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978-0-521-88221-7 - LTE for 4G Mobile Broadband: Air Interface Technologies and Performance
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1 Introduction

The cellular wireless communications industry witnessed tremendous growth in the past decade with over four billion wireless subscribers worldwide. The first generation (1G) analog cellular systems supported voice communication with limited roaming. The second generation (2G) digital systems promised higher capacity and better voice quality than did their analog counterparts. Moreover, roaming became more prevalent thanks to fewer standards and common spectrum allocations across countries particularly in Europe. The two widely deployed second-generation (2G) cellular systems are GSM (global system for mobile communications) and CDMA (code division multiple access). As for the 1G analog systems, 2G systems were primarily designed to support voice communication. In later releases of these standards, capabilities were introduced to support data transmission. However, the data rates were generally lower than that supported by dial-up connections. The ITU-R initiative on IMT-2000 (international mobile telecommunications 2000) paved the way for evolution to 3G. A set of requirements such as a peak data rate of 2 Mb/s and support for vehicular mobility were published under IMT-2000 initiative. Both the GSM and CDMA camps formed their own separate 3G partnership projects (3GPP and 3GPP2, respectively) to develop IMT-2000 compliant standards based on the CDMA technology. The 3G standard in 3GPP is referred to as wideband CDMA (WCDMA) because it uses a larger 5 MHz bandwidth relative to 1.25 MHz bandwidth used in 3GPP2's cdma2000 system. The 3GPP2 also developed a 5 MHz version supporting three 1.25 MHz subcarriers referred to as cdma2000-3x. In order to differentiate from the 5 MHz cdma2000-3x standard, the 1.25 MHz system is referred to as cdma2000-1x or simply 3G-1x.

The first release of the 3G standards did not fulfill its promise of high-speed data transmissions as the data rates supported in practice were much lower than that claimed in the standards. A serious effort was then made to enhance the 3G systems for efficient data support. The 3GPP2 first introduced the HRPD (high rate packet data) [1] system that used various advanced techniques optimized for data traffic such as channel sensitive scheduling, fast link adaptation and hybrid ARQ, etc. The HRPD system required a separate 1.25 MHz carrier and supported no voice service. This was the reason that HRPD was initially referred to as cdma2000-1xEVDO (evolution data only) system. The 3GPP followed a similar path and introduced HSPA (high speed packet access) [2] enhancement to the WCDMA system. The HSPA standard reused many of the same data-optimized techniques as the HRPD system. A difference relative to HRPD, however, is that both voice and data can be carried on the same 5 MHz carrier in HSPA. The voice and data traffic are code multiplexed in the downlink. In parallel to HRPD, 3GPP2 also developed a joint voice data standard that was referred to as cdma2000-1xEVDV (evolution data voice) [3]. Like HSPA, the cdma2000-1xEVDV system supported both voice and data on the same carrier but it was never commercialized. In the later release of HRPD, VoIP (Voice over Internet Protocol) capabilities were introduced to provide both voice and data service on the same carrier. The two 3G standards namely HSPA and HRPD were finally able to fulfill the 3G promise and have been widely deployed in major cellular markets to provide wireless data access.

1.1 Beyond 3G systems

While HSPA and HRPD systems were being developed and deployed, IEEE 802 LMSC (LAN/MAN Standard Committee) introduced the IEEE 802.16e standard [4] for mobile broadband wireless access. This standard was introduced as an enhancement to an earlier IEEE 802.16 standard for fixed broadband wireless access. The 802.16e standard employed a different access technology named OFDMA (orthogonal frequency division multiple access) and claimed better data rates and spectral efficiency than that provided by HSPA and HRPD. Although the IEEE 802.16 family of standards is officially called WirelessMAN in IEEE, it has been dubbed WiMAX (worldwide interoperability for microwave access) by an industry group named the WiMAX Forum. The mission of the WiMAX Forum is to promote and certify the compatibility and interoperability of broadband wireless access products. The WiMAX system supporting mobility as in IEEE 802.16e standard is referred to as Mobile WiMAX. In addition to the radio technology advantage, Mobile WiMAX also employed a simpler network architecture based on IP protocols.

