

Long-Term Evolution Protocol: How the Standard Impacts Media Access Control



Tim Godfrey
WMSG Advanced Technology

FreescalTM and the Freescale logo are trademarks of Freescale Semiconductor, Inc. All other product or service names are the property of their respective owners. © Freescale Semiconductor, Inc. 2007-2008.



- ▶ Introduction to Media Access Controls (MAC)
- ▶ Protocol design as a result of application requirements
 - History and scope of standards
 - Comparison of long-term evolution (LTE) and WLAN architectures
 - Comparison how the MAC sees the baseband physical layer (PHY)
- ▶ Frames and packets – a timeline overview
- ▶ Life of a packet – a protocol overview
- ▶ LTE Protocol Operation
 - Management and control functions
 - Scheduling and QoS
 - Handover and roaming
 - Power save functions
- ▶ Conclusion

► What is this presentation?

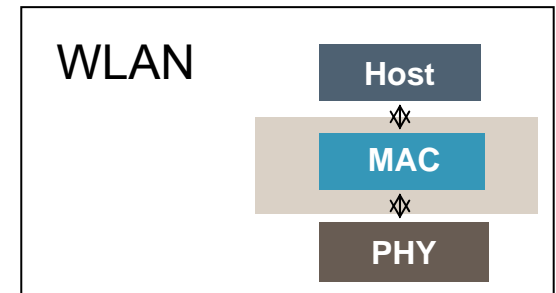
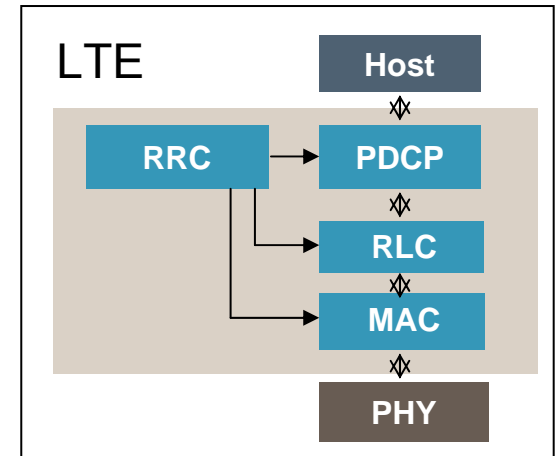
- An overview of the MAC for 3GPP™ LTE (Long Term Evolution, also referred to as E-UTRAN).
- Comparison with other MAC standards, such as 802.11.

► Why is it important?

- LTE is the latest generation of the 3GPP™ standards
- IP-only network support data rates up to 100 Mbps
- Deployment starting in 2009
- This presentation will describe all these functions, which consist of the MAC, Radio Link Control (RLC), Packet Data Convergence Protocol (PDCP), and Radio Resource Control (RRC)

What is the MAC?

- ▶ Medium Access Control – controlling access to a shared medium
 - The medium is the radio spectrum
 - Who gets to transmit?
 - When to transmit?
 - How much and how fast to transmit?
- ▶ What is casually called “the MAC” varies between LTE and WLAN
 - The informal use is to refer to the function that deals in “packets” on the top side, and controls a radio Modem on the bottom side
 - in 3GPP standards this function contains the MAC, RLC, PDCP, and RRC
 - In 802.11, the MAC is everything between the packet interface and the PHY



Protocol design: driven by use cases and requirements

- ▶ WLAN grew out of LAN technologies such as Ethernet
 - Data communication was primary application – voice added recently
 - Mobility and handoff were added recently
 - Requirement for fair and equal access for all nodes
- ▶ LTE grows out of cellular standards: Global System for Mobile Communications (GSM) and Universal Mobile Telecommunications System (UMTS)
 - Voice communication was primary application – data added recently
 - Mobility and handoff were requirements from the start
 - Requirement for central management of all nodes

The spectrum of spectrum

Free
Unlicensed
Shared



Expensive
Licensed
Private

► WLAN

- Designed to work in free spectrum
 - Not highly optimized – packet headers and contention time result in significant overhead
 - Simple protocol, easy to implement

- Designed to work in shared spectrum
 - Protocol is robust to interference

► LTE

- Protocol designed to maximize utilization of expensive spectrum
- Every mS and Hz is utilized to carry the maximum data
- Protocol very complex and highly optimized

- Designed to work in licensed spectrum
- Poor tolerance to interference
- Network planning required

The spectrum of symmetry



▶ WLAN

- ▶ Station and Access points are basically the same
 - Access point consists of station with some additional software

- ▶ Identical power

- ▶ Identical modulation

- ▶ Peer-to-peer communication possible

▶ LTE

- ▶ UE and Base Station are very different

- ▶ Uplink and downlink power are different

- ▶ Uplink and downlink modulation are different

- ▶ Peer-to-peer communication not supported

The spectrum of connection model

Packet
Switched



Circuit
Switched

► WLAN

- 802.11 evolved from Ethernet
 - Packet switched LAN data networks

► LTE

- LTE evolved from GSM and 3GPP 3G (WCDMA)
 - Originally circuit switched only

- 802.11 evolved towards “circuit switched like” capabilities in 802.11e, but retains packet-oriented PHY

- LTE supports packet switched model at the SAP, but retains a circuit switched model at the PHY

The spectrum of control



► WLAN

- Access is by CSMA/CA
 - Probabilistic - based on random backoff
- AP has no “privilege” over stations
 - Except rarely used PCF or HCCA
- Networks function without frequency planning

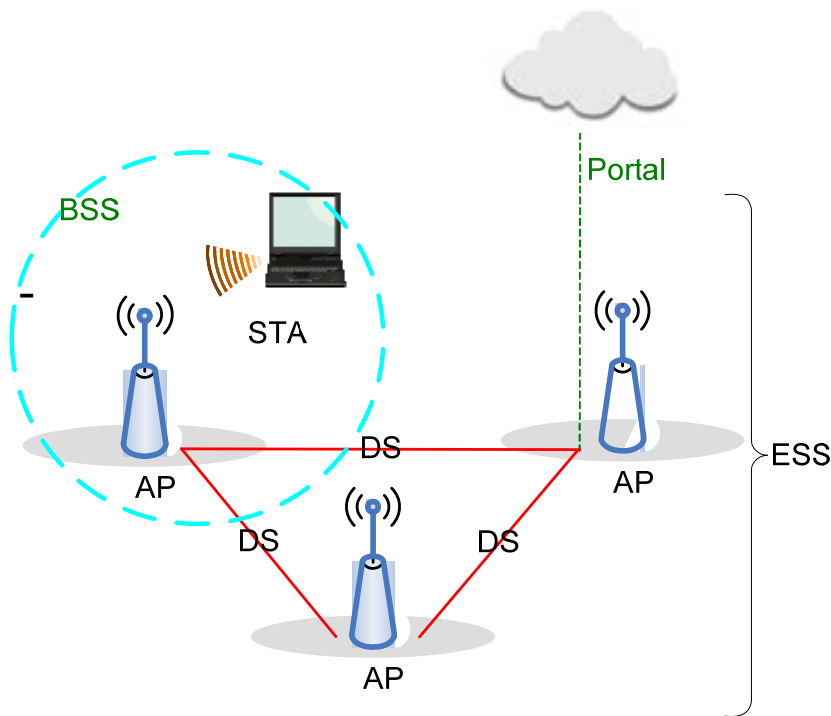
► LTE

- All client access is scheduled
- Base Station has absolute control over network device operation
- Adjacent networks require frequency planning

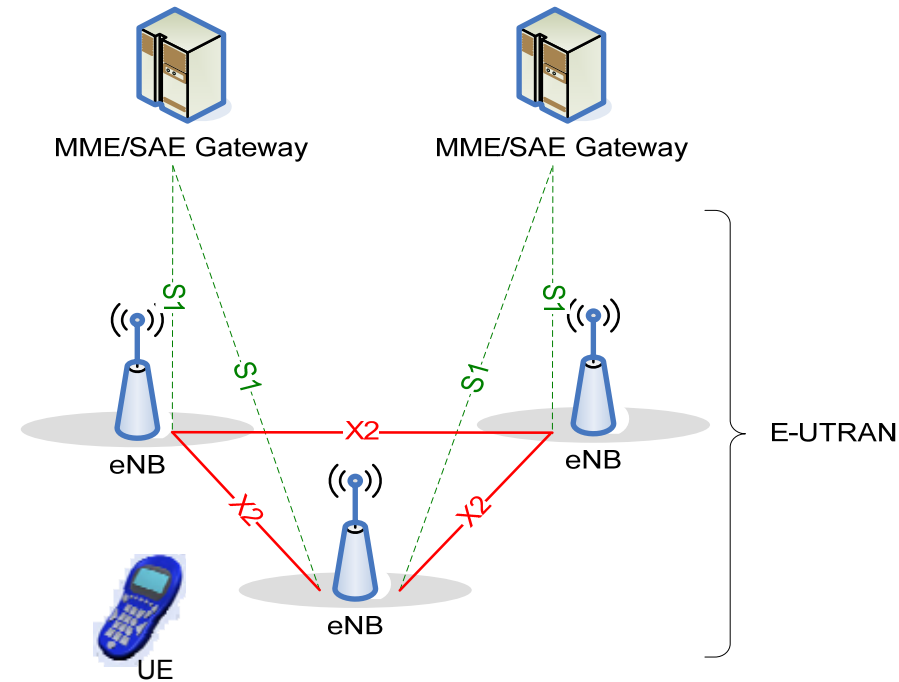
History and scope of wireless standards

- ▶ WLAN standardized IEEE in Project 802
 - First 802 standard was Ethernet
- ▶ 802 standards' scope limited to MAC and PHY
- ▶ Work on 802.11 started in 1990
- ▶ Voting-driven selection process
- ▶ LTE standardized by 3GPP
 - 3rd Generation Partnership Project
 - Grew out of GSM cellular standards
- ▶ 3GPP standards specify entire system
 - Air Interface, Protocol stack, Inter-network
- ▶ Work on LTE started in 2004
- ▶ Consensus-driven selection process

Comparison of wireless architectures



- ▶ AP – Access Point
 - Base Station
- ▶ STA – Station (user equipment)
 - BSS – Basic Service Set
 - ESS – Extended Service Set
- ▶ Portal – gateway to Internet
 - DS – Distribution System (between APs)



- ▶ eNB – Enhanced Node B
 - Base station
- ▶ UE – User Equipment
- ▶ EPC – Evolved Packet Core
 - MME – Mobility Mgmt Entity (Control Plane)
 - SAE – System Architecture Evolved (User Plane)

Comparison of how the MAC sees the PHY

► WLAN

- PHY is half-duplex
- PHY is packet oriented – sync on each packet
- PHY provides a single channel with a single modulation for each packet

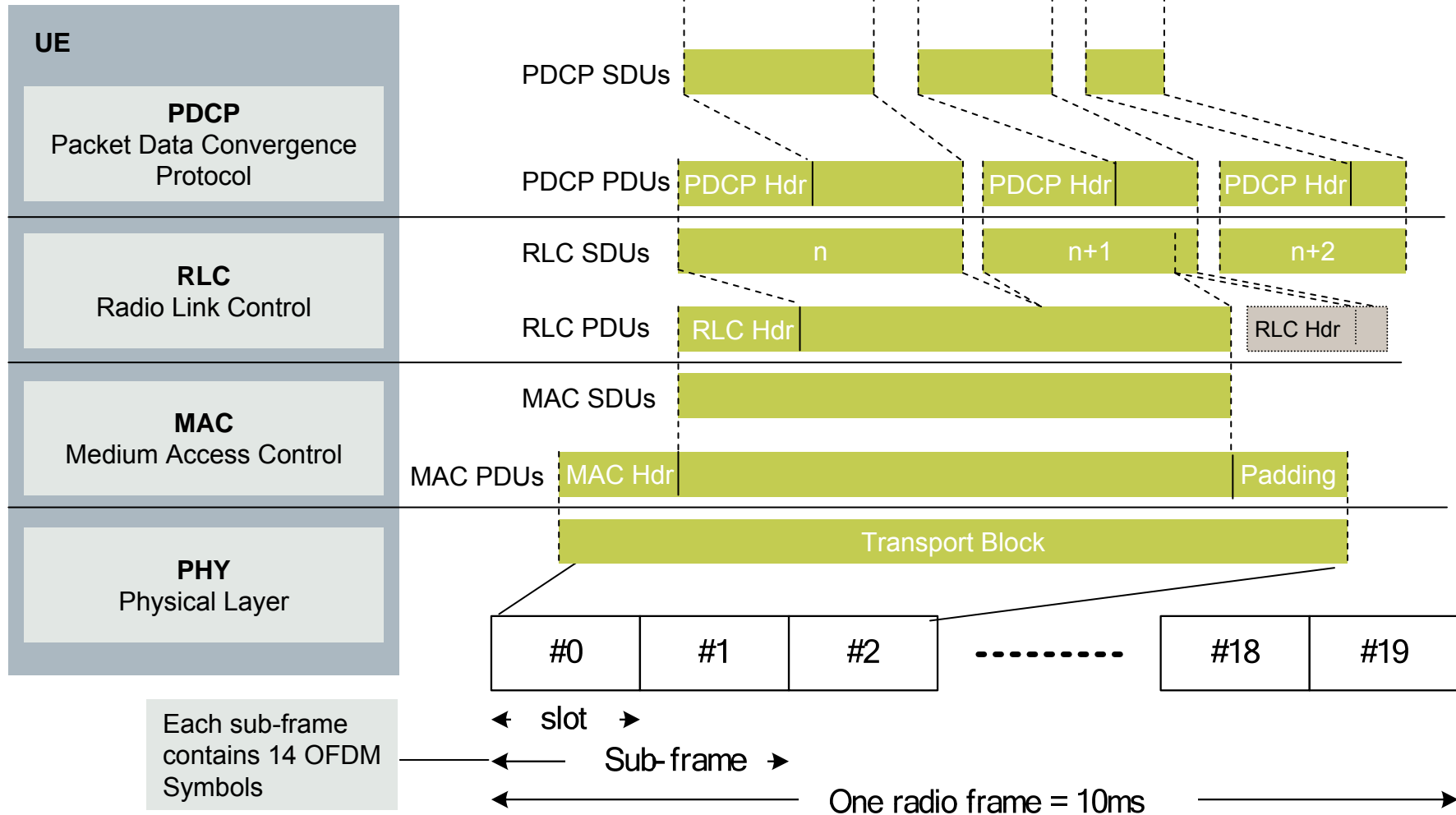
► LTE

- PHY is typically full-duplex
- PHY operates continuously – sync is interspersed
- PHY provides multiple channels simultaneously with varying modulation

