LTE Part 2: Data Link and Physical Layers

Physical Layer based on:

David Astély, Erik Dahlman, Anders Furuskär, Ylva Jading, Magnus Lindström, and Stefan Parkvall, Ericsson Research, *LTE: The Evolution of Mobile Broadband*, IEEE Communications Magazine, April 2009. pp.44-51

Scheduling from:

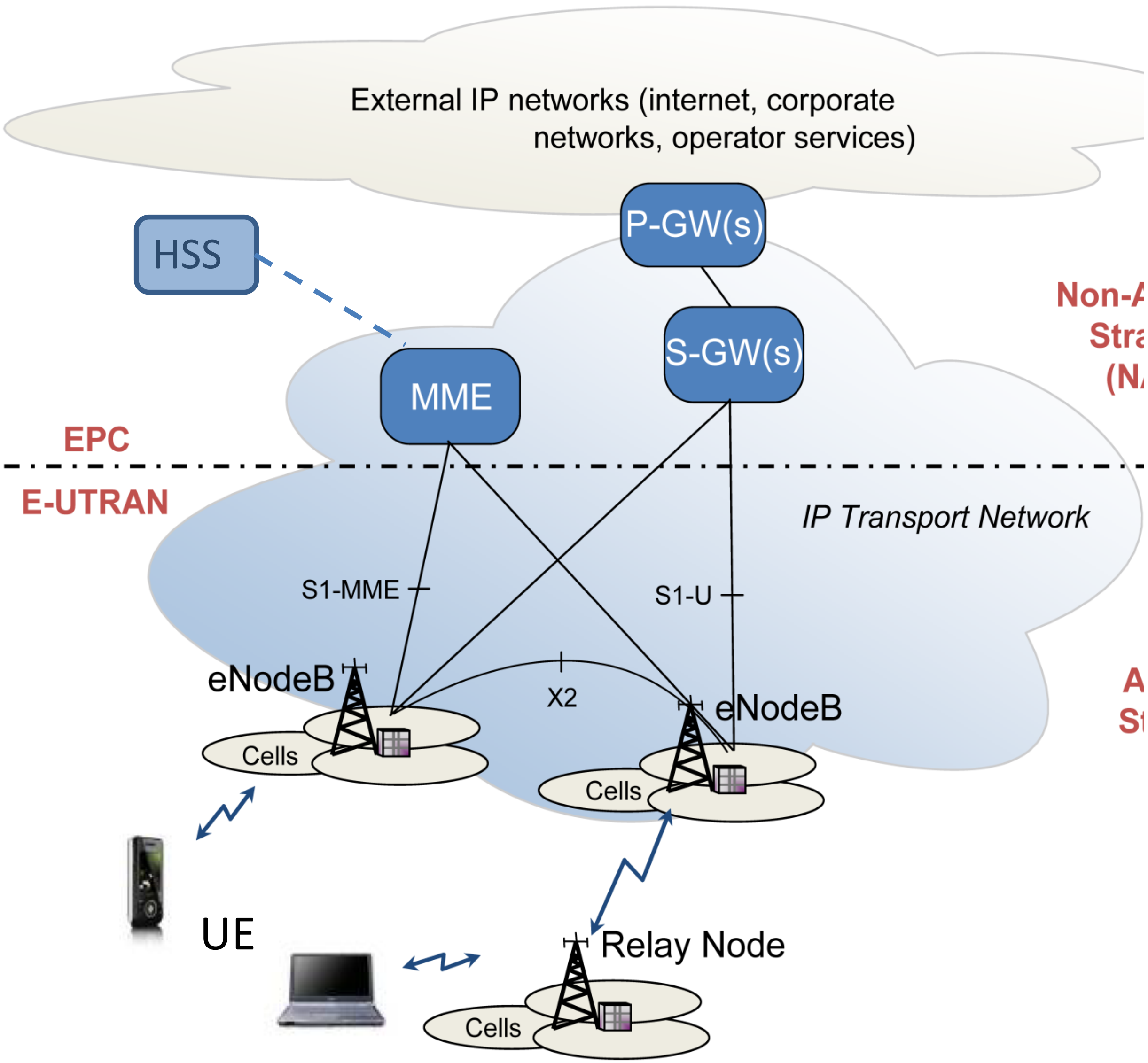
Anna Larmo, Magnus Lindström, Michael Meyer, Ghyslain Pelletier, Johan Torsner, and Henning Wiemann, Ericsson Research: *The LTE Link-Layer Design*, IEEE Communications Magazine, April 2009. pp. 52-59

Additional reading:

C Beard & W. Stalling, Wireless Networks and Systems, 2nd edition, Chapter 14, pp. 470-509

LTE: EPC + E-UTRAN architecture

Evolved Packet Core + Evolved Universal Terrestrial Radio Access Network



- Flat all-IP multi-access core network
- Enhanced NodeB (**eNB**) (former base station/NodeB)
- **UE** – User Equipment
- **MME** – Mobility Management Entity (Control Plane)
- **S-GW** – Serving Gateway (User Plane)
- **P-GW** – Packet Network Gateway
- HSS – Home Subscriber Server

Link Layer – User Plane Protocol Stack

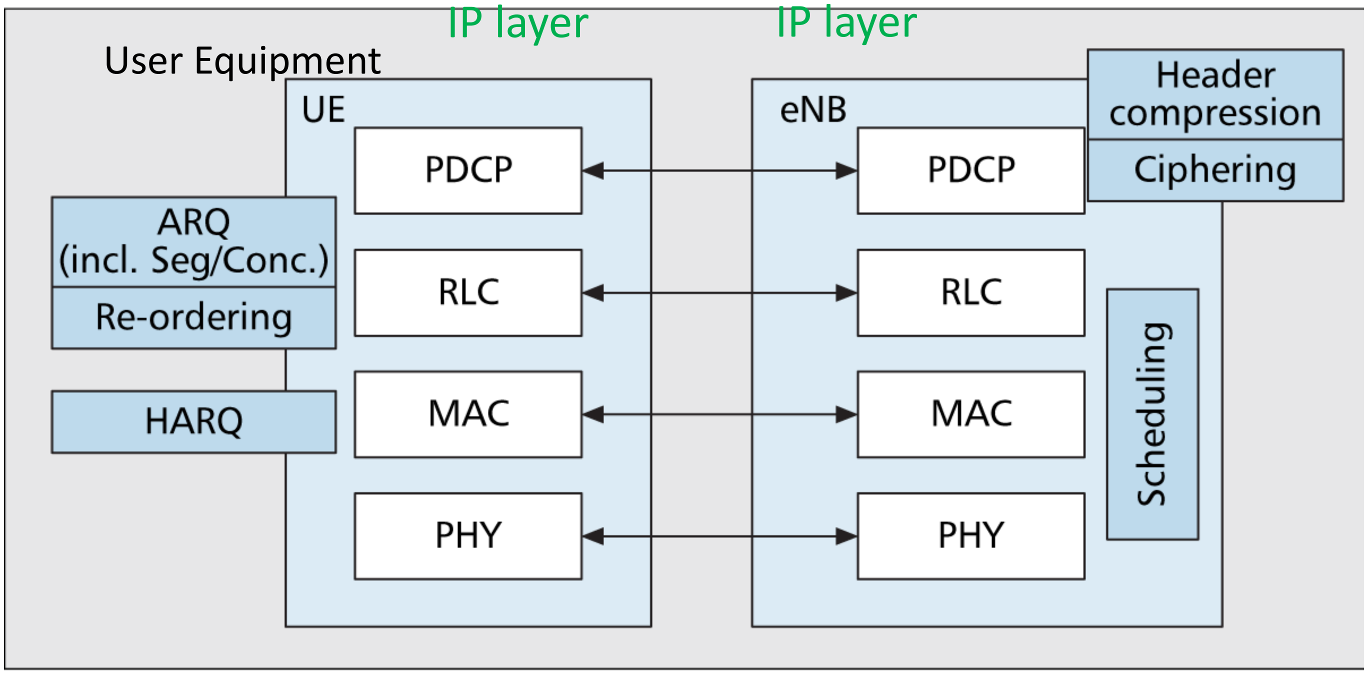


Figure 2. *User plane protocol stack.*

The LTE link layer consists of three sublayers:

- The Packet Data Convergence Protocol (**PDCP**)
- The radio link control (**RLC**)
- The medium access control (**MAC**)

Peer sublayers in UE and eNB are logically connected.

PDCP is responsible for IP header compression and ciphering.

- Supports lossless mobility in case of inter-eNB handovers
- Provides data integrity protection to higher layer protocols.