The introduction of Mobile WiMAX led both 3GPP and 3GPP2 to develop their own version of beyond 3G systems based on the OFDMA technology and network architecture similar to that in Mobile WiMAX. The beyond 3G system in 3GPP is called evolved universal terrestrial radio access (evolved UTRA) [5] and is also widely referred to as LTE (Long-Term Evolution) while 3GPP2's version is called UMB (ultra mobile broadband) [6] as depicted in Figure 1.1. It should be noted that all three beyond 3G systems namely Mobile WiMAX,

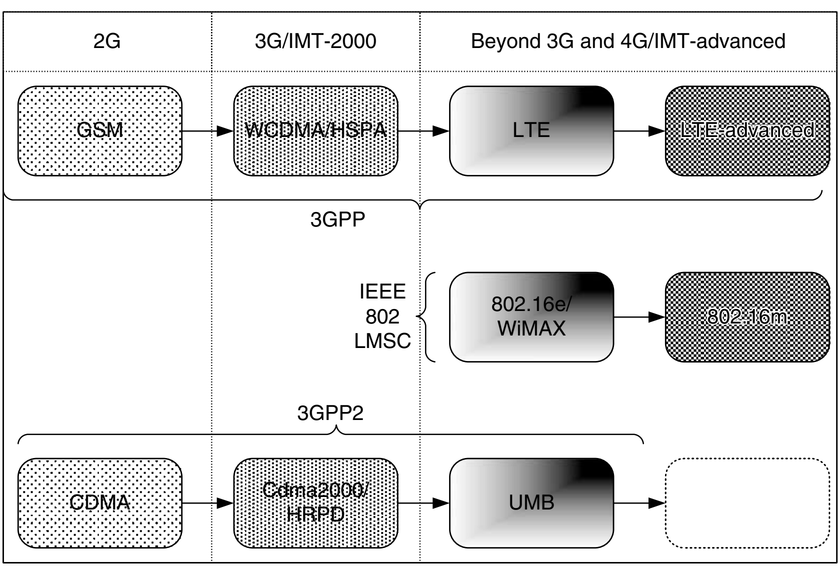

Figure 1.1. Cellular systems evolution.

Table 1.1. LTE system attributes.

Bandwidth		1.25–20 MHz
Duplexing		FDD, TDD, half-duplex FDD
Mobility		350 km/h
Multiple access	Downlink	OFDMA
	Uplink	SC-FDMA
MIMO	Downlink	$2 \times 2, 4 \times 2, 4 \times 4$
	Uplink	$1 \times 2, 1 \times 4$
Peak data rate in 20 MHz	Downlink	173 and 326 Mb/s for 2×2 and 4×4 MIMO, respectively
	Uplink	86 Mb/s with 1×2 antenna configuration
Modulation		QPSK, 16-QAM and 64-QAM
Channel coding		Turbo code
Other techniques		Channel sensitive scheduling, link adaptation, power control, ICIC and hybrid ARQ

LTE and UMB meet IMT-2000 requirements and hence they are also part of IMT-2000 family of standards.

1.2 Long-Term Evolution (LTE)

The goal of LTE is to provide a high-data-rate, low-latency and packet-optimized radio-access technology supporting flexible bandwidth deployments [7]. In parallel, new network architecture is designed with the goal to support packet-switched traffic with seamless mobility, quality of service and minimal latency [8].

The air-interface related attributes of the LTE system are summarized in Table 1.1. The system supports flexible bandwidths thanks to OFDMA and SC-FDMA access schemes. In addition to FDD (frequency division duplexing) and TDD (time division duplexing), half-duplex FDD is allowed to support low cost UEs. Unlike FDD, in half-duplex FDD operation a UE is not required to transmit and receive at the same time. This avoids the need for a costly duplexer in the UE. The system is primarily optimized for low speeds up to 15 km/h. However, the system specifications allow mobility support in excess of 350 km/h with some performance degradation. The uplink access is based on single carrier frequency division multiple access (SC-FDMA) that promises increased uplink coverage due to low peak-to-average power ratio (PAPR) relative to OFDMA.

The system supports downlink peak data rates of 326 Mb/s with 4×4 MIMO (multiple input multiple output) within 20 MHz bandwidth. Since uplink MIMO is not employed in the first release of the LTE standard, the uplink peak data rates are limited to 86 Mb/s within 20 MHz bandwidth. In addition to peak data rate improvements, the LTE system provides two to four times higher cell spectral efficiency relative to the Release 6 HSPA system. Similar improvements are observed in cell-edge throughput while maintaining same-site locations as deployed for HSPA. In terms of latency, the LTE radio-interface and network provides capabilities for less than 10 ms latency for the transmission of a packet from the network to the UE.