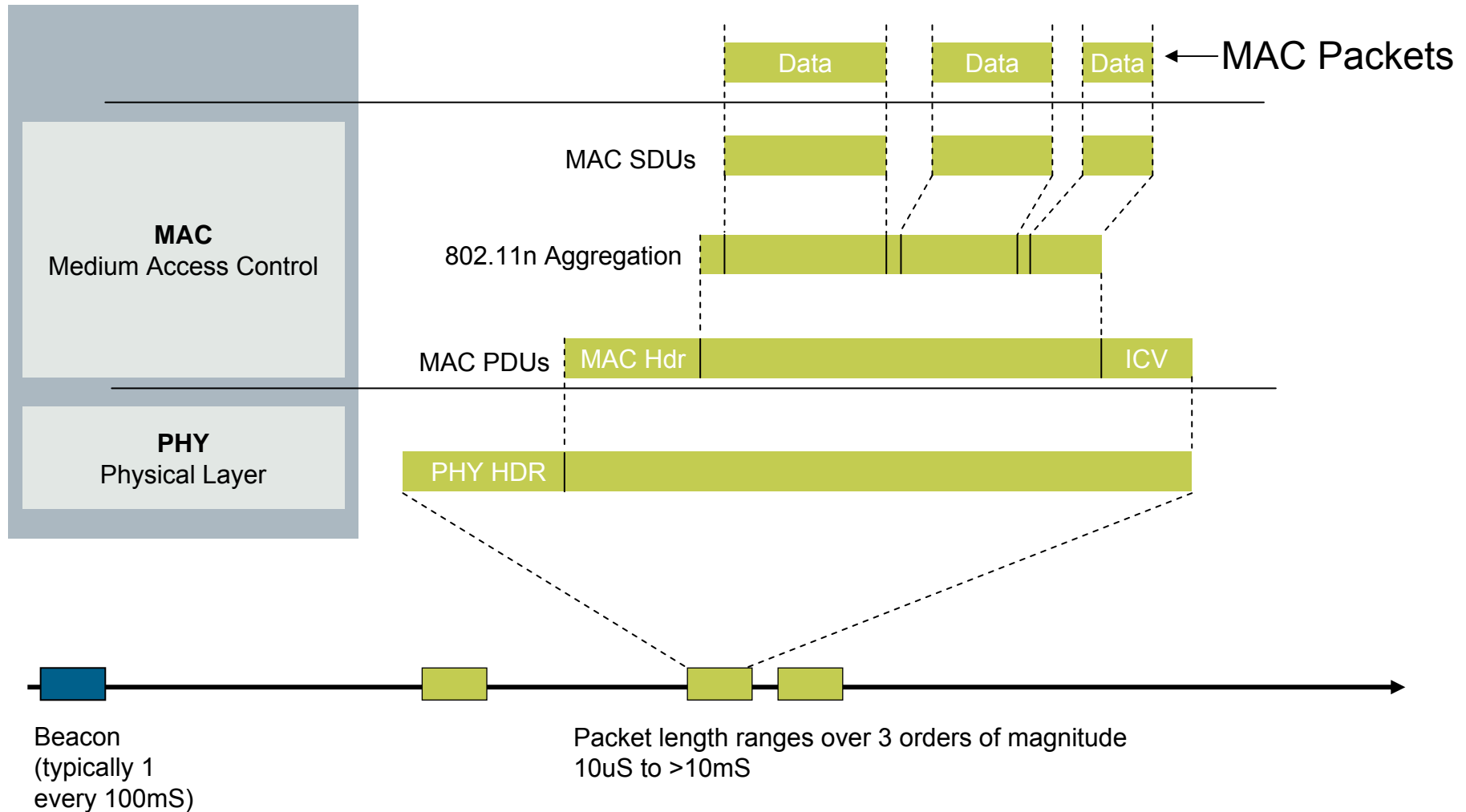
► Impact on the MAC

- The WLAN PHY interface to the MAC is by a PDU (Protocol Data Unit)
 - One (or more with aggregation) packet
 - The MAC controls when to send and when to expect reception in time
- The LTE PHY interfaces with a Transport Block
 - Corresponding to the data carried in a period of time (radio subframe: 1 mS)
 - The MAC controls what to send in a given time

Frames and packet timelines - LTE



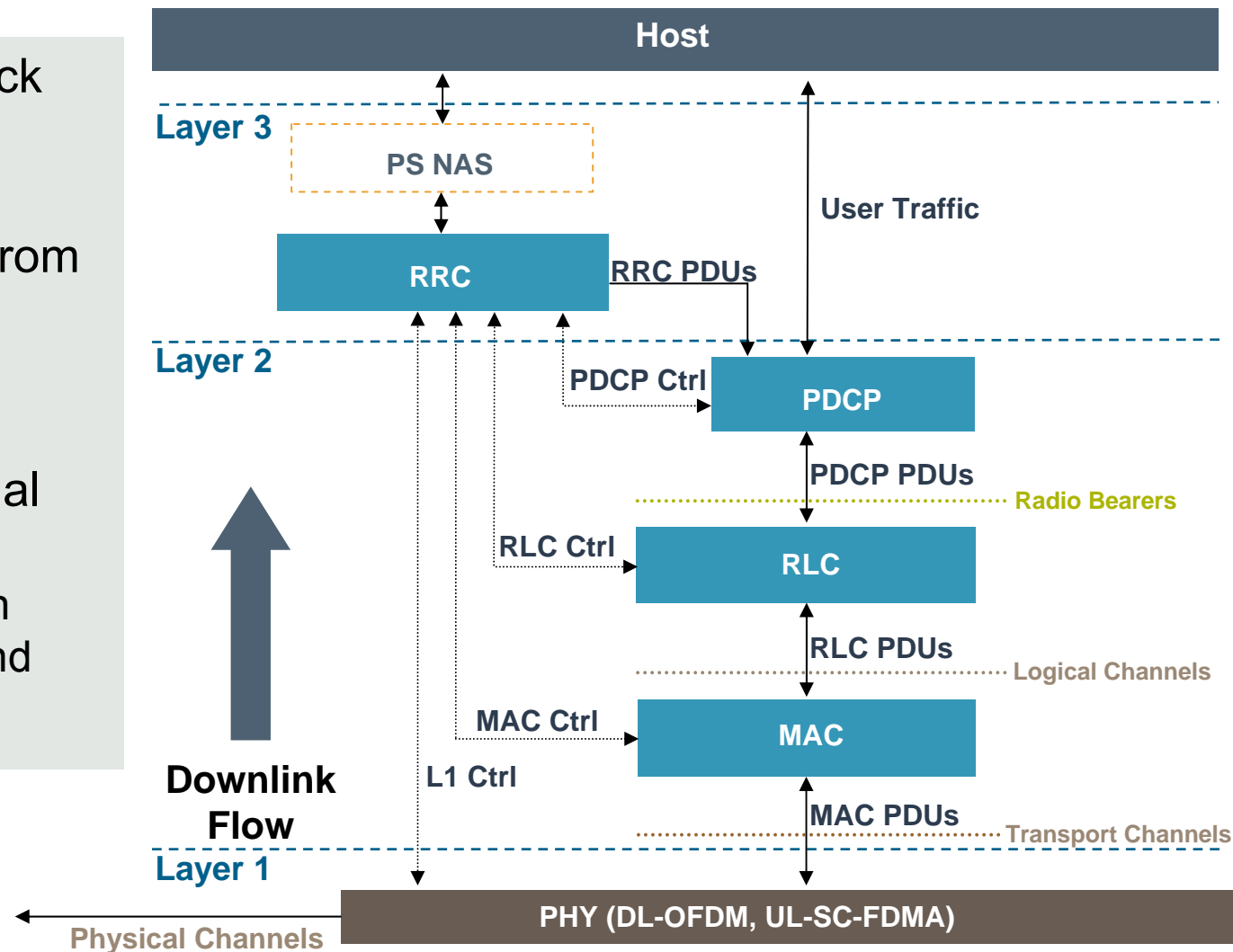
Frames and packet timelines - WLAN



- ▶ The preceding slides show the structure of packets in time
- ▶ The following section traces the flow of a packet through the sublayers of the LTE stack
- ▶ The downlink direction (from network to terminal) is covered first
- ▶ An uplink packet is then described, highlighting any differences

Life of a packet - Downlink

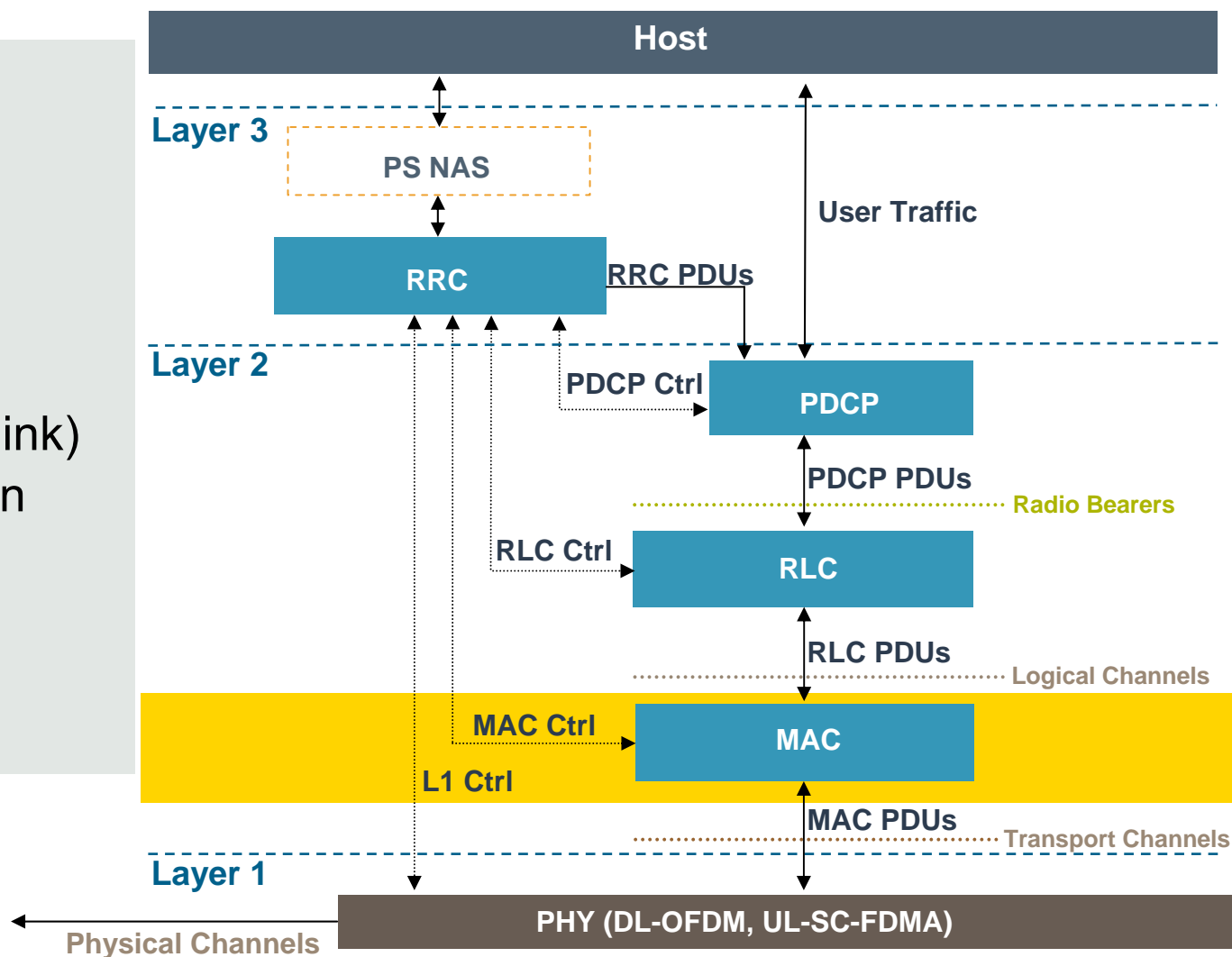
- ▶ The Transport Block
 - Delivered from PHY to MAC
 - Contains data from previous radio subframe
 - May contain multiple or partial packets
 - Depending on scheduling and modulation



Life of a packet – Downlink – MAC layer

► MAC Functions

- Hybrid ARQ
- Mapping
 - Transport ⇔ Logical
 - Mux / DeMux
- Scheduling (uplink)
- Format selection
- Measurements (RRC)