RLC comprises: **ARQ** (Automatic Repeat reQuest) functionality and

- supports data segmentation and concatenation

MAC provides **HARQ** (Hybrid ARQ) and is responsible for

- medium access control
- scheduling operation and random access.

Data Flow Through L2 Protocol Stack

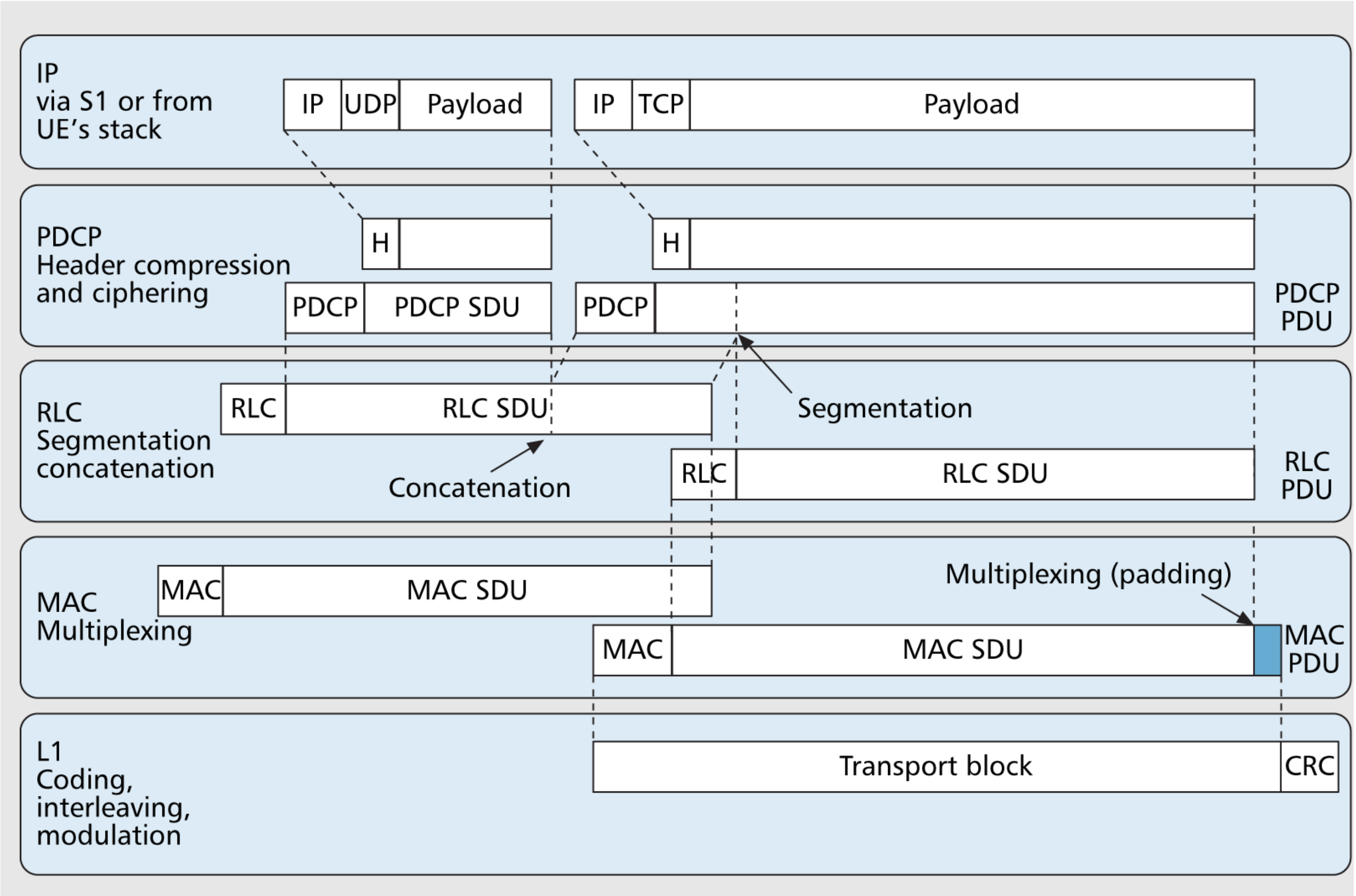


Figure 3. *Illustration of data flow through L2 protocol stack.*

The data flow of an IP packet through the link-layer protocols down to the physical layer (L1). The figure shows that each protocol sublayer adds its own protocol header to the data units.

Protocol Data Units (PDUs)

- Each sublayer of the link layer operates with its own PDU consisting of a header and Service Data Unit (SDU)
- **The Packet Data Convergence Protocol** (PDPC) header has a D/C bit distinguishing Data from Control frame and the Sequence Number (SN) field of the varying length (5, 7, 12 bits)
- **The Radio Link Control** (RLC) PDU has four basic formats
  - Transparent Mode Data (TMD) PDU
  - Unacknowledged Mode Data (UMD) PDU
  - Acknowledged Mode Data (AMD) PDU
  - Status PDU
- **The Medium Access Con**trol (MAC) PDU can multiplex data from different channels, therefore, the header contains sub-headers control elements for a collection of multiplexed SDUs
- **The Physical Layer** (L1) operates with a Transport Block related to the **time-frequency resource block**

Error Handling 1

- As in any communication system, there are occasional data transmission errors, due to noise, interference, fading, etc.
- In mobile/wireless networks one in ten data blocs can be corrupted.
- Link-layer, network-layer (IP), and transport-layer protocols are not prepared to cope with bit errors in headers, and the majority of the protocols are not also capable of handling errors in the payload.
- Therefore, a fundamental design choice for LTE has been
  - **not to propagate** any bit errors to higher layers but rather
  - to **drop or retransmit** the entire data unit containing bit errors.

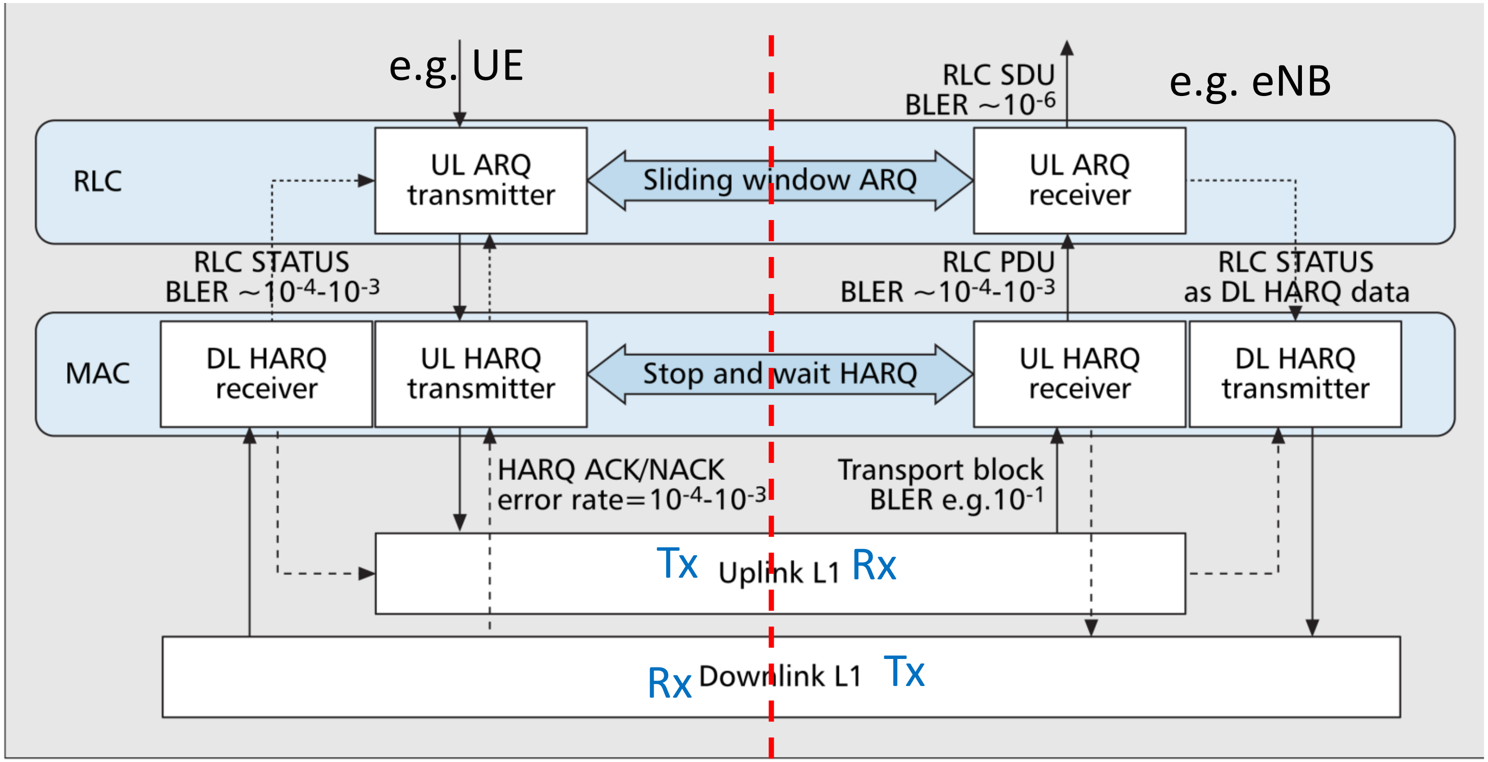
Error Handling 2

- The **physical layer** uses **Forward Error Coding** (Turbo codes) to **correct** as many errors as possible.
- The 24-bit CRC attached by the physical layer allows detecting bit errors by the MAC layer
- **MAC layer** uses the mechanisms of fast **HARQ** (Hybrid Automatic Repeat reQuest)
- The RLC layer uses the mechanism of the **Sliding Window ARQ**
- As the result, very few errors slips through the above mechanisms and reaches the IP layer