1.3 Evolution to 4G

The radio-interface attributes for Mobile WiMAX and UMB are very similar to those of LTE given in Table 1.1. All three systems support flexible bandwidths, FDD/TDD duplexing, OFDMA in the downlink and MIMO schemes. There are a few differences such as uplink in LTE is based on SC-FDMA compared to OFDMA in Mobile WiMAX and UMB. The performance of the three systems is therefore expected to be similar with small differences.

Similar to the IMT-2000 initiative, ITU-R Working Party 5D has stated requirements for IMT-advanced systems. Among others, these requirements include average downlink data rates of 100 Mbit/s in the wide area network, and up to 1 Gbit/s for local access or low-mobility scenarios. Also, at the World Radiocommunication Conference 2007 (WRC-2007), a maximum of a 428 MHz new spectrum is identified for IMT systems that also include a 136 MHz spectrum allocated on a global basis.

Both 3GPP and IEEE 802 LMSC are actively developing their own standards for submission to IMT-advanced. The goal for both LTE-advanced [9] and IEEE 802.16 m [10] standards is to further enhance system spectral efficiency and data rates while supporting backward compatibility with their respective earlier releases. As part of the LTE-advanced and IEEE 802.16 standards developments, several enhancements including support for a larger than 20 MHz bandwidth and higher-order MIMO are being discussed to meet the IMT-advanced requirements.

References

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2 Network architecture and protocols

The LTE network architecture is designed with the goal of supporting packet-switched traffic with seamless mobility, quality of service (QoS) and minimal latency. A packet-switched approach allows for the supporting of all services including voice through packet connections. The result in a highly simplified flatter architecture with only two types of node namely evolved Node-B (eNB) and mobility management entity/gateway (MME/GW). This is in contrast to many more network nodes in the current hierarchical network architecture of the 3G system. One major change is that the radio network controller (RNC) is eliminated from the data path and its functions are now incorporated in eNB. Some of the benefits of a single node in the access network are reduced latency and the distribution of the RNC processing load into multiple eNBs. The elimination of the RNC in the access network was possible partly because the LTE system does not support macro-diversity or soft-handoff.

In this chapter, we discuss network architecture designs for both unicast and broadcast traffic, QoS architecture and mobility management in the access network. We also briefly discuss layer 2 structure and different logical, transport and physical channels along with their mapping.

2.1 Network architecture

All the network interfaces are based on IP protocols. The eNBs are interconnected by means of an X2 interface and to the MME/GW entity by means of an S1 interface as shown in Figure 2.1. The S1 interface supports a many-to-many relationship between MME/GW and eNBs [1].

The functional split between eNB and MME/GW is shown in Figure 2.2. Two logical gateway entities namely the serving gateway (S-GW) and the packet data network gateway (P-GW) are defined. The S-GW acts as a local mobility anchor forwarding and receiving packets to and from the eNB serving the UE. The P-GW interfaces with external packet data networks (PDNs) such as the Internet and the IMS. The P-GW also performs several IP functions such as address allocation, policy enforcement, packet filtering and routing.

The MME is a signaling only entity and hence user IP packets do not go through MME. An advantage of a separate network entity for signaling is that the network capacity for signaling and traffic can grow independently. The main functions of MME are idle-mode UE reachability including the control and execution of paging retransmission, tracking area list management, roaming, authentication, authorization, P-GW/S-GW selection, bearer management including dedicated bearer establishment, security negotiations and NAS signaling, etc.

Evolved Node-B implements Node-B functions as well as protocols traditionally implemented in RNC. The main functions of eNB are header compression, ciphering and reliable delivery of packets. On the control side, eNB incorporates functions such as admission

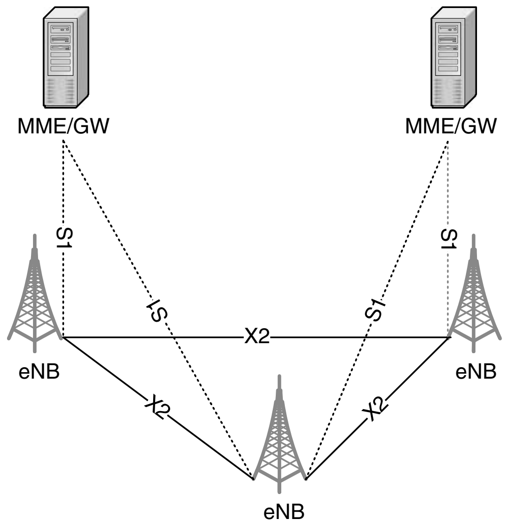

Figure 2.1. Network architecture.