MAC - Downlink - Hybrid ARQ

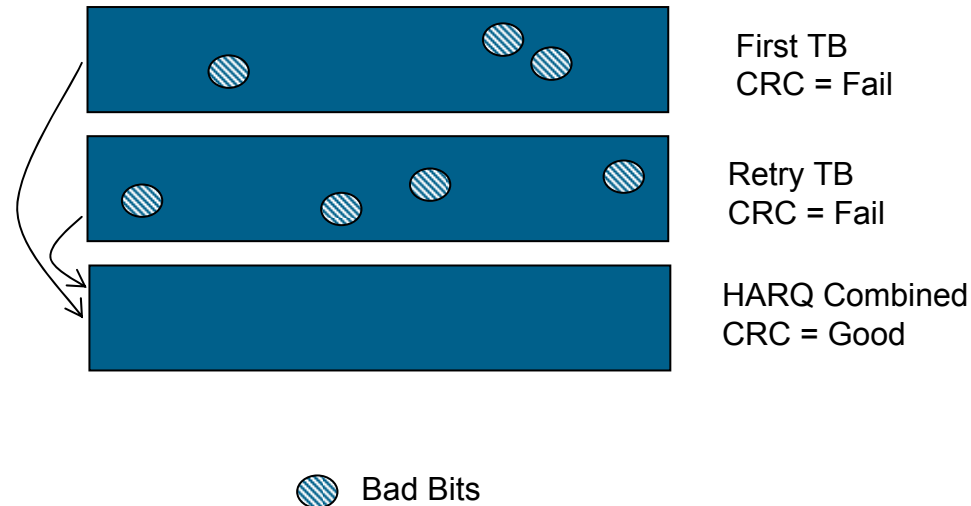
► Retransmission of Transport blocks for error recovery

- MAC sends “NACK” message when TB fails CRC
- Transport Blocks with errors are retained
- PHY retransmits with different puncturing code
- Retransmission combined with saved transport block(s)
- When correct transport block is decoded, MAC signals “ACK”
- Multiple HARQ processes run in parallel – retry several TBs

► Hybrid ARQ function involves both MAC and PHY

- PHY performs retention and re-combination (incremental redundancy)
- MAC controls signaling

Simplified HARQ Operation



- ▶ Logical Channels exist at the top of the MAC
 - Represent data transfer services offered by the MAC
 - They are defined by [what type of information](#) they carry

- ▶ Types of Logical Channels
 - Control channels (for control plane data)
 - Traffic channels (for user plane data)

- ▶ Transport Channels exist at the bottom of the MAC
 - Represent data transfer services offered by the PHY
 - They are defined by [how](#) the information is carried

MAC – Downlink Mapping

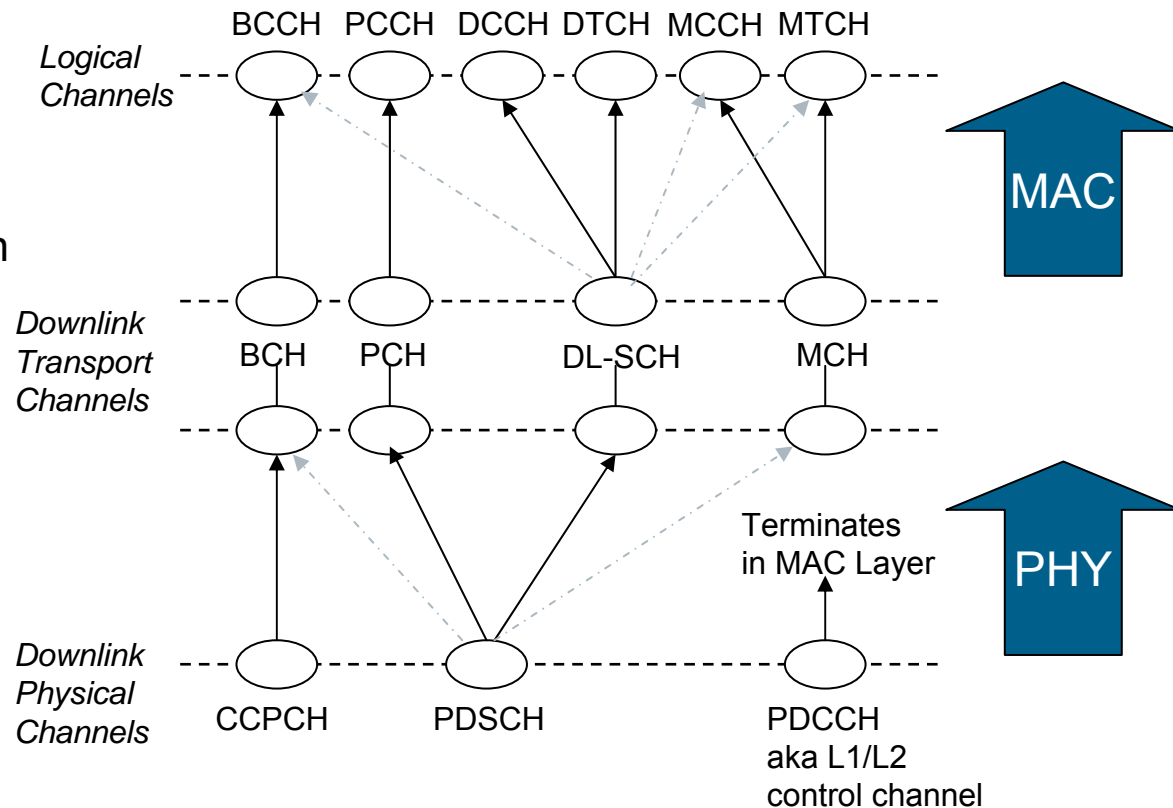
- ▶ A valid Transport block is available from the HARQ process
- ▶ Next, the transport channels are mapped to logical channels

▶ Logical Channels

- PCCH: Paging Control Chan
- BCCH: Broadcast Ctrl Chan
- DCCH: Dedicated Ctrl Chan
- DTCH: Dedicated Traffic Chan
- MCCH: Multicast Ctrl Chan
- MTCH: Multicast Traffic Chan

▶ Transport Channels

- PCH: Paging Channel
- BCH: Broadcast Channel
- DL-SCH: Downlink Shared Ch
- MCH: Multicast Channel



MAC – Format selection, measurements

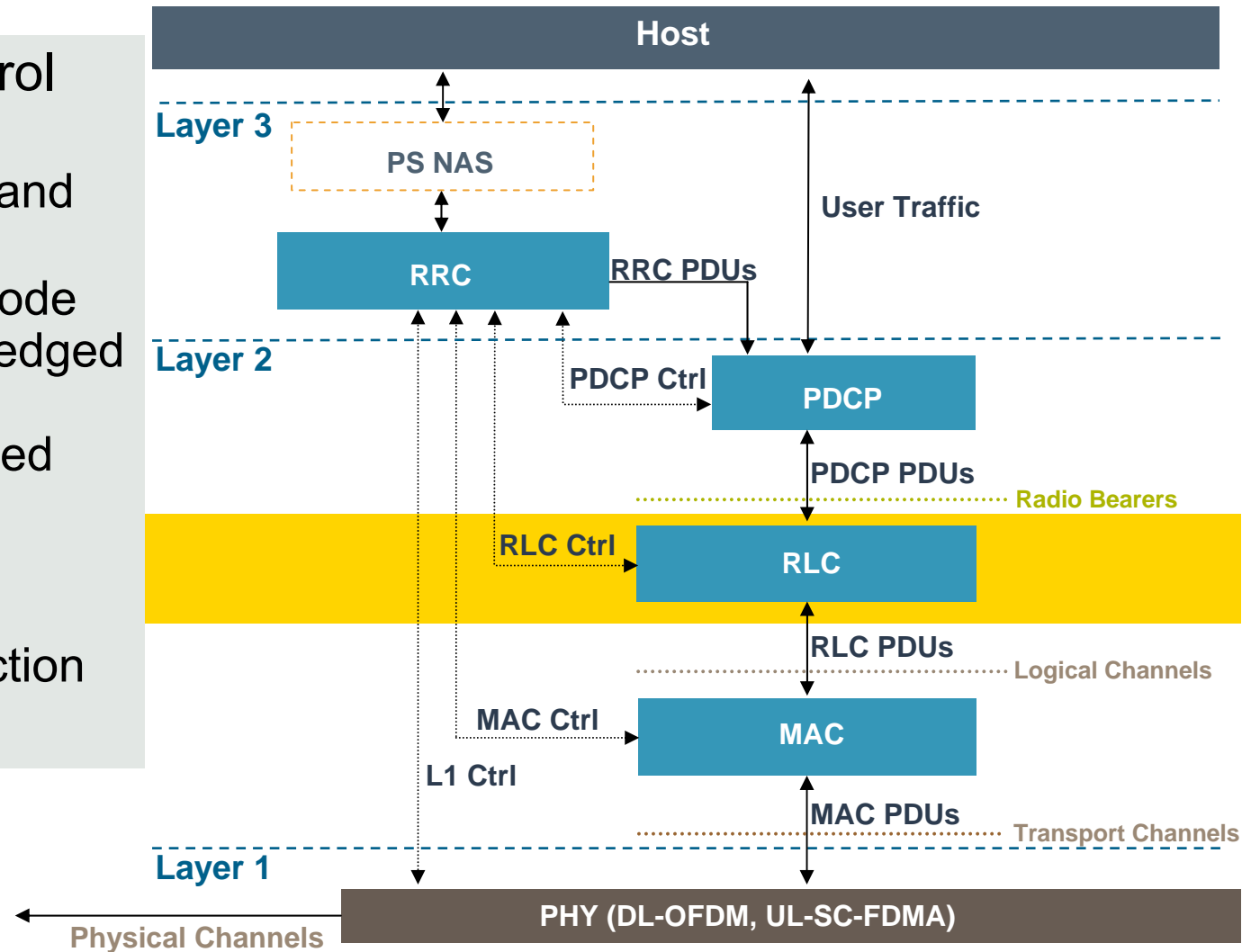
- ▶ The MAC sets the transport format on downlink
 - The eNB includes information in each transport block that specifies the format (MCS: Modulation Coding Scheme) for the **next** Transport Block
 - The MAC configures the PHY for the next TB

- ▶ The MAC coordinates measurements
 - From local PHY to RRC regarding local
 - RRC reports back to eNB via control messages
 - From eNB to RRC
 - RRC controls local PHY modulation and configuration settings

- ▶ MAC measurements support downlink scheduling
 - Rates and radio conditions at the UE are used by the eNB
 - If the rate is high, fewer time slots are needed to send data

Life of a packet – Downlink – RLC layer

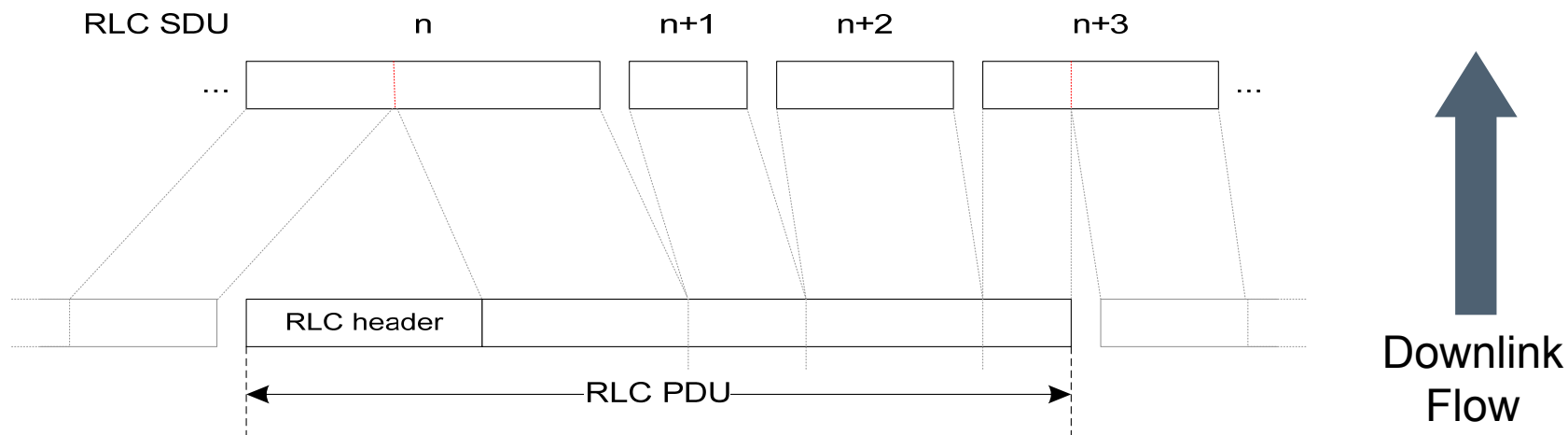
- ▶ Radio Link Control
- ▶ RLC Functions
 - Segmentation and re-assembly
 - Transparent Mode (TM), Acknowledged mode (AM), or Unacknowledged mode (UM)
 - In-Sequence delivery and duplicate detection



RLC Segmentation

► Segmentation: unpacking an RLC PDU into RLC SDUs

- The RLC PDU size is based on transport block size.
- If an RLC SDU is large, or the available radio data rate is low (result in small transport blocks), the RLC SDU may be split among several RLC PDUs
- If the RLC SDU is small, or the available radio data rate is high, several RLC SDUs may be packed into a single PDU
- In many cases both splitting and packing may be present:



- ▶ The RLC ensures in-order delivery of SDUs
 - Out of order packets can be delivered during handover
 - The PDU sequence number carried by the RLC header is independent of the SDU sequence number (i.e. PDCP sequence number);
 - An RLC SDU is built from (one or more) RLC PDUs for downlink.
 - Ordering is corrected in the RLC using sequence numbers

- ▶ Transparent
 - No RLC header

- ▶ Unacknowledged and Acknowledged
 - RLC header is used

- ▶ ARQ and HARQ Interactions
 - ARQ applies to an RLC SDU
 - HARQ applies to a transport block
 - May contain partial SDU, one SDU, or multiple SDUs
 - If HARQ transmitter detects a failed delivery of a TB due to e.g. maximum retransmission limit is reached the relevant transmitting ARQ entities are notified and potential retransmissions and re-segmentation can be initiated