Hybrid ARQ – HARQ

- The HARQ scheme on the MAC sublayer performs **retransmissions** of corrupted transport blocks and thereby corrects the majority of all transmission errors (from 10^{-1} down to 10^{-3})
- The HARQ mechanism uses **multiple stop-and-wait** HARQ processes.
- HARQ uses a **single-bit** feedback ACK/NACK
- Short **round-trip time** of only 8ms to provide information about the successful transmission.
- **Multiple stop-and-wait** processes allow continuous transmission, which cannot be achieved with a **single** stop-and-wait scheme.
- The resulting functionality and performance is comparable to that of a **window-based selective repeat** protocol.

HARQ and ARQ retransmissions on MAC and RLC layers



■ **Figure 4** *HARQ and ARQ retransmissions on MAC and RLC layer.*

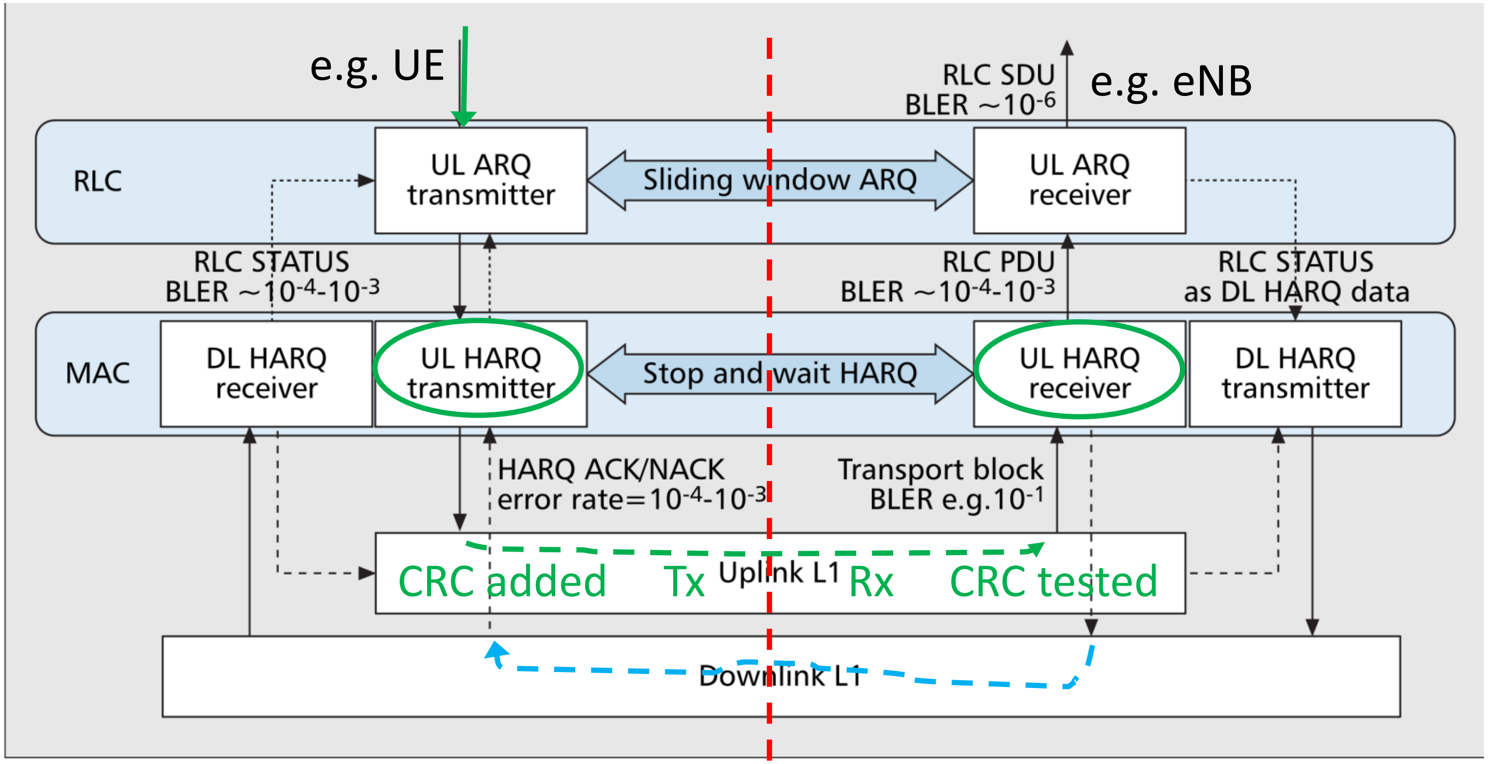
BLER – Block Error Rate

Rx – Receiver

Tx – Transmitter

- The figure shows the RLC, MAC and L1 layers in the User Equipment (UE) and the Evolved Node B (eNB) aka the base station
- The **physical transmission** occurs in the L1 layer:
  - Uplink (UL) from UE to eNB, and Downlink (DL) from eNB to UE
  - From a related Transmitter (Tx) to the Receiver (Rx)
- The RLC and MAC layers communicate logically with the equivalent peer layers through the logical Tx and Rx

HARQ ACK/NACK



BLER – Block Error Rate

■ **Figure 4** *HARQ and ARQ retransmissions on MAC and RLC layer.*

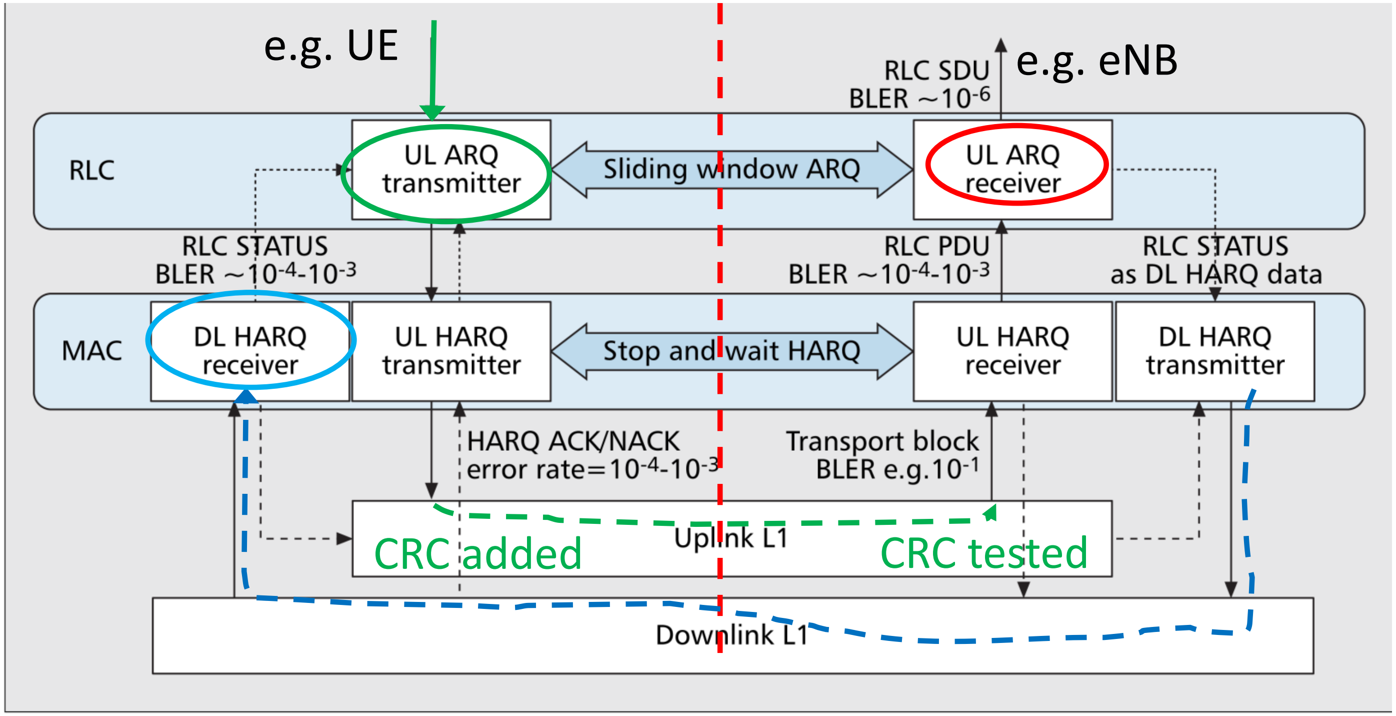
- Assume that data is **uploaded** from the UE ⟶ to the eNB :

