplink control channel* (PUCCH) is used by the device to send hybrid-ARQ acknowledgments, 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 device.
- The *physical random-access channel* (PRACH) is used for random access, as described in Chapter 11.
- The *physical sidelink shared channel* (PSSCH) is used for sidelink data transfer, see Chapter 21.
- The *physical sidelink control channel* (PSCCH), used for sidelink-related control information.
- The *physical sidelink discovery channel* (PSDCH), used for sidelink discovery.
- The *physical sidelink broadcast channel* (PSBCH), used to convey basic sidelink-related information between devices.

Note that some of the physical channels, more specifically the channels used for downlink control information (namely, PCFICH, PDCCH, PHICH, EPDCCH, and R-PDCCH), uplink control information (namely, PUCCH), and sidelink control information (namely, PSCCH) do not have a corresponding transport channel mapped to them.

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 device 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 devices 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 11.

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 device is paged, hybrid ARQ cannot be used as there is no possibility for the device to transmit a hybrid-ARQ acknowledgment.

The MCH is used for MBMS transmissions, typically with single-frequency network operation 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.

4.3 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 devices 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 device. For a detailed discussion about the NAS control-plane functionality, see [5].

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

- Broadcast of system information necessary for the device to be able to communicate with a cell. Acquisition of system information is described in Chapter 11.
- Transmission of paging messages originating from the MME to notify the device about incoming connection requests. Paging, discussed further in Chapter 11, is used in the RRC_IDLE state (described later) when the device is not connected to a particular cell. Indication of system-information updates 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 device and the RAN.
- Mobility functions such as cell (re)selection.

- Measurement configuration and reporting.
- Handling of device capabilities; when connection is established the device (UE) will announce its capabilities as all devices are not capable of supporting all the functionality described in the LTE specifications, as briefly discussed in Chapter 3.

RRC messages are transmitted to the device using *signaling radio bearers* (SRBs), using the same set of protocol layers (PDCP, RLC, MAC, and PHY) as described in Section 4.2. The SRB is mapped to the CCCH during establishment of connection and, once a connection is established, to the DCCH. Control-plane and user-plane data can be multiplexed in the MAC layer and transmitted to the device 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.

4.3.1 STATE MACHINE

In LTE, a device can be in two different states from an RRC perspective,[8] RRC_CONNECTED and RRC_IDLE, as illustrated in Figure 4.12.

In RRC_CONNECTED, there is an RRC context established—that is, the parameters necessary for communication between the device and the RAN are known to both entities. The cell to which the device belongs is known, and an identity of the device, the *cell radio-network temporary identifier* (C-RNTI), used for signaling purposes between the device and the network, has been configured. RRC_CONNECTED is intended for data transfer to/from the device, but DRX can be configured in order to reduce device power consumption (DRX is described in further detail in Chapter 9). 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 setup with its associated signaling is needed.

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

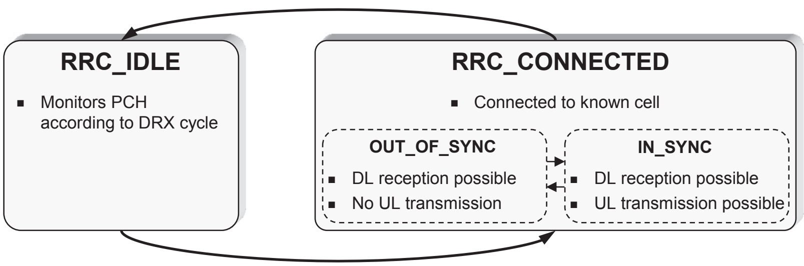

FIGURE 4.12

LTE states.

[8]There are also different core-network states for a device, but these are not described here.

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 devices such that they arrive at the receiver at (about) the same time. The procedure for obtaining and maintaining uplink synchronization is described in Chapter 7, but in short the receiver measures the arrival time of the transmissions from each actively transmitting device 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 and therefore timing alignment has not been possible, uplink synchronization cannot be guaranteed and the uplink is declared to be nonsynchronized. In this case, the device 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 RAN, and the device does not belong to a specific cell. No data transfer may take place as the device 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 11, to move to RRC_CONNECTED. When moving to RRC_CONNECTED the RRC context needs to be established in both the RAN and the device. Compared to leaving DRX this takes a somewhat longer time. In the downlink, devices in RRC_IDLE periodically wake up in order to receive paging messages, if any, from the network, as described in Chapter 11.