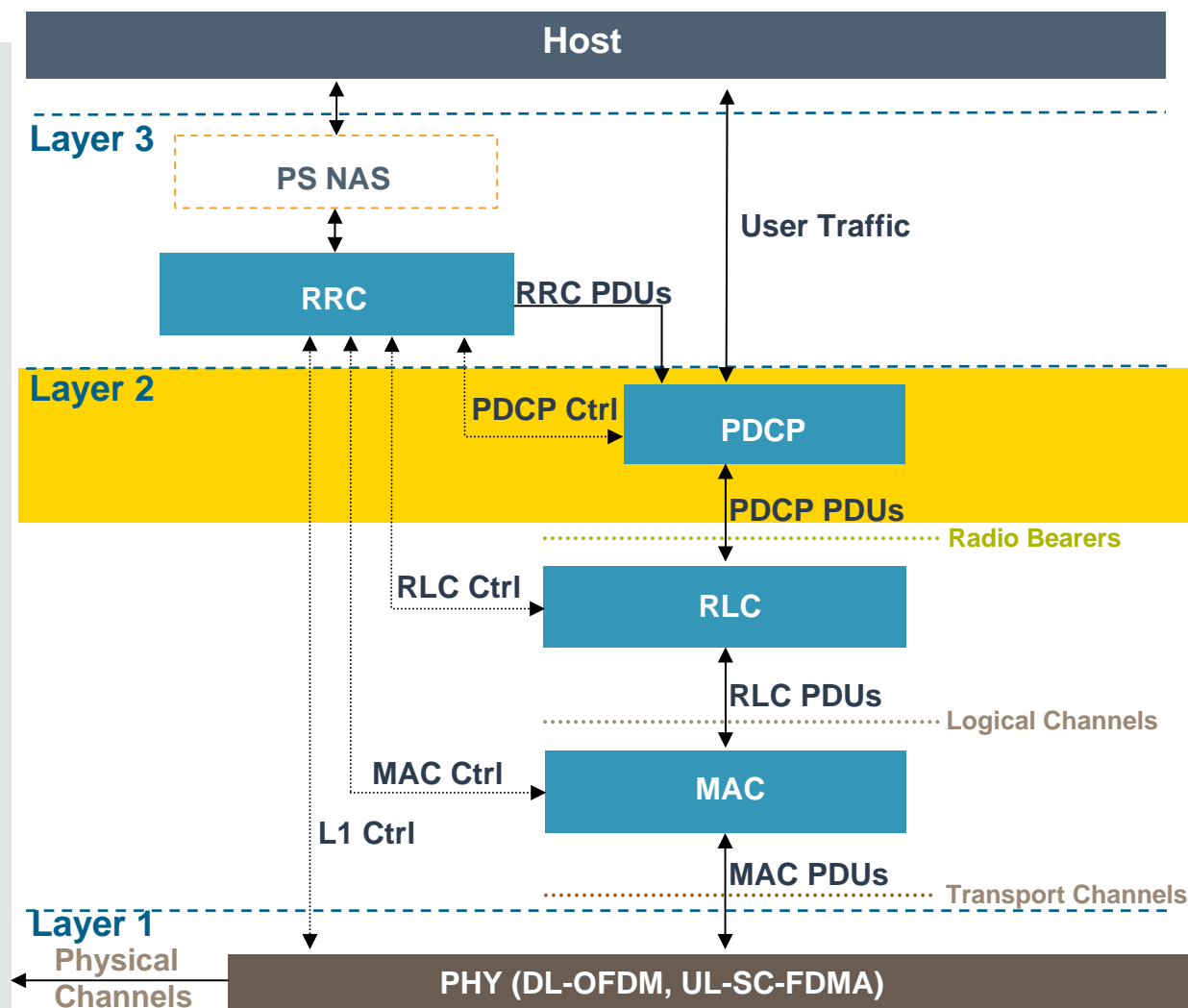
Life of a packet – Downlink – PDCP layer

► Packet Data Convergence Protocol (PDCP)

► PDCP Functions

- User plane
 - Decryption
 - ROHC Header Decompression
 - Transfer of user data
- Control Plane
 - Decryption
 - Integrity Protection

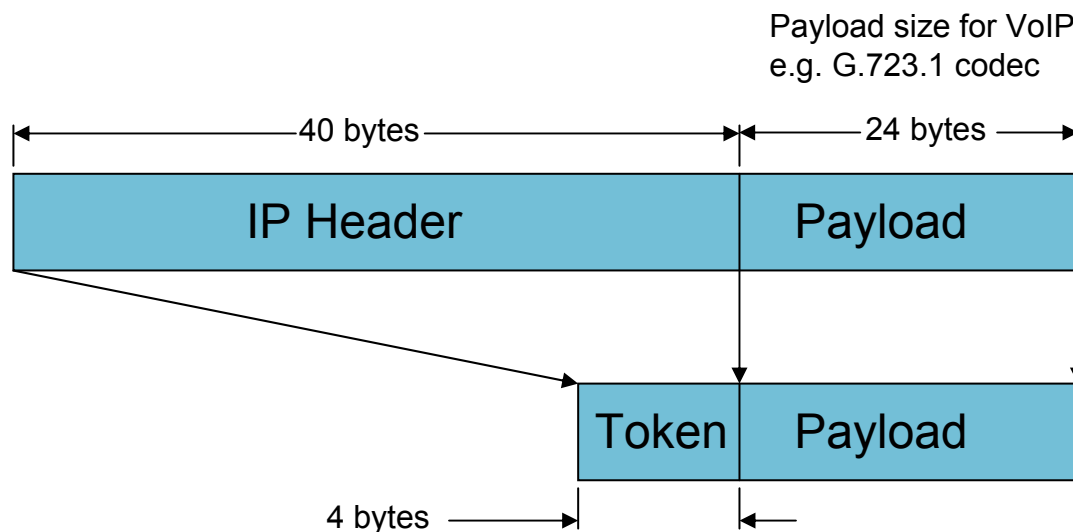
► One PDCP instance per radio bearer



PDCP – Header Compression

► ROHC – Robust Header Compression

- Defined in IETF RFC 3095



PDCP – Ciphering and integrity protection

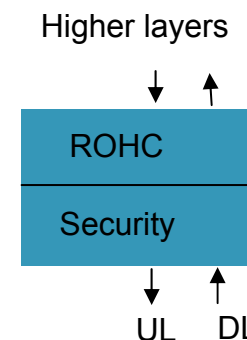
► Ciphering (Encryption / Decryption)

- Protects User Plane data
- Protects RRC (Radio Resource Control) Data
- Protects NAS (Non Access Stratum) Data

► Processing order in PDCP

- For downlink, first decryption then ROHC decompression
- For uplink, first ROHC compression, then encryption

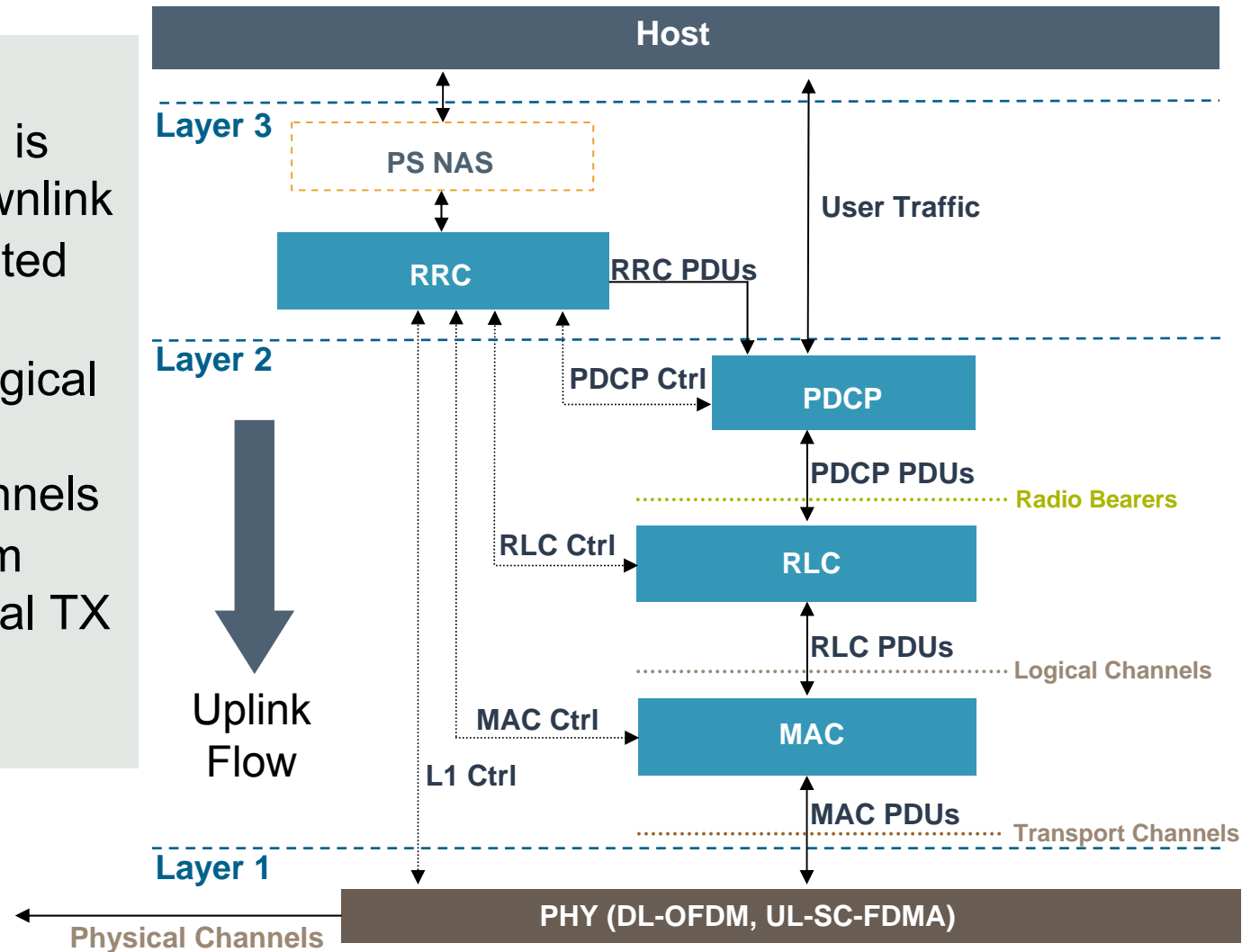
► Details of LTE security architecture are still being defined in 3GPP™ SA3 (System Architecture Working Group 3)



Life of a packet – Uplink

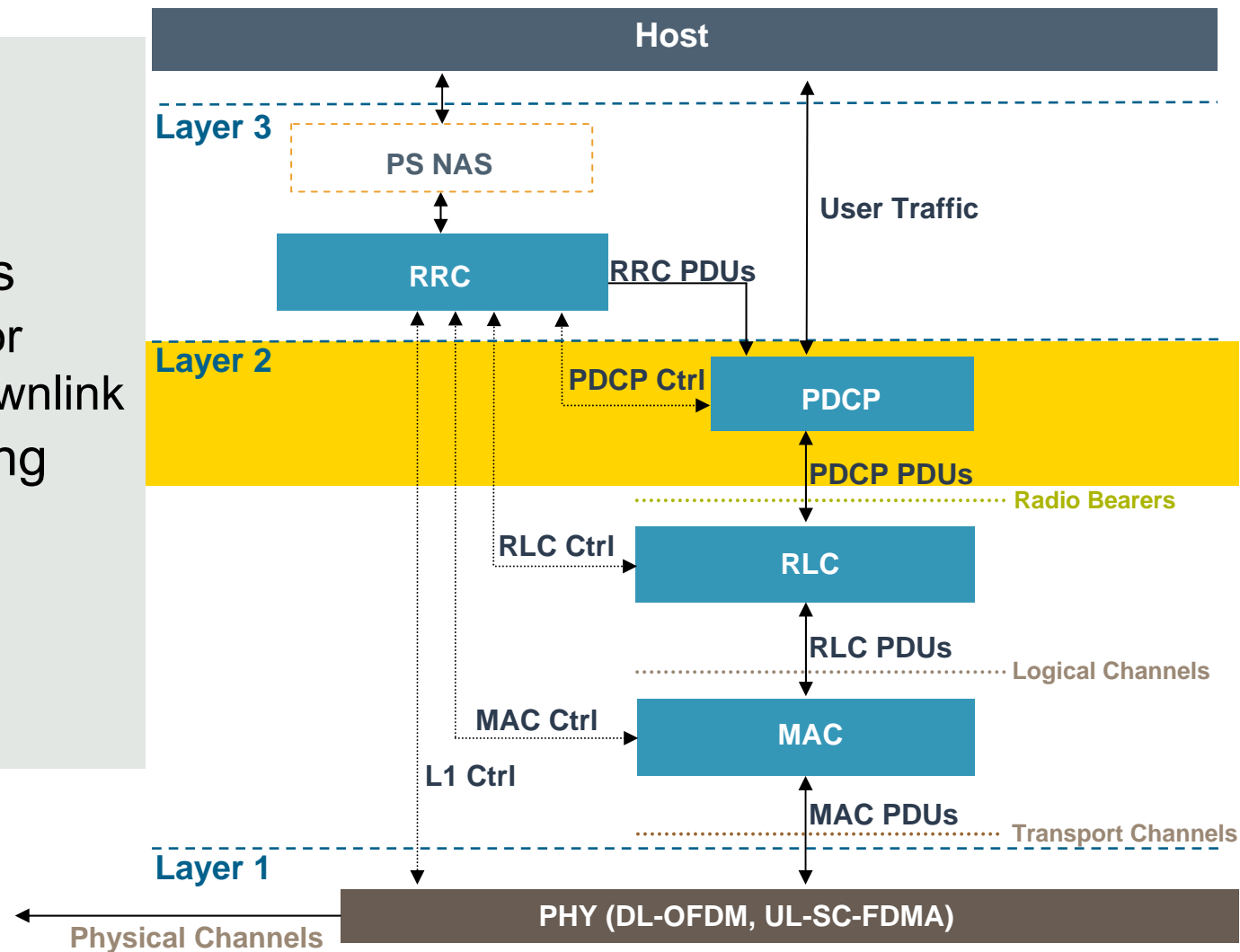
► Key Differences

- Peak data rate is half that of downlink
- Access is granted by eNB
- Changes in Logical Channels and Transport channels
- Use of Random Access for initial TX