  RLC: UL ARQ Tx ⟶ MAC: UL HARQ Tx ⟶ L1: UL Tx
- The CRC is added by the physical layer (L1) of the UL Tx and tested by the L1 of the Rx. (green line) BLER = 10^{-1}
- The Rx MAC layer (UL HARQ Rx) sends ACK or NACK through the "DL L1" back to Tx MAC layer (UL HARQ Tx) (blue line) ACK/NACK error rate ≈ 10^{-3}
- In the case of NACK, the MAC PDU is re-transmitted (green again)

From HARQ to ARQ

- In the single-bit HARQ feedback the probability for misinterpreting a negative acknowledgment (NACK) as a positive acknowledgment (ACK), and thereby causing a residual packet loss, is in the order of 10^{-4} to 10^{-3}.
- Such residual loss rates is too high to achieve high-data rates at the TCP level.
- Certain errors in other control signalling, such as scheduling information, also result in HARQ failures.
- Therefore, the fast HARQ protocol with low-overhead, ACK/NACK feedback and retransmissions with incremental redundancy
- is complemented by a highly reliable **window-based selective repeat-ARQ** protocol that resides in the RLC sublayer.
- PDUs are numbered and re-transmitted if error is detected within a specified sliding window.

ARQ ACK n / NACK m



■ **Figure 4** *HARQ and ARQ retransmissions on MAC and RLC layer.*

BLER – Block Error Rate

- Assume that data is uploaded from the UE to a eNB and the error in RLC PDU is detected by the UL ARQ receiver. BLER $\approx 10^{-3}$
- In the sliding window ARQ the data is acknowledged up to PDU # n inside the agreed sliding window.
- If there is an error in the RLC **PDU #m**, this PDU needs to be re-transmitted.
- The RLC **transmission status is sent as data** from DL HARQ Tx to DL HARQ Rx and if it is correctly received, the status is sent to UL ARQ Tx which re-transmits the **PDU #m**

HARQ and ARQ retransmission (1)

- All **re-transmissions are timed** to make sure that operations are completed in the set amount of time.
- If the RLC receiver detects a gap in the sequence of received PDUs based on the **RLC sequence number**, it starts a **reordering timer** assuming that the missing packet still is being retransmitted in the HARQ protocol.
- The reordering functionality reuses the same RLC sequence numbers as the ARQ mechanism
- In the rare case that the reordering timer expires:
  - an RLC acknowledged-mode (AM) receiver sends

    a **status message** to its transmitting peer entity
  - comprising **the sequence number** of the missing RLC PDU(s)

HARQ and ARQ retransmission (2)

- The MAC layer treats the RLC status message as any other data, meaning that it also applies the same HARQ operation and CRC to this message.
- Consequently, errors or loss of the ARQ feedback can be detected and recovered by sending another RLC status.
- HARQ retransmissions correct most errors (from 10^{-1} to 10^{-3}).
- ARQ retransmissions BLER reduces further down to 10^{-6}
- Together, the BLER has been reduce from 10^{-1} in the original transport block to only 10^{-6} in the resulting RLC SDU.
- Such amount is acceptable to the TCP layer.

Unacknowledged Mode (UM)

- Services that can sustain error rates on the order of 10^{-3} to 10^{-2}, while gaining from reduced delays,
- can be mapped to a radio bearer running the RLC protocol in **unacknowledged mode** (UM), that is, without the second ARQ layer.
- In that case, residual errors on the MAC layer are not recovered, but packet losses propagate to higher layers.
- RLC UM generally is assumed to be used for VoIP and real-time gaming traffic.

Handover support (1)

- In LTE, the UE performs measurements when radio conditions reach a certain configured threshold and provides measurement reports to the eNB it is connected to.
- The involved eNBs must negotiate through the X2 interface and decide whether or not to handover a UE to another cell or eNB.
- The EPC (evolved packet core) is not involved in the preparation signalling unless the change of serving cell involves an S1 handover as well.
- In the case of inter-eNB handover, the source eNB prepares neighboring eNBs over the X2 interface and then transmits a handover command to the UE with the required information to perform the handover to one of the prepared eNBs.
- The source eNB can forward data to the target eNB.

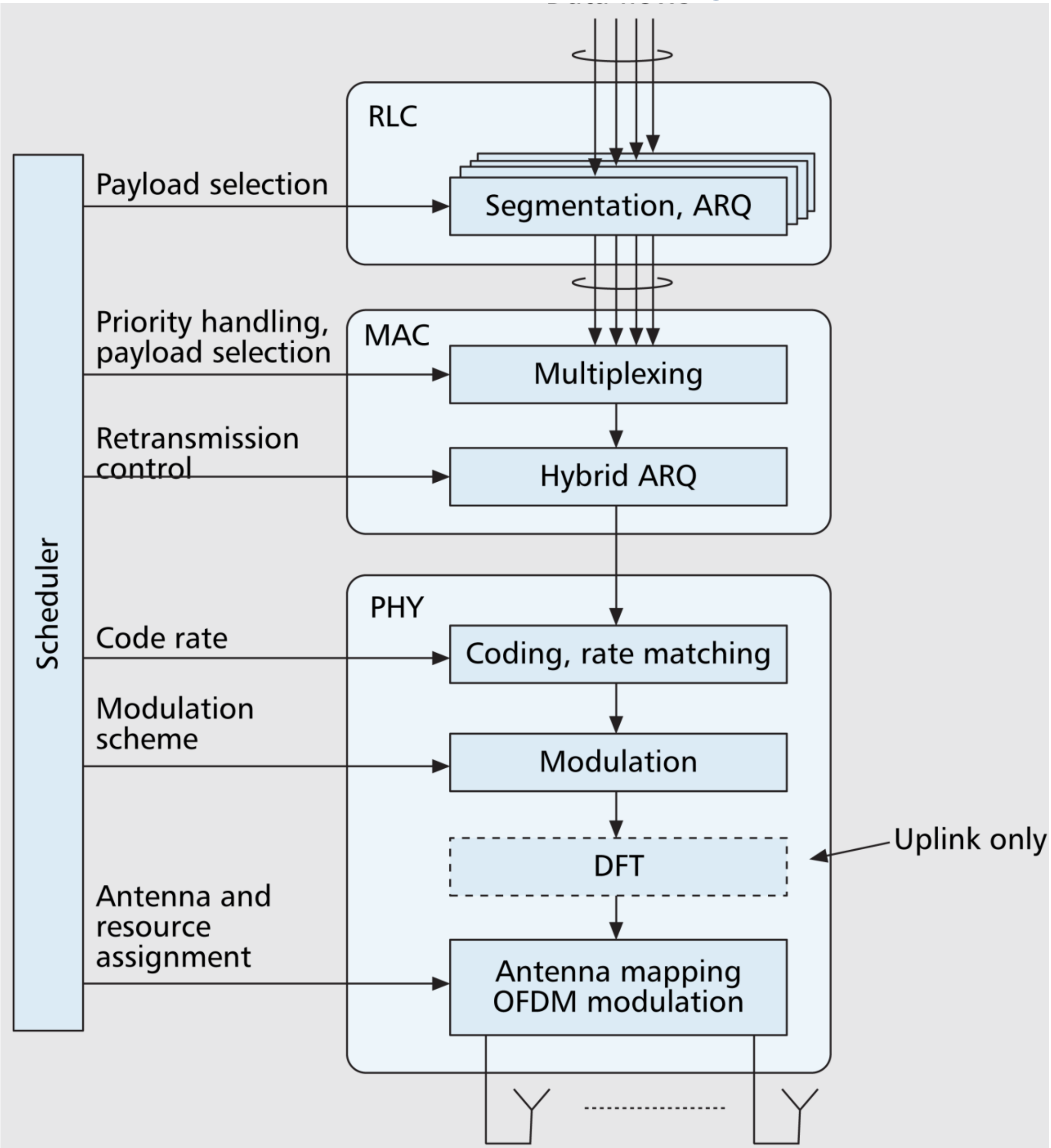
[Handover illustration]

Handover support (2)

- **For RLC AM** (Acknowledge Mode) data bearers, the source eNB forwards unacknowledged downlink PDCP PDUs with their sequence number (SN) and not-yet-transmitted IP packets received over the S1 interface to the target eNB.
- It also can forward the uplink-PDCP-service-data units (SDUs) received out-of-sequence to the target eNB.
- **For RLC UM** data bearers in the downlink, only the not-yet-transmitted IP packets received from the S1 interface are forwarded.
- The PDCP layer ensures that no data is lost at handover for RLC AM bearers by retransmitting missing data.
- PDCP in the UE also handles duplicate removal and in-sequence delivery of the PDCP SDUs received from the source eNB and from the target eNB based on the PDCP SN (Sequence Number)
- For RLC UM, no data is retransmitted by the PDCP.