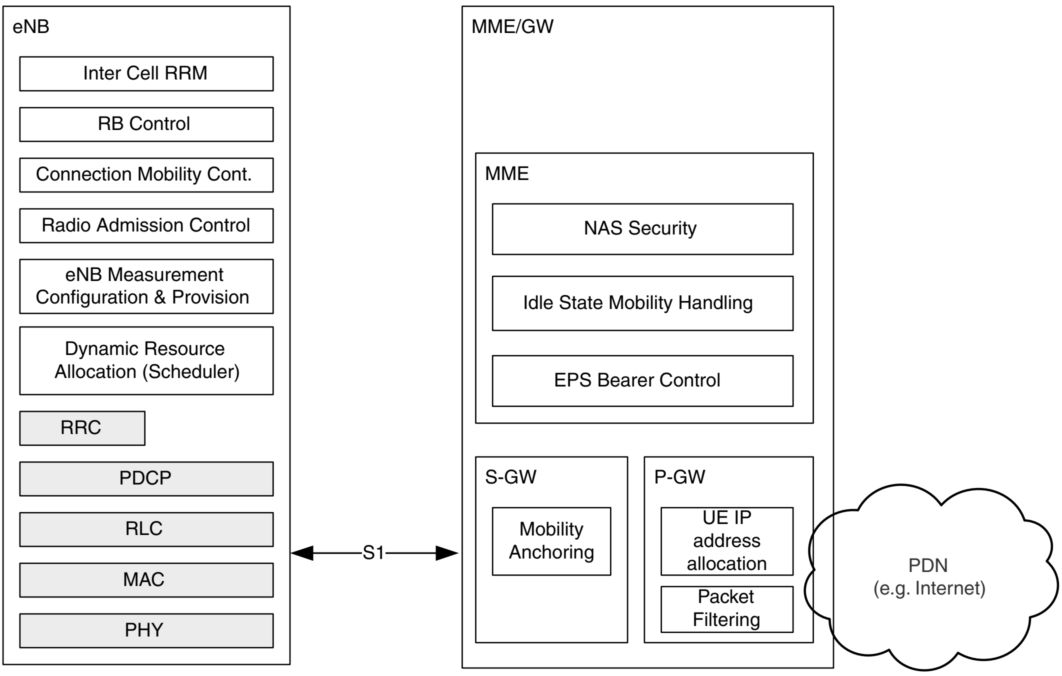

Figure 2.2. Functional split between eNB and MME/GW.

control and radio resource management. Some of the benefits of a single node in the access network are reduced latency and the distribution of RNC processing load into multiple eNBs.

The user plane protocol stack is given in Figure 2.3. We note that packet data convergence protocol (PDCP) and radio link control (RLC) layers traditionally terminated in RNC on

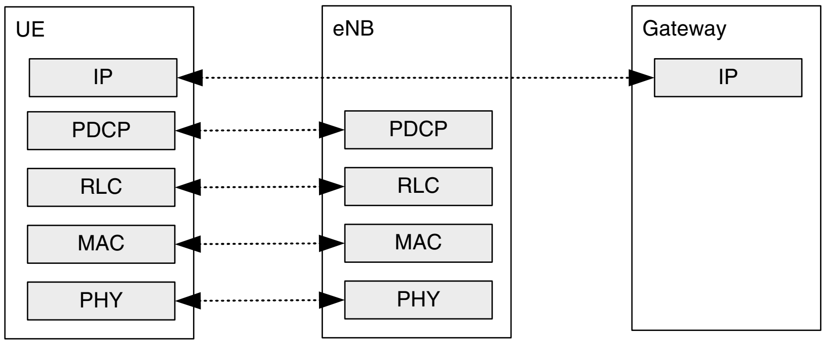

Figure 2.3. User plane protocol.