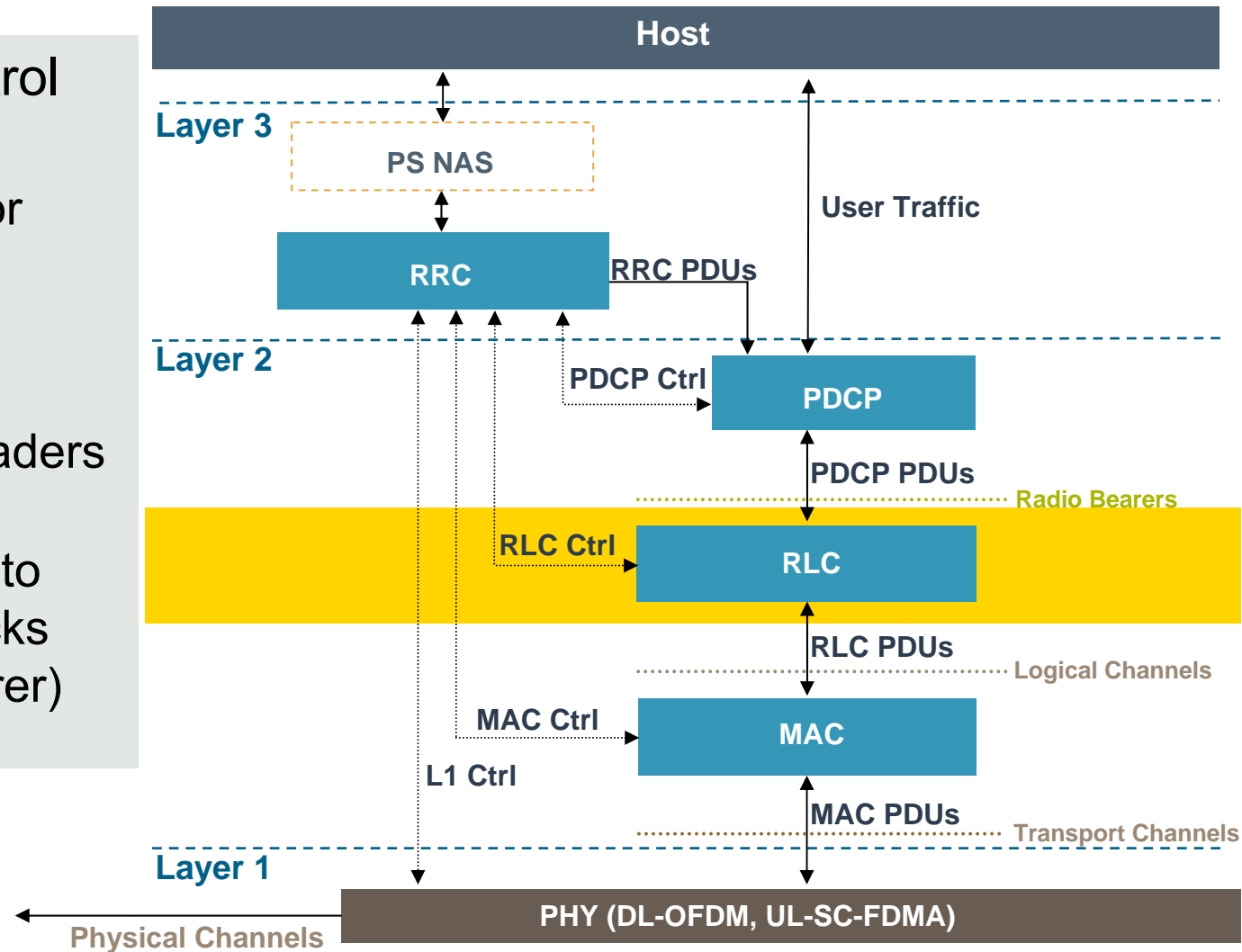
Life of a packet – Uplink – PDCP layer

- ▶ Packet Data Convergence Protocol
- ▶ PDCP Functions
 - Symmetrical for Uplink and Downlink
- ▶ Uplink Processing
 - Header Compression
 - Encryption



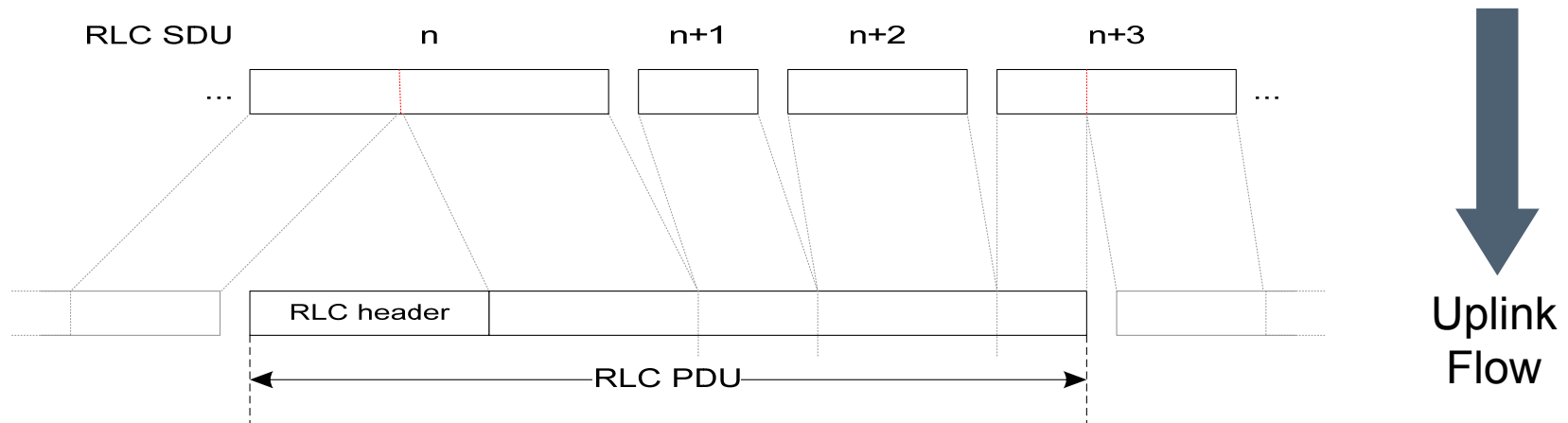
Life of a packet – Uplink – RLC layer

- ▶ Radio Link Control
- ▶ RLC Functions
 - Symmetrical for Uplink and Downlink
- ▶ Uplink Function
 - Apply RLC headers
 - Segment and concatenate into Transport Blocks (per radio bearer)



RLC – Segmentation

- ▶ Segmentation is the process of packing an RLC SDU into a size appropriate for transport blocks
 - The RLC PDU size is chosen based on the transport block size for the radio bearer.
 - If the RLC SDU is large, or the available radio data rate is low, the RLC SDU may be split into several RLC PDUs
 - If the RLC SDU is small, or the available radio data rate is high, several RLC SDUs may be packed into a single PDU
 - In many cases both splitting and packing occur:



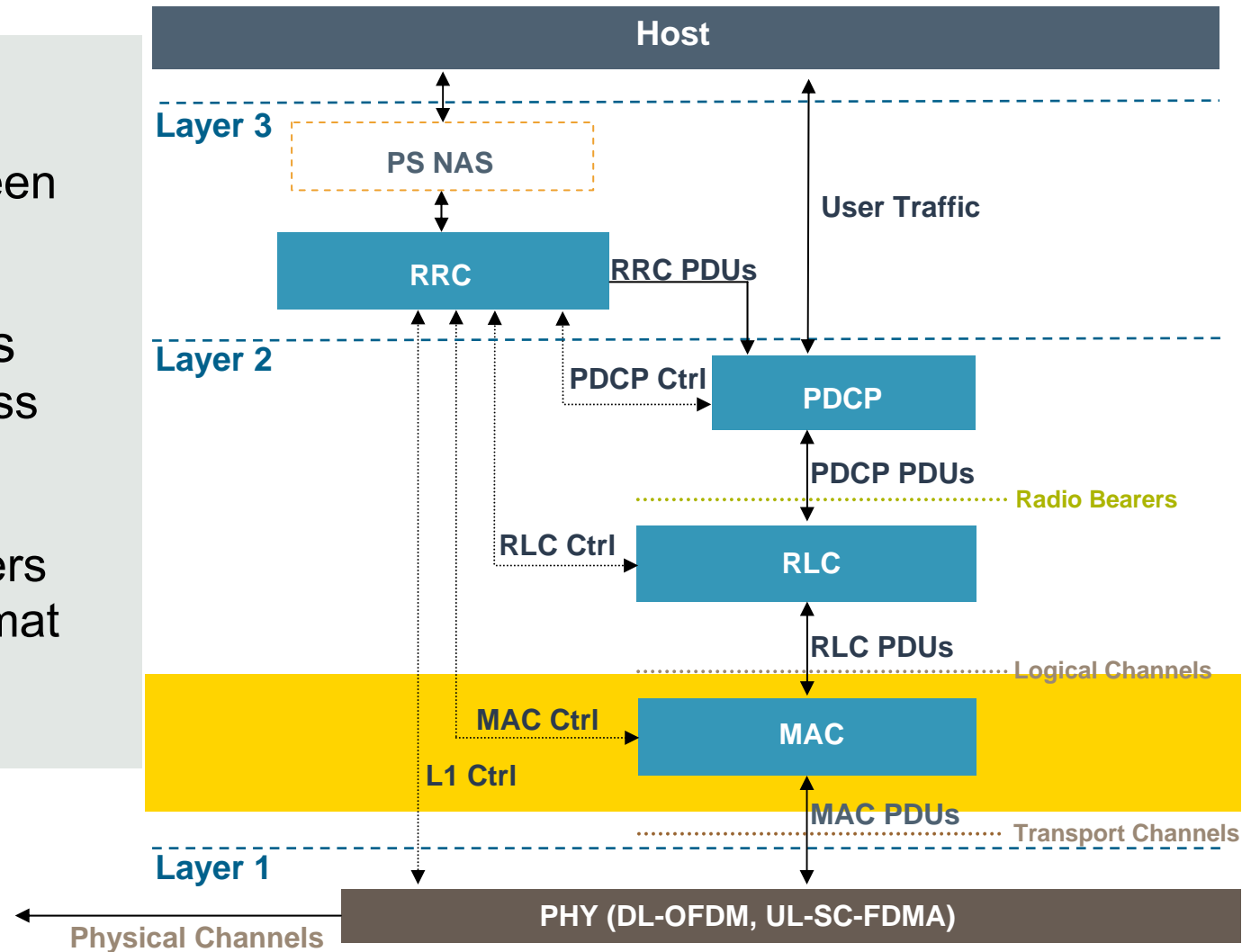
Life of a packet – Uplink – MAC layer

► MAC Functions

- Significantly different between Uplink and Downlink

► Uplink Functions

- Random Access Channel
- Scheduling
- Building headers
- Transport Format selection



MAC – Transport Format Selection

- ▶ The MAC determines the Transport Format
 - The Uplink Shared Channel (UL-SCH) is the primary transport channel
- ▶ Format variables are modulation and coding, which determine data rate.
 - The MAC determines the capacity of a transport block based on the transport format

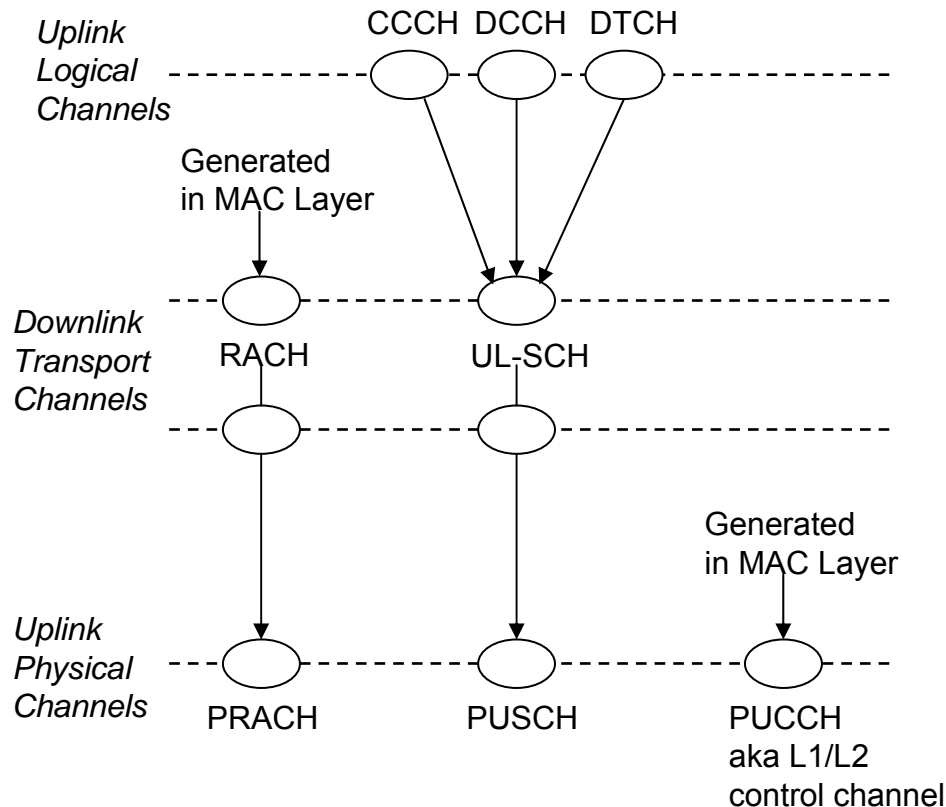
MAC – Uplink Channel Mapping

► UL-SCH: Uplink Shared Channel

- The CCCH (Common Control Channel), DCCH (Dedicated Control Channel), and DTCH (Dedicated Traffic Channel) are all mapped to the Uplink Shared Channel