LTE Layers Controlled by the Scheduler

From PDCP (Packet Data Convergence Protocol



Note:

- the basic functions of the **scheduler** located at the eNB (base station)
- some details of the Physical Layer:
- Bit coding includes: QPSK, 16QAM and 64QAM, followed by OFDM modulation
- Subcarrier spacing is 15kHz

Bit processing includes:

- A 24-bit cyclic redundancy check (CRC),
- Forward Error Coding in the form of turbo-coding,
- Scrambling, puncturing, interleaving similar to 802.11

Physical Layer Characteristics (1)

The physical layer transport block, is protected by

- A cyclic redundancy check (24-bit CRC),
- Forward Error Coding in the form of turbo-coding,
- Scrambling, puncturing, interleaving is similar to 802.11

The basic LTE radio **resource block** is
an addressable **time-frequency grid** that:

- Assembles 12 15kHz subcarriers and has a bandwidth of 180 kHz.
- Has a subframe duration of only 1 ms.
- Such a short subframe enables the exploitation of channel variations by **scheduling users** depending on their **current channel quality**.
- It allows a short **H**ybrid **A**utomatic **R**epeat re**Q**uest (**HARQ**) round-trip time of only 8ms.

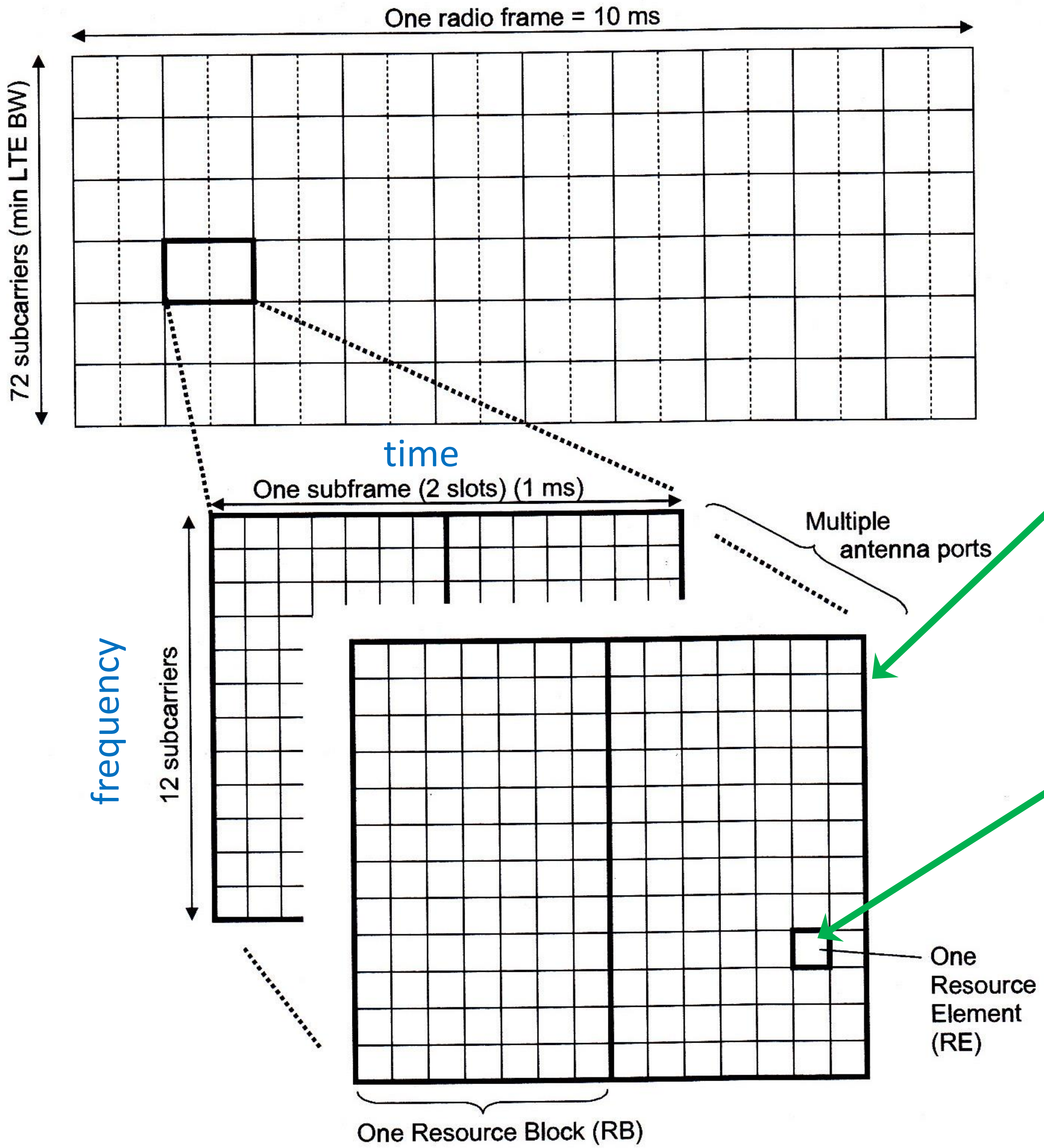


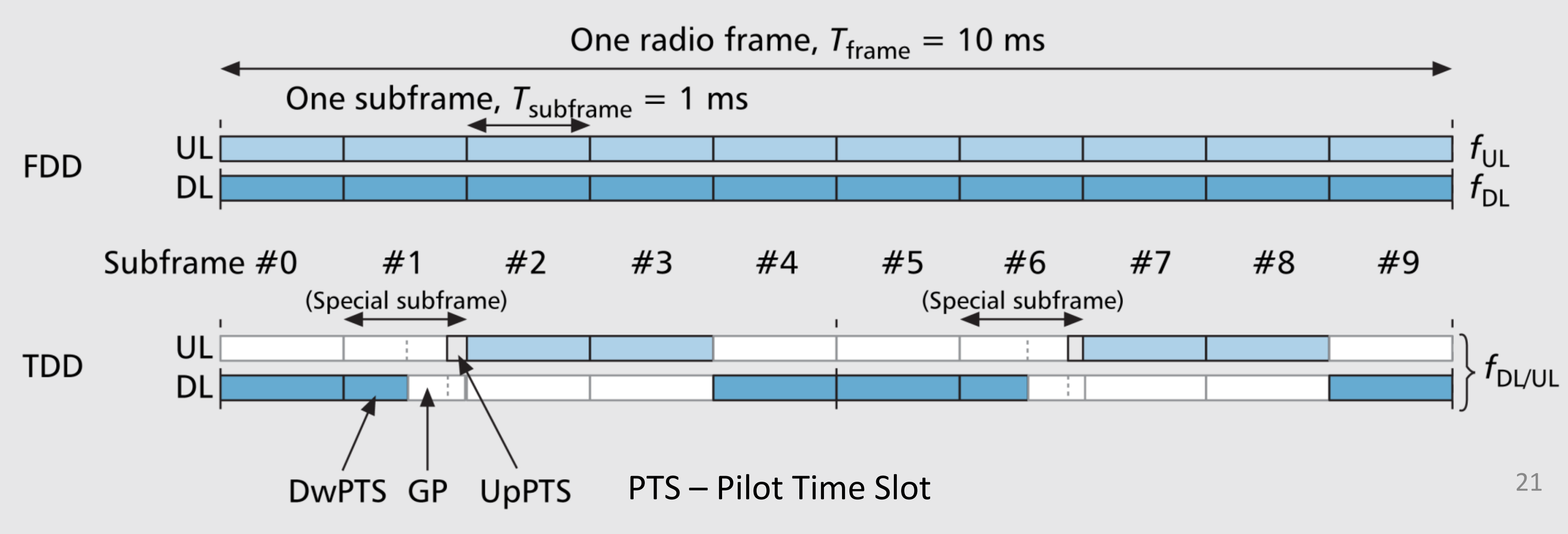
Figure 6.1: Basic time-frequency resource structure of LTE (normal cyclic prefix case).