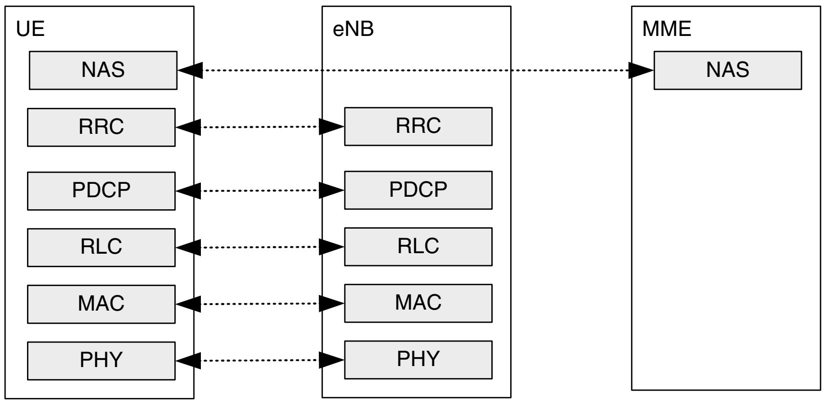

Figure 2.4. Control plane protocol stack.

the network side are now terminated in eNB. The functions performed by these layers are described in Section 2.2.

Figure 2.4 shows the control plane protocol stack. We note that RRC functionality traditionally implemented in RNC is now incorporated into eNB. The RLC and MAC layers perform the same functions as they do for the user plane. The functions performed by the RRC include system information broadcast, paging, radio bearer control, RRC connection management, mobility functions and UE measurement reporting and control. The non-access stratum (NAS) protocol terminated in the MME on the network side and at the UE on the terminal side performs functions such as EPS (evolved packet system) bearer management, authentication and security control, etc.

The S1 and X2 interface protocol stacks are shown in Figures 2.5 and 2.6 respectively. We note that similar protocols are used on these two interfaces. The S1 user plane interface (S1-U) is defined between the eNB and the S-GW. The S1-U interface uses GTP-U (GPRS tunneling protocol – user data tunneling) [2] on UDP/IP transport and provides non-guaranteed delivery of user plane PDUs between the eNB and the S-GW. The GTP-U is a relatively simple IP based tunneling protocol that permits many tunnels between each set of end points. The S1 control plane interface (S1-MME) is defined as being between the eNB and the MME. Similar to the user plane, the transport network layer is built on IP transport and for the reliable

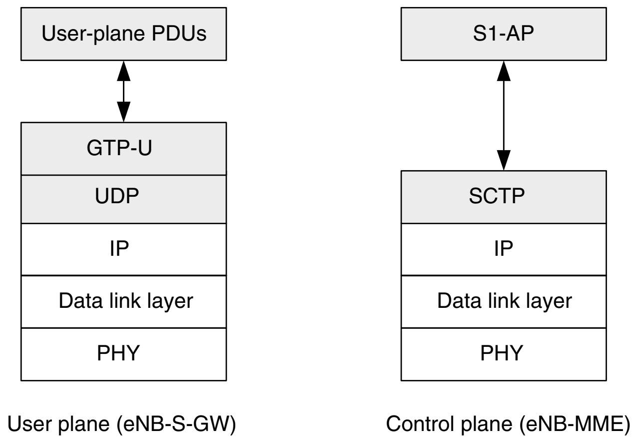

Figure 2.5. S1 interface user and control planes.

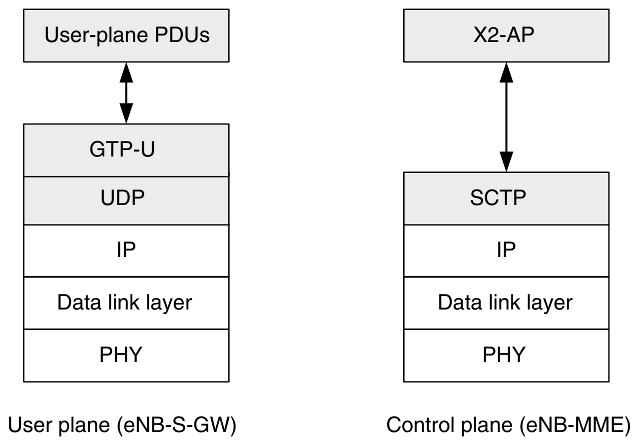

Figure 2.6. X2 interface user and control planes.

transport of signaling messages SCTP (stream control transmission protocol) is used on top of IP. The SCTP protocol operates analogously to TCP ensuring reliable, in-sequence transport of messages with congestion control [3]. The application layer signaling protocols are referred to as S1 application protocol (S1-AP) and X2 application protocol (X2-AP) for S1 and X2 interface control planes respectively.