► RACH: Random Access Channel

- All MAC transmissions on the UL-SCH must be scheduled
- When the UE is not connected, no transmit slots are ever scheduled
- The RACH provides a means for disconnected devices to transmit



MAC – Random Access Procedure

- ▶ The Random Access Procedure is used for four cases:
 - Initial access from disconnected state (RRC_IDLE)
 - Handover requiring random access procedure
 - DL or UL data arrival during RRC_CONNECTED after UL PHY has lost synchronization (possibly due to power save operation)
 - UL data arrival when are no dedicated scheduling request channels available

- ▶ There are two forms of the Random Access Procedure
 - Contention based (applicable to all four events)
 - Non-contention based (applicable to only handover and DL data arrival)

MAC – Contention Based Random Access

1. Random Access Preamble

- Uses CDMA-like coding to allow simultaneous transmissions to be decoded
- 6 bit random ID

2. Random Access Response

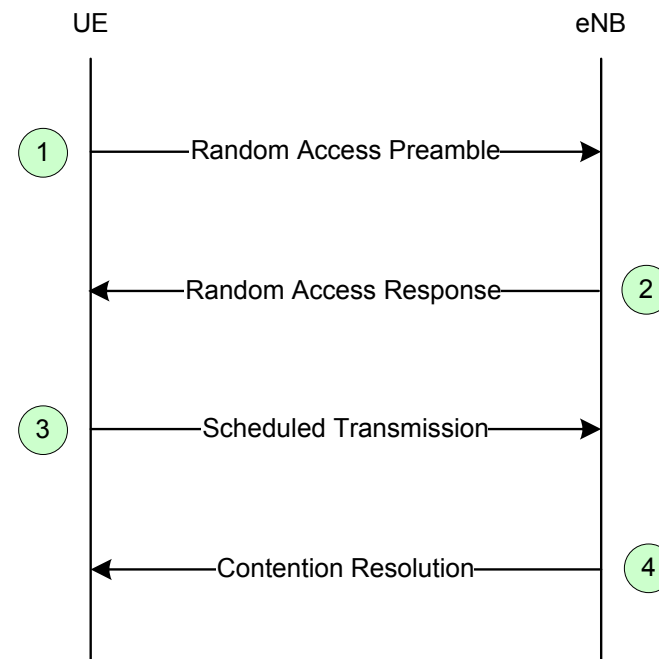
- Sent on DL-SCH (Downlink Shared Channel)
- Sent within a time window of a few TTI
- For initial access, conveys at least RA-preamble identifier, Timing Alignment information, initial UL grant and assignment of Temporary C-RNTI
- One or more UE's may be addressed in one response

3. Scheduled Transmission

- Uses HARQ and RLC Transparent Mode
- Conveys UE Identifier

4. Contention Resolution

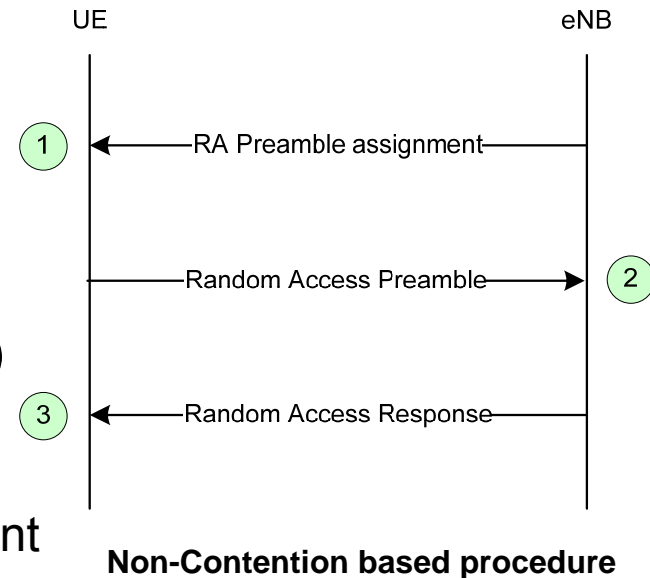
- Optional – used by eNB to end Random Access procedure



Contention based procedure

MAC – Non-Contention Based Random Access

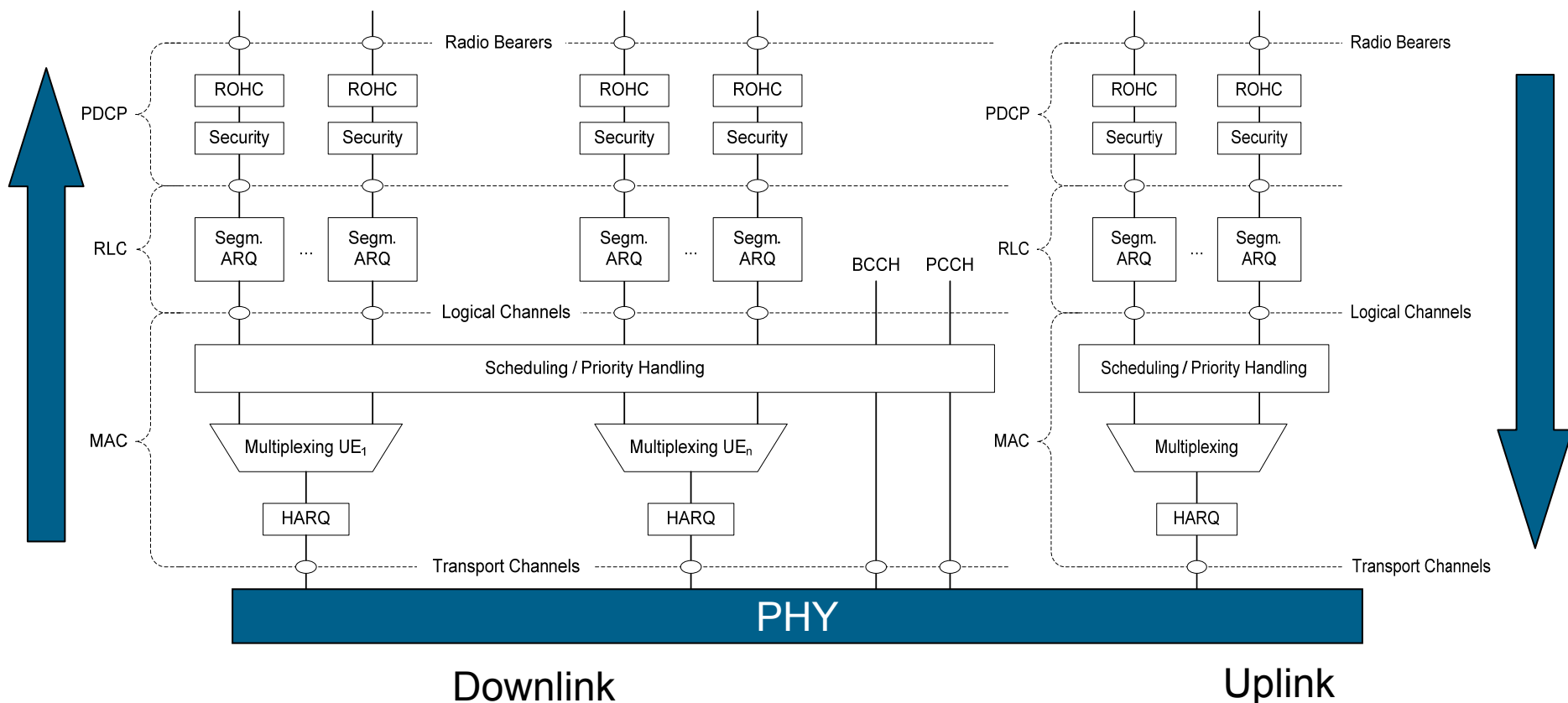
1. Random access preamble assignment
 - eNB assigns the 6 bit preamble code
2. Random access preamble
 - UE transmits the assigned preamble
3. Random access response
 - Same as for contention based RA
 - Sent on DL-SCH (Downlink Shared Channel)
 - Sent within a time window of a few TTI
 - Conveys at least:
 - Timing Alignment information and initial UL grant for handover
 - Timing Alignment information for DL data arrival;
 - In addition, RA-preamble identifier if addressed to RA-RNTI on L1/L2 control channel.
 - One or more UE's may be addressed in one response

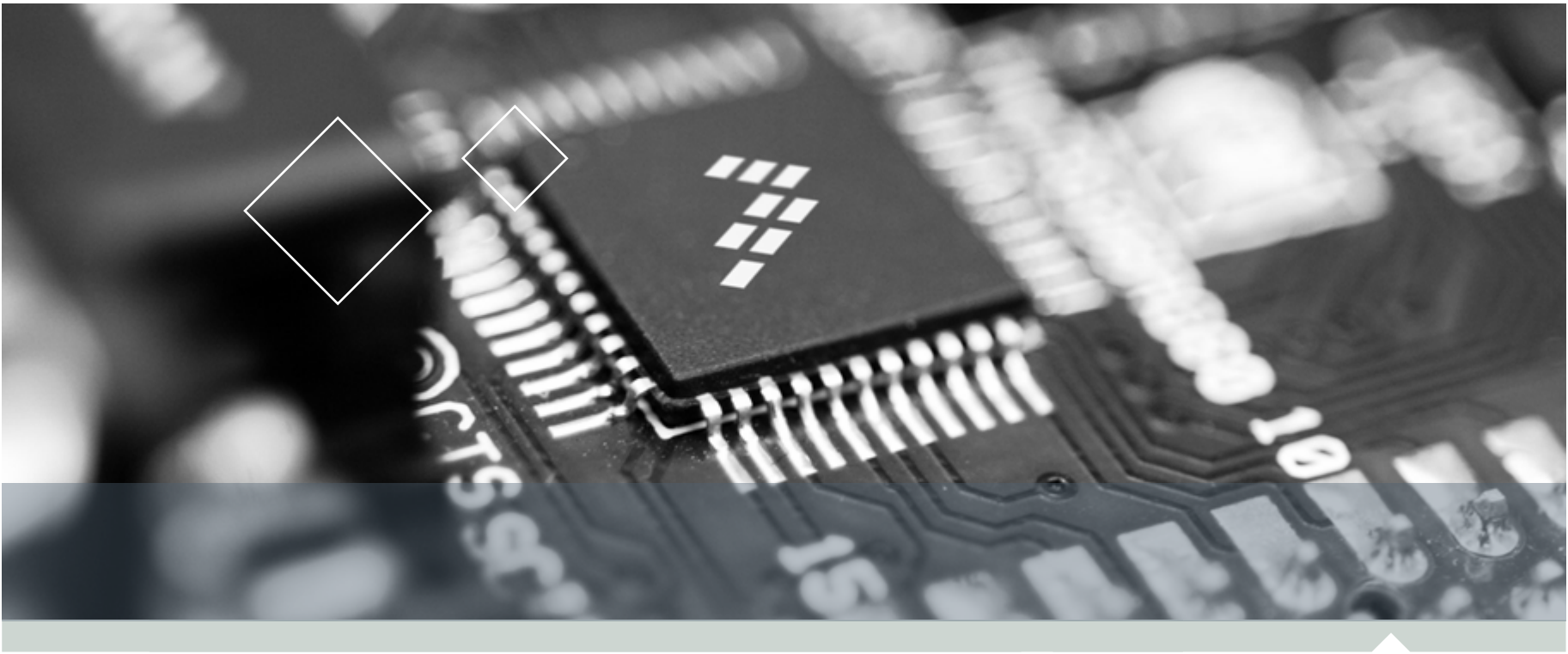


MAC – Uplink Scheduling

- ▶ All access to the uplink shared channel (UL-SCH) is scheduled
- ▶ Uplink scheduling information is carried on the physical downlink control channel
 - Along with
 - Transport format, resource allocation, and hybrid-ARQ information related to DL-SCH
 - ACK/NAK in response to uplink transmission.
 - Modulation for control channels is QPSK (most robust)
- ▶ The UE sends an Uplink Scheduling Request to the eNB
 - The eNB responds with a grant.