- The **radio resource structure** is a 3D object: time, frequency, antenna
- The **Resource Block** (RB): one time slot, 12 subcarriers, one antenna.
- The **Resource Element** (RE): 1/14 ms, 180kHz/12 =15kHz subcarrier.
- Minimum LTE Bandwidth is

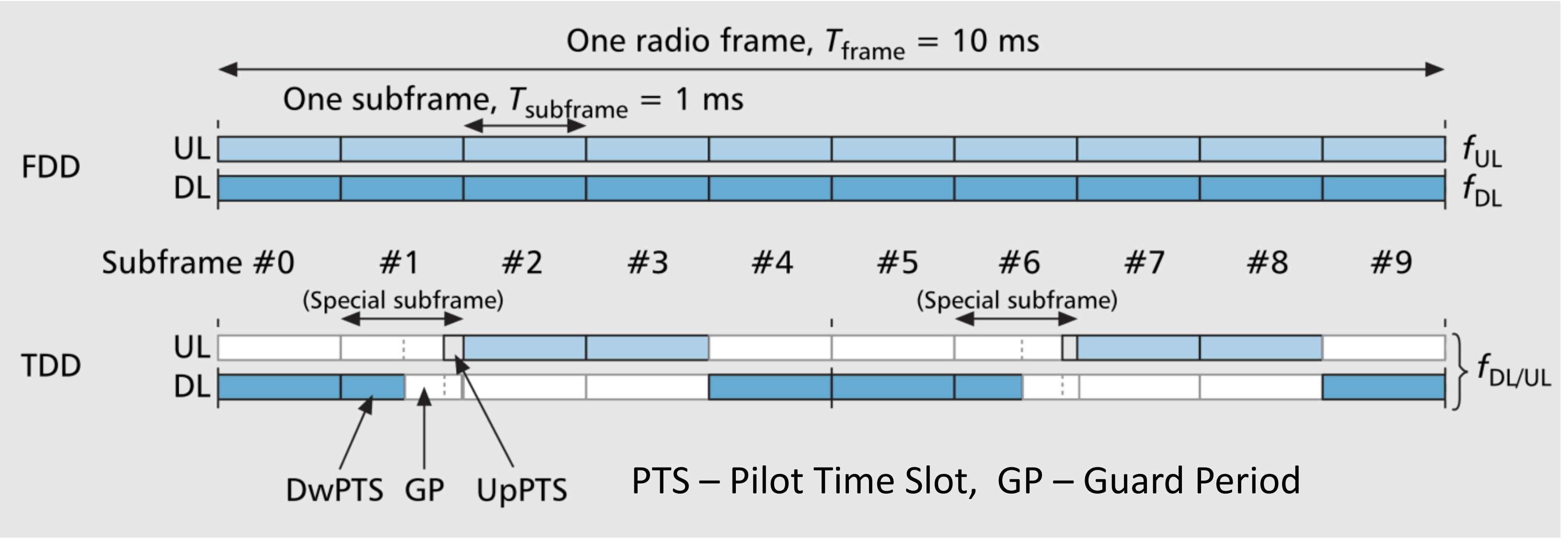
$$72 \cdot 15 = 1080\ kHz$$

Frames

- The transmitted signal is organized into **subframes** of 1ms duration, each consisting of 14 or 12 OFDM symbols, depending on whether normal (4.7μs) or extended (16.7μs) **cyclic prefix** (time guard) is used.
- Ten subframes form a 10ms **radio frame**.
- The short subframe duration of 1ms results in small delays for:
  - user data,
  - control signalling such as the HARQ feedback



FDD and TDD



- LTE supports two duplexing schemes:
  - FDD (frequency division duplex)
  - TDD (time division duplex) aka TD-LTE.
- The frame structure is almost identical for both duplexing schemes and can be handled by one chip set.
- In TD-LTE a special subframe with pilots is added to provide the required guard time for downlink-to-uplink switching
- FDD/TDD **deployment issues** are discussed here

LTE Physical Transmission Formats

- Channel coding

  First add CRC codes of 8, 16, or 24 parity bits.
- Modulation

  Supports downlink and uplink QPSK, 16QAM, and 64QAM, depending on channel conditions and UE capabilities. Use 4-Bit CQI (see Table 14.7 of textbook, p.497)
- Scrambling
- Reference Signal

  Use for measuring channel conditions
- H-ARQ

  Turbo code first applied to code block. Any transmission will use H-ARQ at receiver to combined new data with previously received block.

Table 14.7 4-Bit CQI Table

CQI Index 60	Modulation	Code Rate x 1024	Efficiency (bit/Hz)
0		Out of range	
1	QPSK	78	0.1523
2	QPSK	120	0.2344
3	QPSK	193	0.3770
4	QPSK	308	0.6016
5	QPSK	449	0.8770
6	QPSK	602	1.1758
7	**16QAM**	**378**	**1.4766**
8	16QAM	490	1.9141
9	16QAM	616	2.4063
10	64QAM	466	2.7305
11	64QAM	567	3.3223
12	64QAM	666	3.9023
13	64QAM	772	4.5234
14	64QAM	**873**	**5.1152**
15	64QAM	948	5.5547

LTE radio resource block showing scheduling

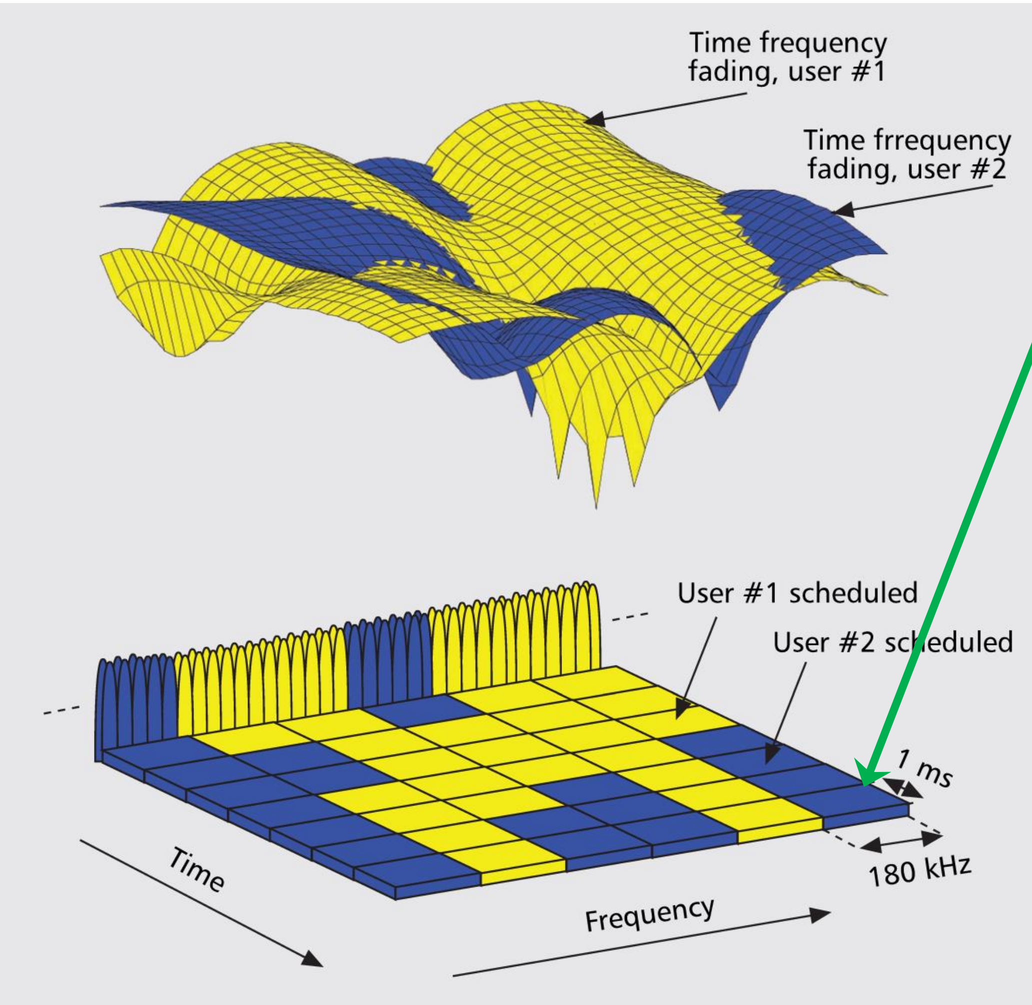


Figure 3. *Channel-quality variations in frequency and time.*

- The **radio channel quality** varies with time and frequency.
- In the example the scheduler allocate the radio **resource blocks**
- The basic **radio allocation unit** is a 1ms subframe with 12 15kHz subcarriers = 180kHz
- The scheduler can re-allocate the radio resources every radio frame (10ms)
- Some blocks carry the control information.