2.2 QoS and bearer service architecture

Applications such as VoIP, web browsing, video telephony and video streaming have special QoS needs. Therefore, an important feature of any all-packet network is the provision of a QoS mechanism to enable differentiation of packet flows based on QoS requirements. In EPS, QoS flows called EPS bearers are established between the UE and the P-GW as shown in Figure 2.7. A radio bearer transports the packets of an EPS bearer between a UE and an eNB. Each IP flow (e.g. VoIP) is associated with a different EPS bearer and the network can

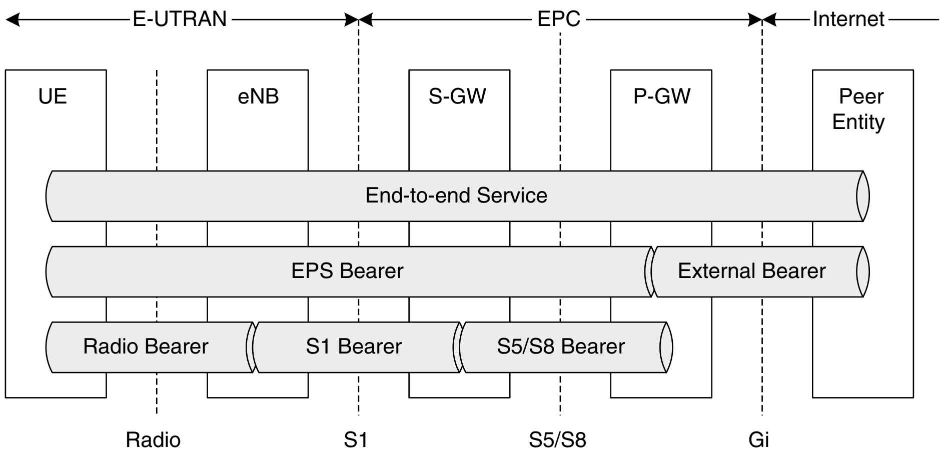

Figure 2.7. EPS bearer service architecture.

prioritize traffic accordingly. When receiving an IP packet from the Internet, P-GW performs packet classification based on certain predefined parameters and sends it an appropriate EPS bearer. Based on the EPS bearer, eNB maps packets to the appropriate radio QoS bearer. There is one-to-one mapping between an EPS bearer and a radio bearer.

2.3 Layer 2 structure

The layer 2 of LTE consists of three sublayers namely medium access control, radio link control (RLC) and packet data convergence protocol (PDCP). The service access point (SAP) between the physical (PHY) layer and the MAC sublayer provide the transport channels while the SAP between the MAC and RLC sublayers provide the logical channels. The MAC sublayer performs multiplexing of logical channels on to the transport channels.

The downlink and uplink layer 2 structures are given in Figures 2.8 and 2.9 respectively. The difference between downlink and uplink structures is that in the downlink, the MAC sublayer also handles the priority among UEs in addition to priority handling among the logical channels of a single UE. The other functions performed by the MAC sublayers in both downlink and uplink include mapping between the logical and the transport channels, multiplexing of RLC packet data units (PDU), padding, transport format selection and hybrid ARQ (HARQ).

The main services and functions of the RLC sublayers include segmentation, ARQ in-sequence delivery and duplicate detection, etc. The in-sequence delivery of upper layer PDUs is not guaranteed at handover. The reliability of RLC can be configured to either acknowledge mode (AM) or un-acknowledge mode (UM) transfers. The UM mode can be used for radio bearers that can tolerate some loss. In AM mode, ARQ functionality of RLC retransmits transport blocks that fail recovery by HARQ. The recovery at HARQ may fail due to hybrid ARQ NACK to ACK error or because the maximum number of retransmission attempts is reached. In this case, the relevant transmitting ARQ entities are notified and potential retransmissions and re-segmentation can be initiated.