Life of a Packet - Conclusion

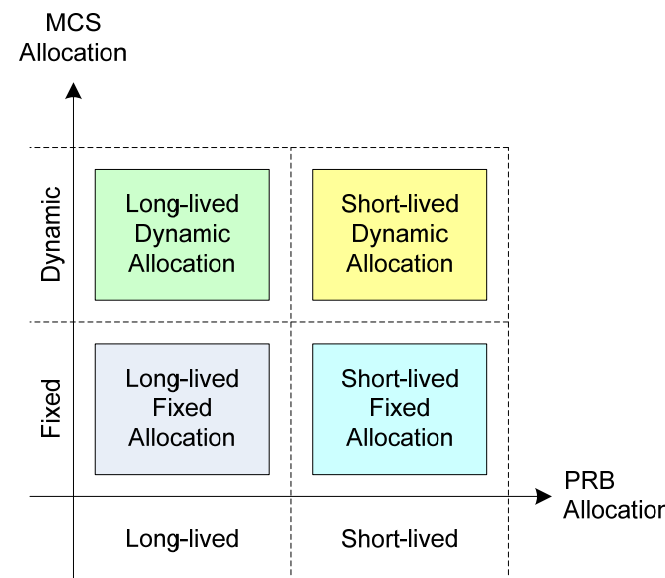




LTE Protocol Operation

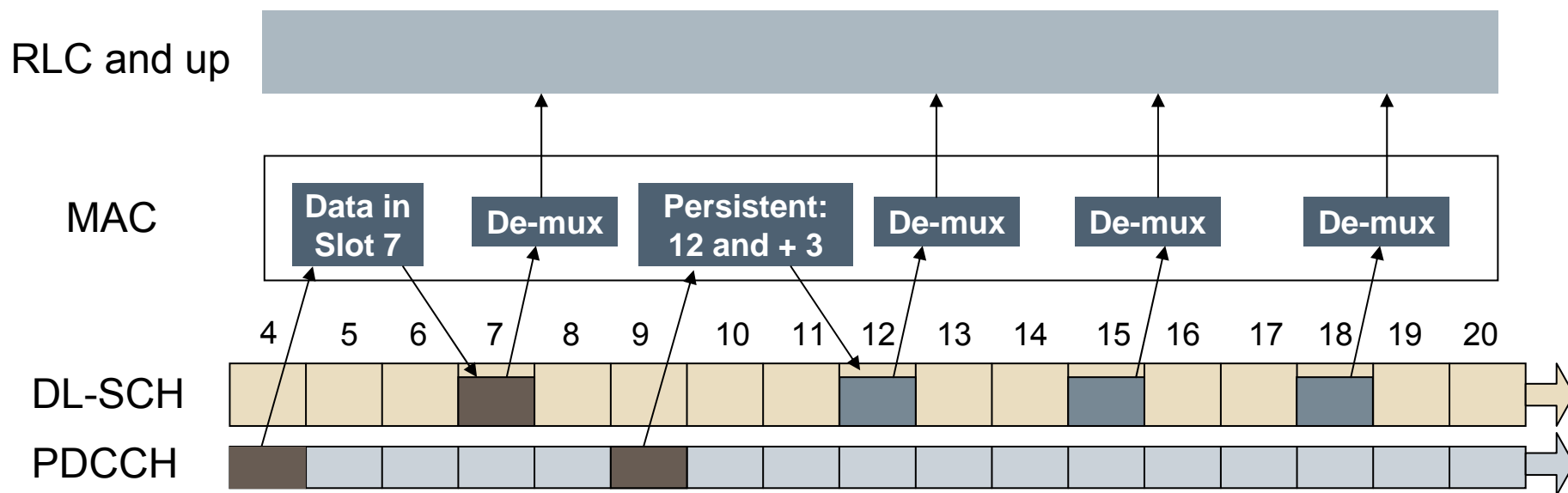


- ▶ The eNB allocates physical layer resources for the UL and DL SCH
 - Resources are Physical Resource Blocks (PRB) and Modulation Coding Scheme (MCS)
 - MCS determines bit rate, and thus capacity of PRB
 - Allocations may be valid for one or more TTI's (Transmission Time Int)
 - TTI interval is one Sub-Frame (1mS)
- ▶ Four types of scheduling allocations to a given UE:
 - Short lived dynamic allocation
 - Both PRB(s) and allowed MCS are allocated for a defined duration
 - Short lived fixed allocation
 - PRB(s) are allocated for a defined duration, and the allowed MCS is allocated for an undefined duration
 - Long lived dynamic allocation
 - PRB(s) are allocated for an undefined duration, and the MCS is dynamically controlled by the network
 - Long lived fixed allocation
 - Both PRB(s) and allowed MCS are allocated for an undefined duration.



Downlink scheduling

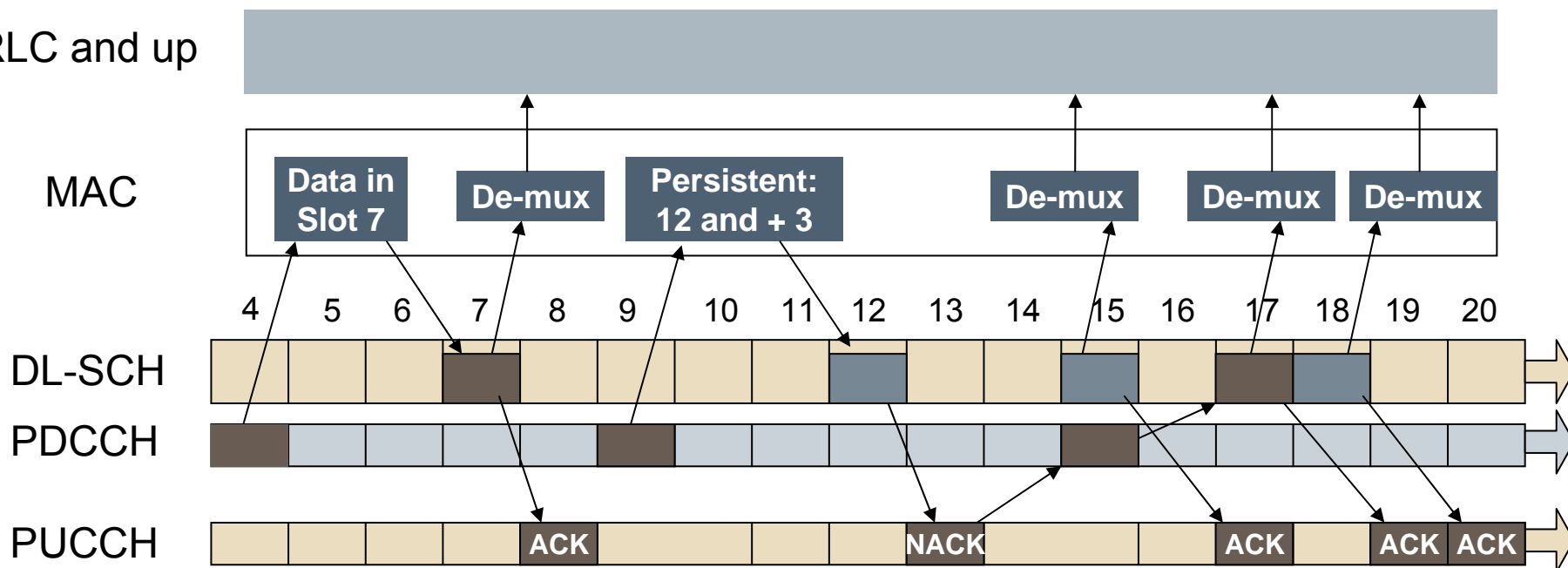
- ▶ C-RNTI (dynamic UE identifier) is found on control channel (PDCCH)
 - Indicates upcoming downlink resource is scheduled for this UE



Downlink scheduling with HARQ

- ▶ C-RNTI (dynamic UE identifier) is found on control channel (PDCCH)
 - Indicates upcoming downlink resource is scheduled for this UE
- ▶ HARQ generates ACK or NACK for each DL transport block
 - Asynchronous – UE can respond with ACK/NACK in variable amount of time
 - ACK / NACK is send on L1/L2 control channel (PUCCH)

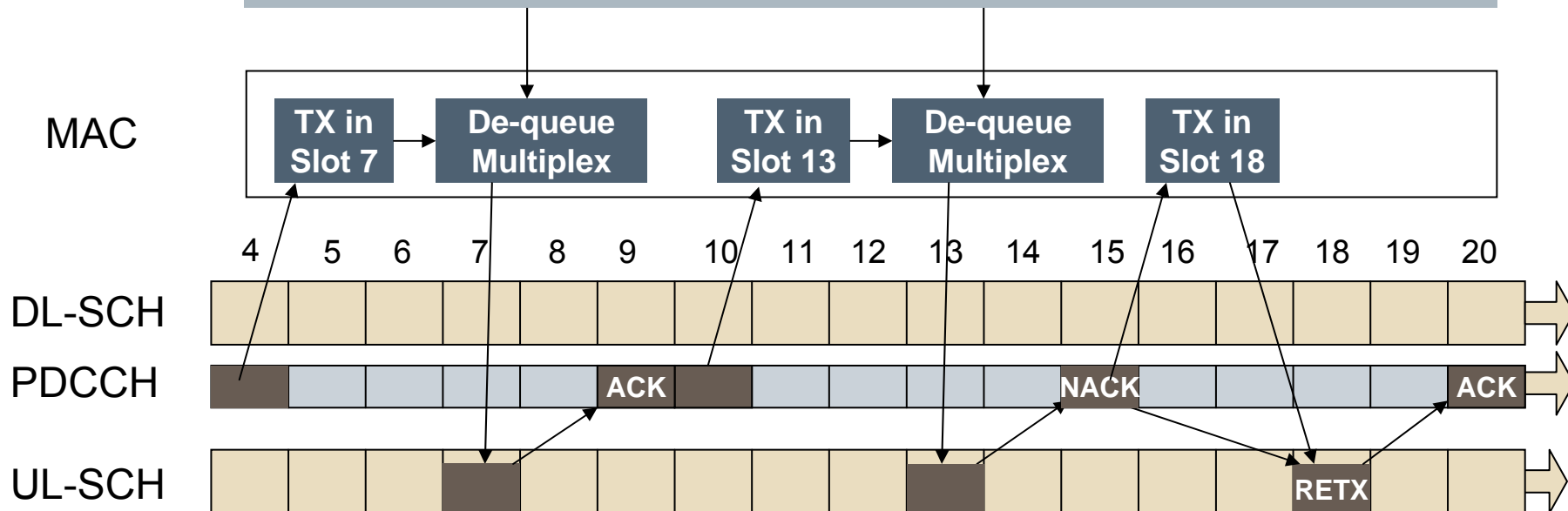
RLC and up



Uplink scheduling with HARQ

- ▶ C-RNTI (dynamic UE identifier) is found on control channel (PDCCH)
 - Indicates upcoming uplink resource is scheduled for this UE
 - Carries ACK / NACK messages for uplink data transport blocks
- ▶ HARQ is synchronous
 - Fixed time from UL to ack/nack on DL from eNB

RLC and up



- ▶ LTE architecture support “Hard QoS”
 - End-to-end Quality of Service
 - Guaranteed Bit Rate (GBR) for Radio Bearers
- ▶ Evolved Packet System (EPS) bearers
 - One to One correspondence with RLC Radio Bearers
 - Provide support for Traffic Flow Templates (TFT)
- ▶ Types of EPS Bearers
 - GBR Bearer – resources permanently allocated by admission control
 - Non-GBR Bearer – no admission control
 - Dedicated Bearer – associated with specific TFT (GBR or non-GBR)
 - Default Bearer – Non GBR, “catch-all” for unassigned traffic

Management and Control Functions

- ▶ UE management and control is handled in the Radio Resource Control (RRC)
- ▶ Functions handled by RRC
 - Broadcast of system information to the AS and NAS
 - Paging
 - RRC connection management (UE \leftrightarrow eNB)
 - Integrity Protection and Ciphering of RRC messages
 - RRC uses different keys than User Plane
 - Radio Bearer control (logical channels at top of PDCP)
 - Mobility functions (handover and cell reselection)
 - UE measurement reporting and control
 - QoS Management
- ▶ RRC States
 - RRC_Idle – not active, but ID assigned and tracked by the network
 - RRC_Connected – active operation, with context in eNB

► WLAN Handover

- Station dis-associates with one AP and associates with another
- All APs must be part of the same ESS (Extended Service Set)
- 802.11r extends basic functions to enable secure, make-before-break

► LTE Handover

- Intra-RAT (within one Radio Access Technology)
 - Basic handover from one eNB to another, all a part of LTE network
 - Seamless transition assumed – less than 10mS interruption
- Inter-RAT (between Radio Access Technologies)
 - Handover between LTE and any other network
 - GSM, 3G (WCDMA), even WLAN
 - Inter-RAT handover involves higher layers
 - Different radio modems are often involved
 - Call continuity assumed
 - Some disruption possible (up to 300mS) per current thinking in 3GPP SA1 WG

Handover – Measurement

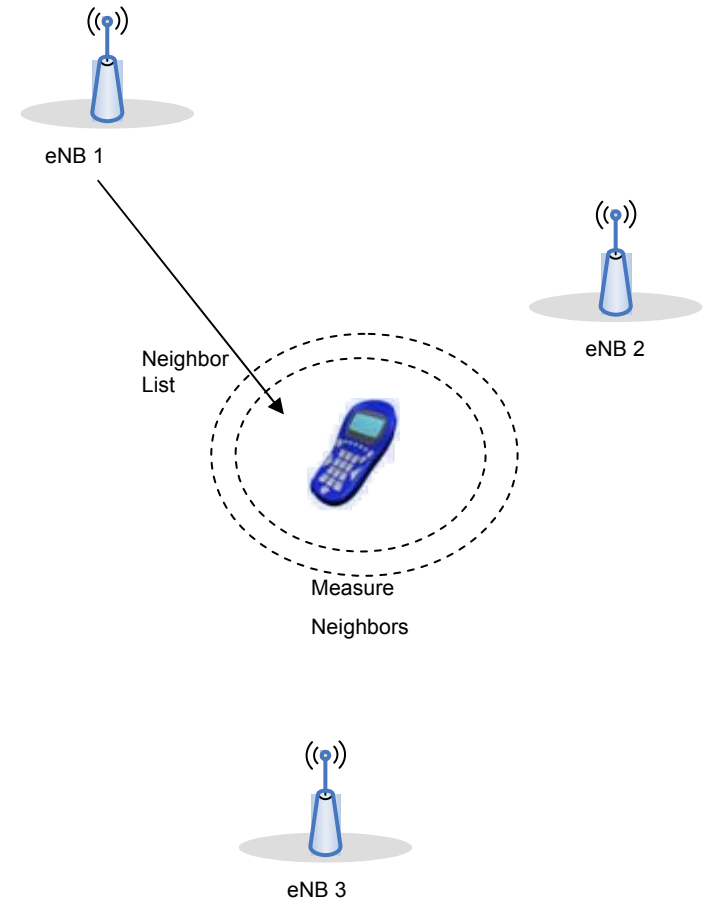
- ▶ In a single-radio architecture, it is challenging to monitor other networks while the receiver is active
 - The radio can only receive on one channel at a time
 - The radio needs to listen on other frequencies to determine if a better base station (access point) is available to make a decision to switch
- ▶ In 802.11, the process for roaming/handover is not standardized
 - The radio must temporarily leave the current channel to check others
 - 802.11k defines measurements
 - Except in scheduled modes, there is a chance of missing a packet
 - The client device is responsible for making the roaming decision

- ▶ In LTE, the measurement and handover process is fully specified
 - Handover occurs in the active state
 - Controlled by the network (eNB)
 - The network uses measurements from the UE (and its own knowledge of the network topology) to determine when to handover a UE, and to which eNB.
 - Cell Re-selection occurs in the idle state
 - Controlled by the mobile device (UE)

- ▶ LTE measurements
 - In the active state, the eNB provides measurement gaps in the scheduling of the UE.
 - The gap provides the UE sufficient time to change frequency, make a measurement, and switch back to the active channel.