Allocating the resource blocks

- A short subframe enables the exploitation of channel variations by **scheduling users** depending on their **current channel quality**.

Wide **range of user-data rates** is available by:

- Allocating a variable number of resource blocks to a user
- Selecting a modulation and coding scheme to meet the current channel conditions
- Selecting scalable transport block sizes.

➢ Data rates can be increased further by aggregating up to **eight radio streams** by utilizing multiple-input multiple-output (MIMO) transmissions

Scheduling Request Mechanism

- To allow the UE to request uplink-transmission resources from the eNB, LTE provides a **Scheduling Request** (SR) mechanism.
- The SR conveys a single bit of information, indicating that the UE has new data to transmit.
- Two types of the SR mechanism:
  - **dedicated SR** (D-SR), where the SR is conveyed on a dedicated resource on the **Physical Upload Control Channel** (PUCCH)
  - **random access-based SR** (RA-SR), where the SR is indicated by performing an RA (Random Access) procedure.
- The D-SR is simpler than the RA-SR but assumes that the uplink of the UE already is time aligned.

Random Access (1)

- To keep transmissions from different UEs orthogonal, uplink transmissions in LTE are aligned with the frame timing at the eNB.
- A random access (RA) procedure is performed to acquire time alignment when:
  - timing is not aligned yet,
  - or alignment was lost due to a period of inactivity during which time alignment was not maintained by the eNB,
- The RA procedure establishes uplink time alignment by means of a four-phase contention based procedure :

Random Access Procedure

RA Preamble (1)

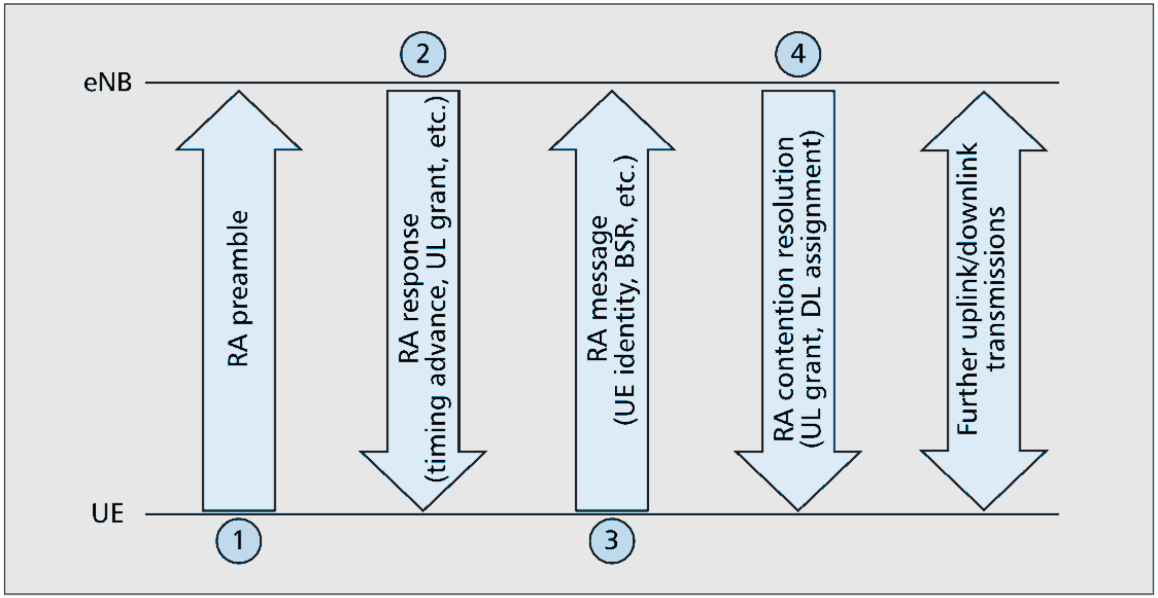


Figure 5. *Contention-based random access procedure.*

- The UE randomly selects an RA preamble sequence from the set of sequences available in the cell and transmits it on an RA channel.

RA Response (2)

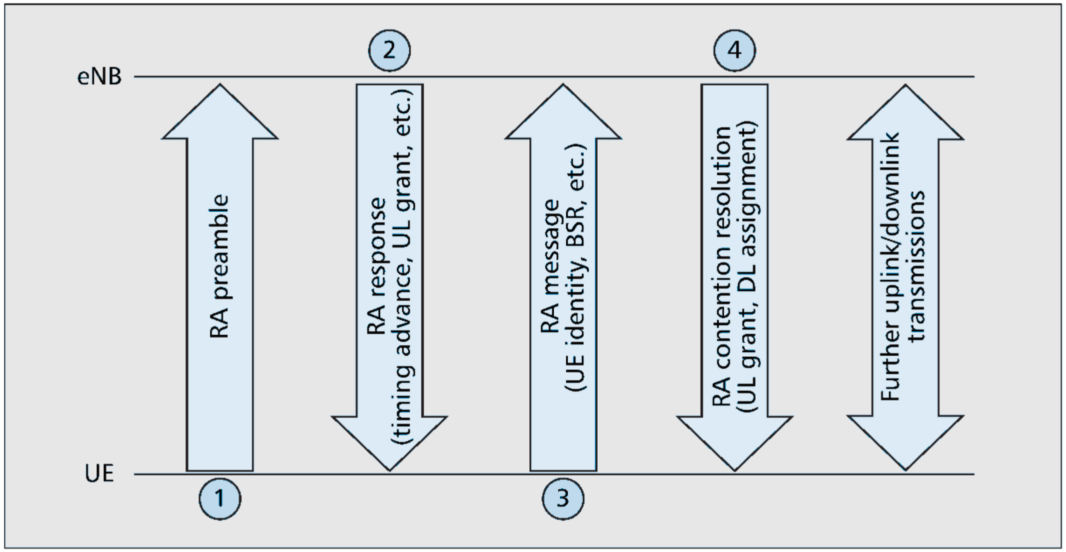


Figure 5. *Contention-based random access procedure.*

The eNB detects the preamble transmission,

- estimates the uplink transmission timing of the UE,
- responds with an RA response providing the UE with
- the correct timing-advance value to be used for subsequent transmissions and with a first grant for an uplink transmission.

RA Message (3)

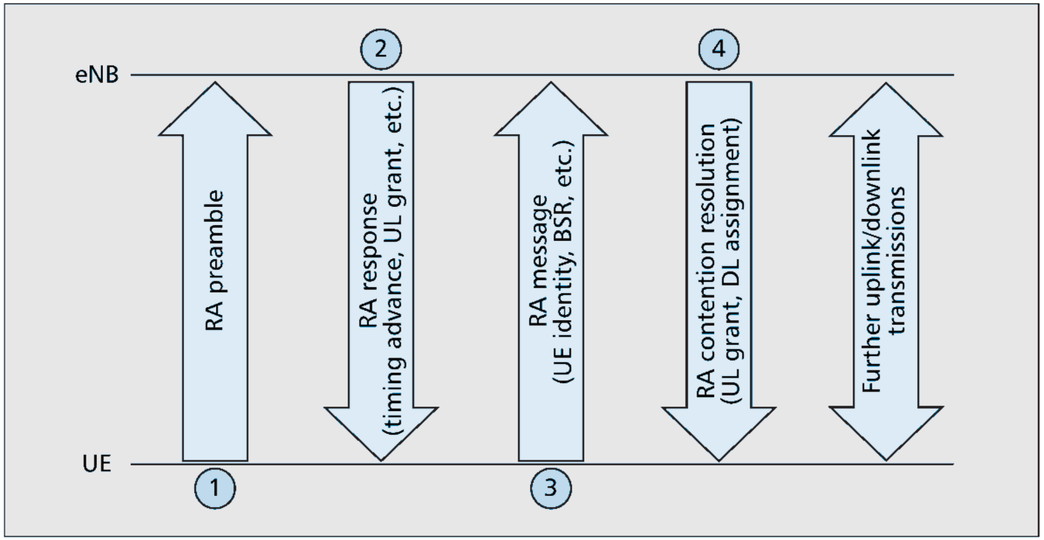


Figure 5. *Contention-based random access procedure.*

- The randomly selected RA preamble does not enable unique identification of the UE,
- it is possible that multiple UEs attempted RA with the same RA preamble sequence on the same RA channel
- The UE provides its identity to the eNB with the first scheduled uplink transmission.