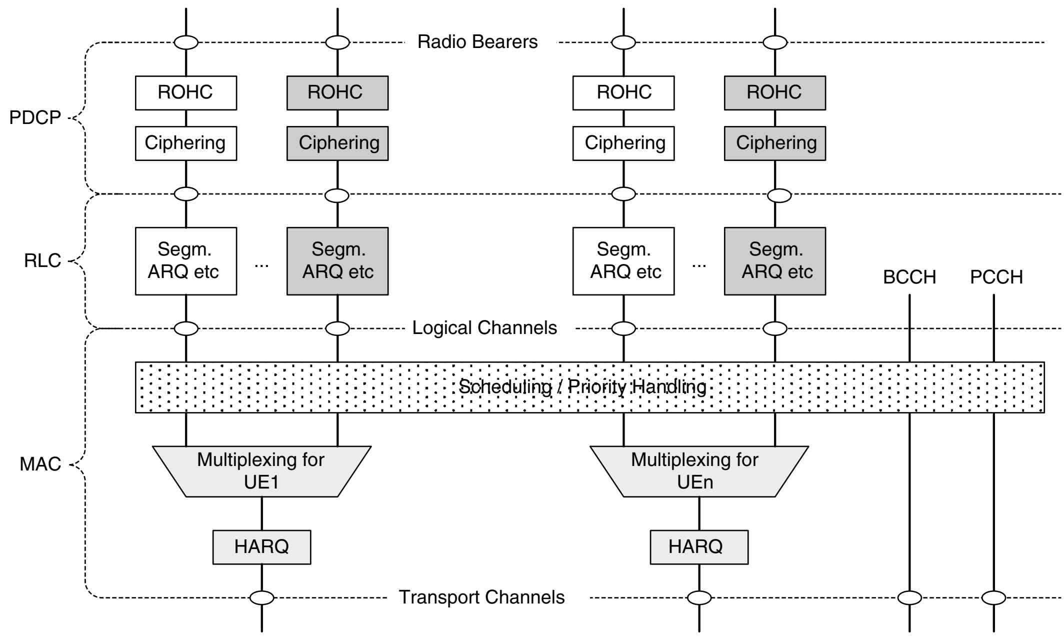

Figure 2.8. Downlink layer 2 structure.

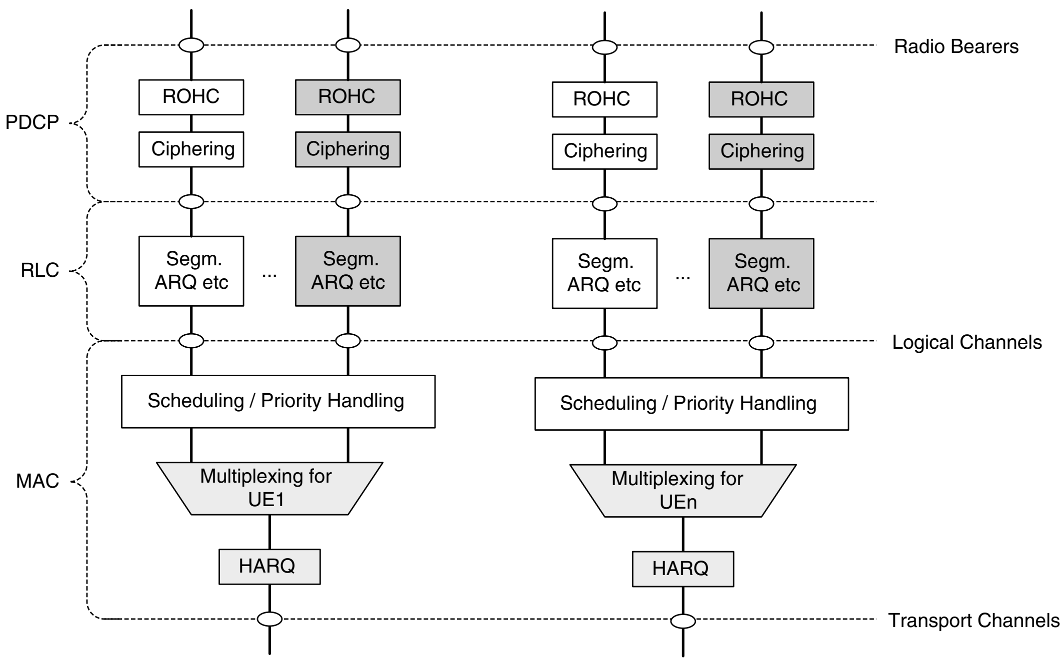

Figure 2.9. Uplink layer 2 structure.