RA Contention Resolution (4)

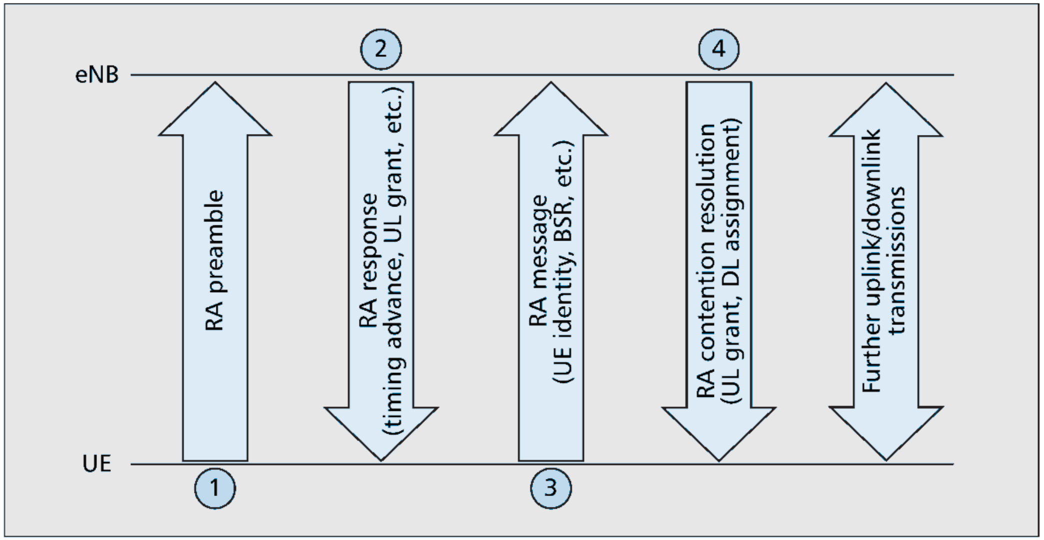


Figure 5. *Contention-based random access procedure.*

- The eNB receives the RA message transmitted in phase 3
- Only one RA message is typically received even if two or more were transmitted by contending UEs.
- The eNB resolves the (potential) contention by echoing the received UE identity back.
- The UE, seeing its own identity echoed back, concludes that the RA was successful and proceeds with time-aligned operation.

More on the Random Access Procedure

- UEs that do not receive an RA response or do not receive their own identity in the contention resolution, must repeat the RA procedure.
- In the case of congestion, the eNB can provide a back-off indicator to instruct UEs that did not succeed with their RA attempt to apply a back-off procedure.
- The back-off indicator is multiplexed with the RA responses.
- Note that for cases where an RA is anticipated by the network, that is, at handover completion and eNB-triggered uplink re-alignment, LTE also provides a faster two-phase contention free RA procedure.
- In this case the eNB assigns a dedicated preamble to be used by the UE.
- Because the UE that corresponds to the received dedicated preamble is known, phase 3 and 4 are not required.

More on Scheduling Request

- If the uplink of the UE is not time aligned, RA-SR must be used to (re-)establish time alignment.
- RA-SR also is used, regardless of the uplink-timing state, when no PUCCH resources for D-SR were assigned to the UE.
- The SR procedure conveys little detail about the UE resource requirement, therefore

➢ a **buffer status report** (BSR) with more detailed information about the amount of data waiting in the UE

➢ is attached to the first uplink transmission following the SR procedure.

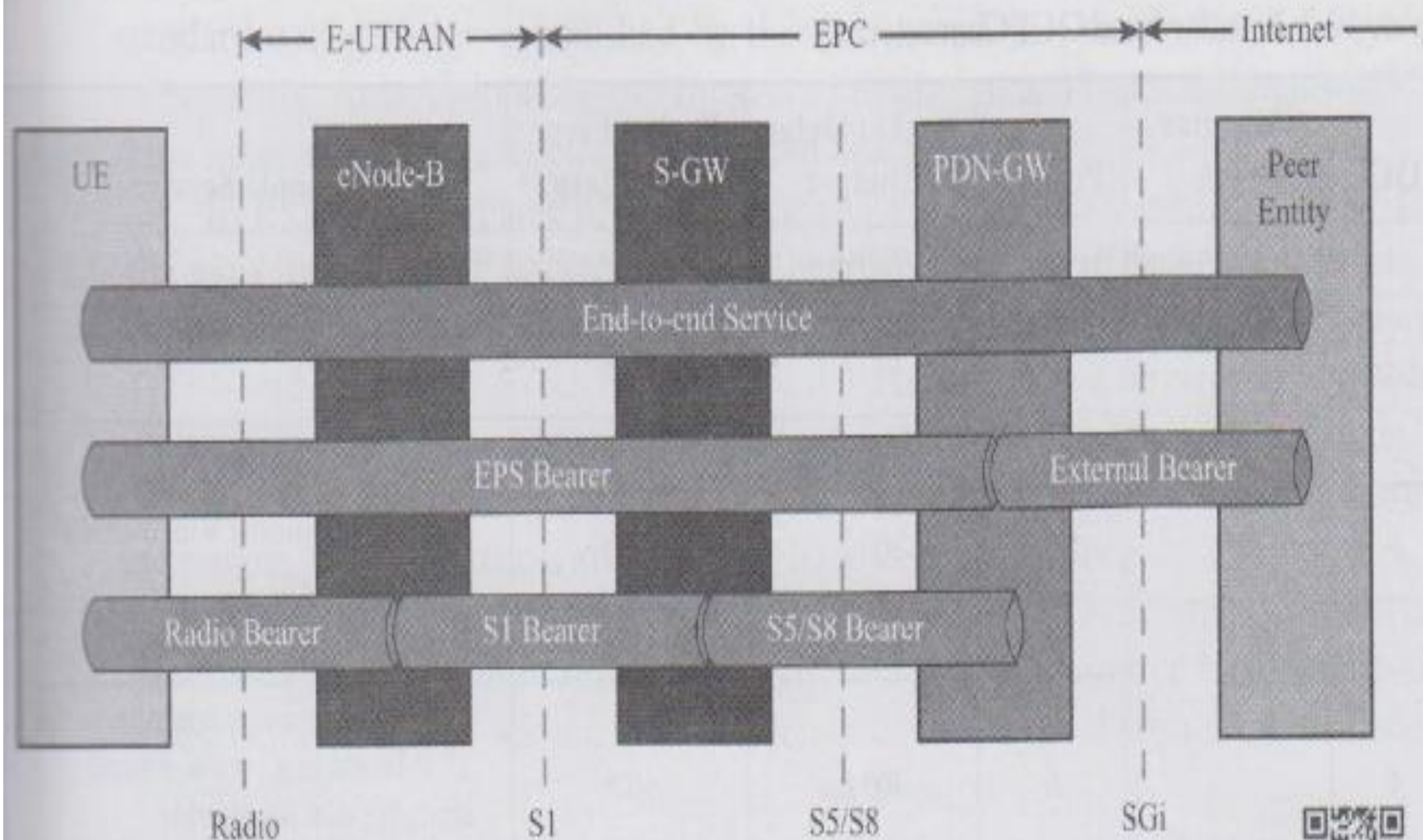


Figure 14.3 LTE QoS Bearers

Scheduling for Quality of Service (QoS) - 1

- A particular challenge for the schedulers is to provide the **desired quality of service** (QoS) on a shared channel.
- GSM and UMTS provide **guaranteed bit rates** by pre-allocating radio resources statically to dedicated channels.
- LTE does not provide dedicated channels but only **shared channels.**

A number of default QoS characteristics suitable for:

- VoIP (Voice over the IP protocol)
- Signaling traffic
- Internet access
- …

have been standardized for EPS (Evolved Packet Services).

Scheduling for Quality of Service (QoS) - 2

- The required QoS characteristic are assigned by the EPC (Evolved Packet Core) .
- It is the responsibility of the scheduler in the eNB to assign radio resources to satisfy the required characteristics.
- Depending on the implementation, the scheduler can base its scheduling decision on
  - the QoS class and the queuing delay of the available data
  - the instantaneous channel conditions
  - fairness indicators.

Summary of LT09-I & II

- Describe and revise the basic facts related to three coexisting technologies: GSM/EDGE, UMTS/HSPA, LTE
- Understand LTE architecture: EPC and E-UTRAN principles and functionalities at link-layer

  UE and eNB

  Serving Gateway S-GW

  Packet Delivery Network PDN-GW

  MME – Mobility Management Entity

  Today's tutorial- discussion of assignment 2 progress

  Next lecture: LT10 on 5G and mesh network