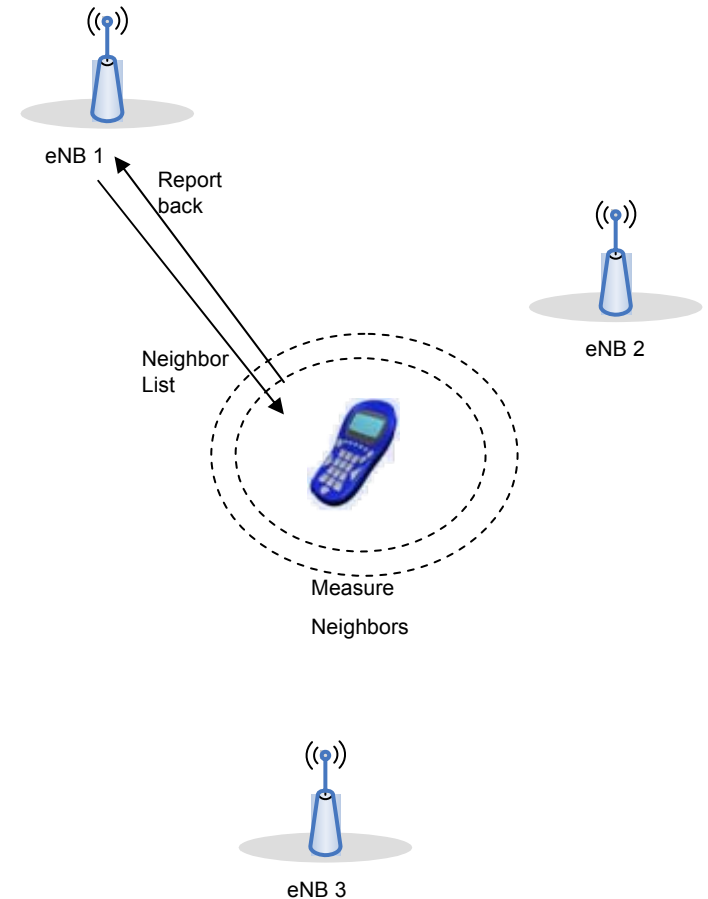
Handover – Neighbor Lists

- ▶ The LTE network provides the UE with neighbor lists
 - Based on the network knowledge configuration, the eNB provides the UE with neighboring eNB's identifiers and their frequency.
 - The UE measures the signal quality of the neighbors it can receive (during measurement gaps or idle periods)
 - The UE reports results back to the eNB
 - The network decides the best handover (if any), based on signal quality, network utilization, etc.



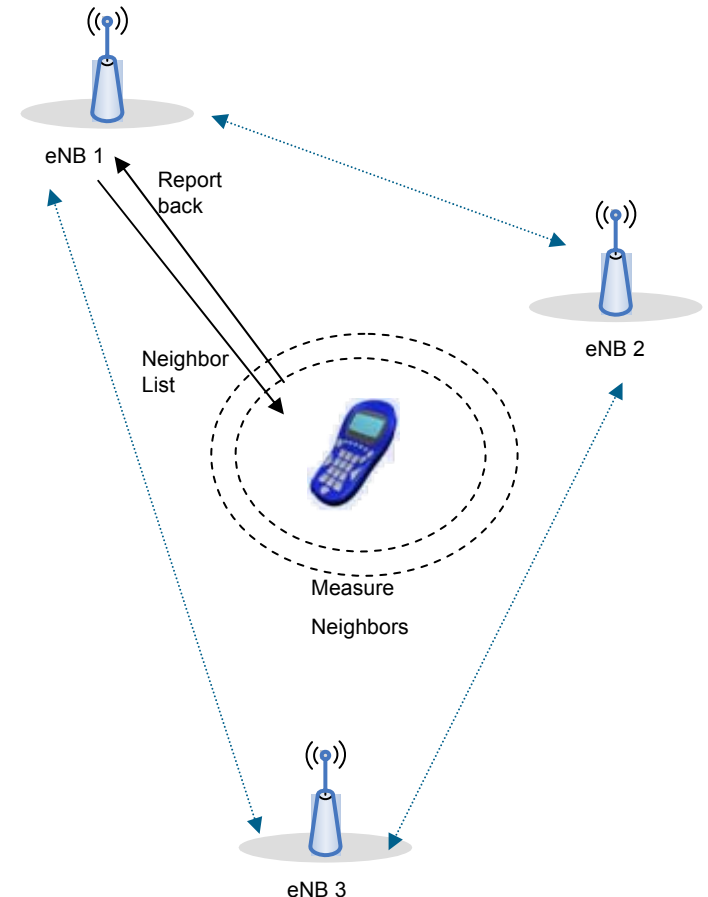
Handover – Neighbor Lists

- ▶ The LTE network provides the UE with neighbor lists
 - Based on the network knowledge configuration, the eNB provides the UE with neighboring eNB's identifiers and their frequency.
 - The UE measures the signal quality of the neighbors it can receive (during measurement gaps or idle periods)
 - The UE reports results back to the eNB
 - The network decides the best handover (if any), based on signal quality, network utilization, etc.



Handover – Neighbor Lists

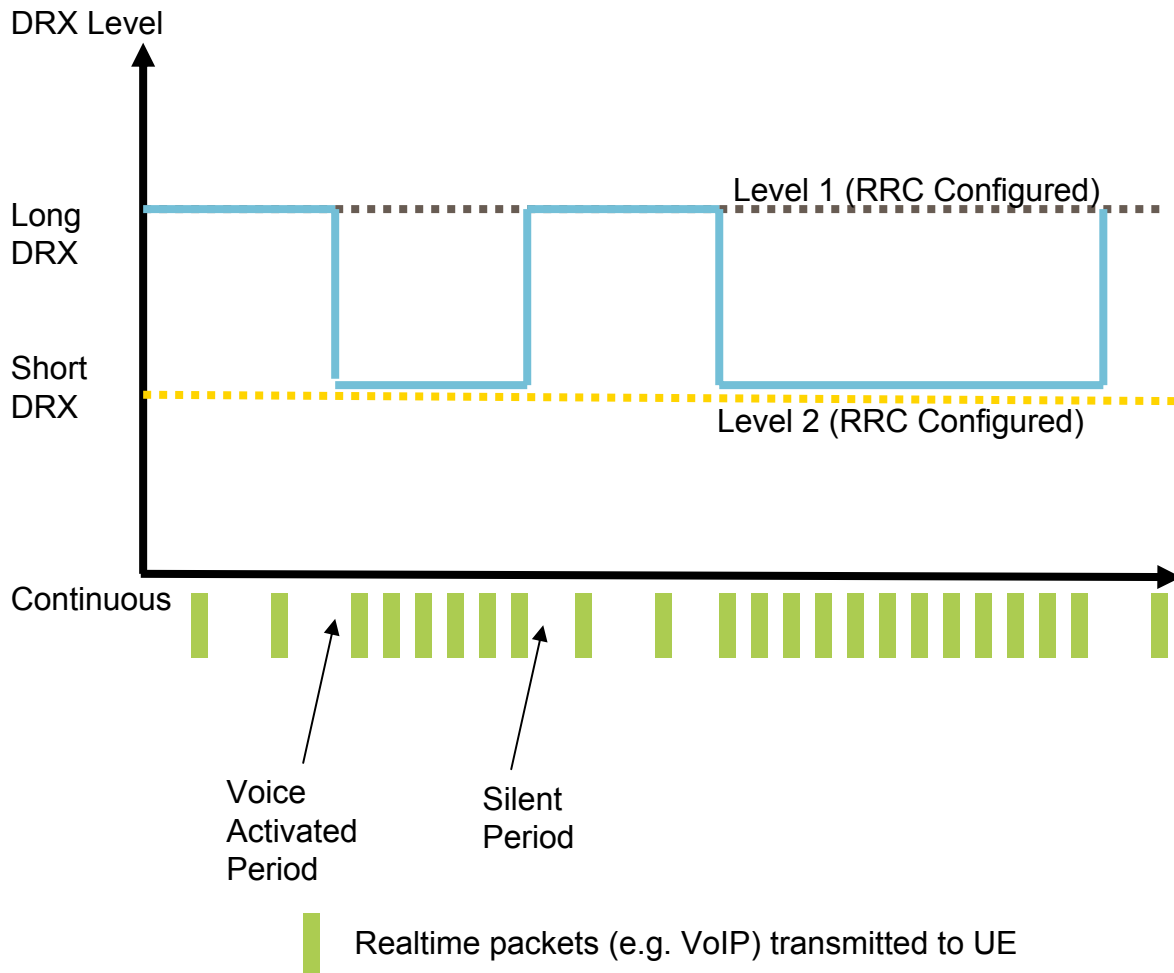
- ▶ The LTE network provides the UE with neighbor lists
 - Based on the network knowledge configuration, the eNB provides the UE with neighboring eNB's identifiers and their frequency.
 - The UE measures the signal quality of the neighbors it can receive (during measurement gaps or idle periods)
 - The UE reports results back to the eNB
 - The network decides the best handover (if any), based on signal quality, network utilization, etc.



- ▶ In both LTE and WLAN, the receiver uses significant power
 - RF Transceiver, fast A/D Converters, wideband signal processing, etc
- ▶ Both standards provide power save mechanisms
 - The radio modem can be turned off for “most” of the time
 - The device stays connected to the network with reduced throughput.
 - The receiver is turned on at specific times for updates
 - Devices can quickly transition to full power mode for full performance
- ▶ 802.11 Power save modes
 - “Legacy” Power Save mode defined in the original standard
 - Automatic Power Save Delivery (APSD)
 - Added in 802.11e, enhanced in 802.11n
 - Two forms – Scheduled APSD, and Unscheduled APSD

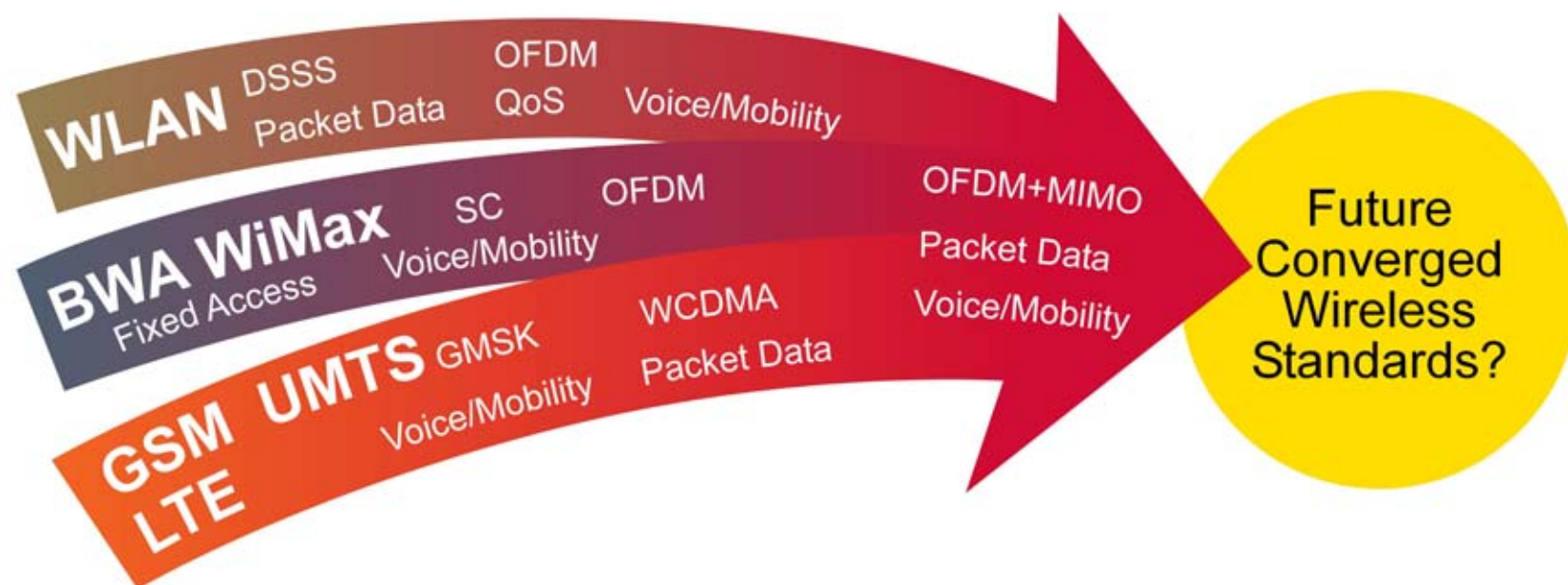
LTE Power Save Operation - DRX

- ▶ Discontinuous Reception (DRX) and Discontinuous Transmission (DTX) are the power save function in LTE
- ▶ DRX details are still being developed
 - Current plan of record is a two-step approach



► Key points on the LTE MAC

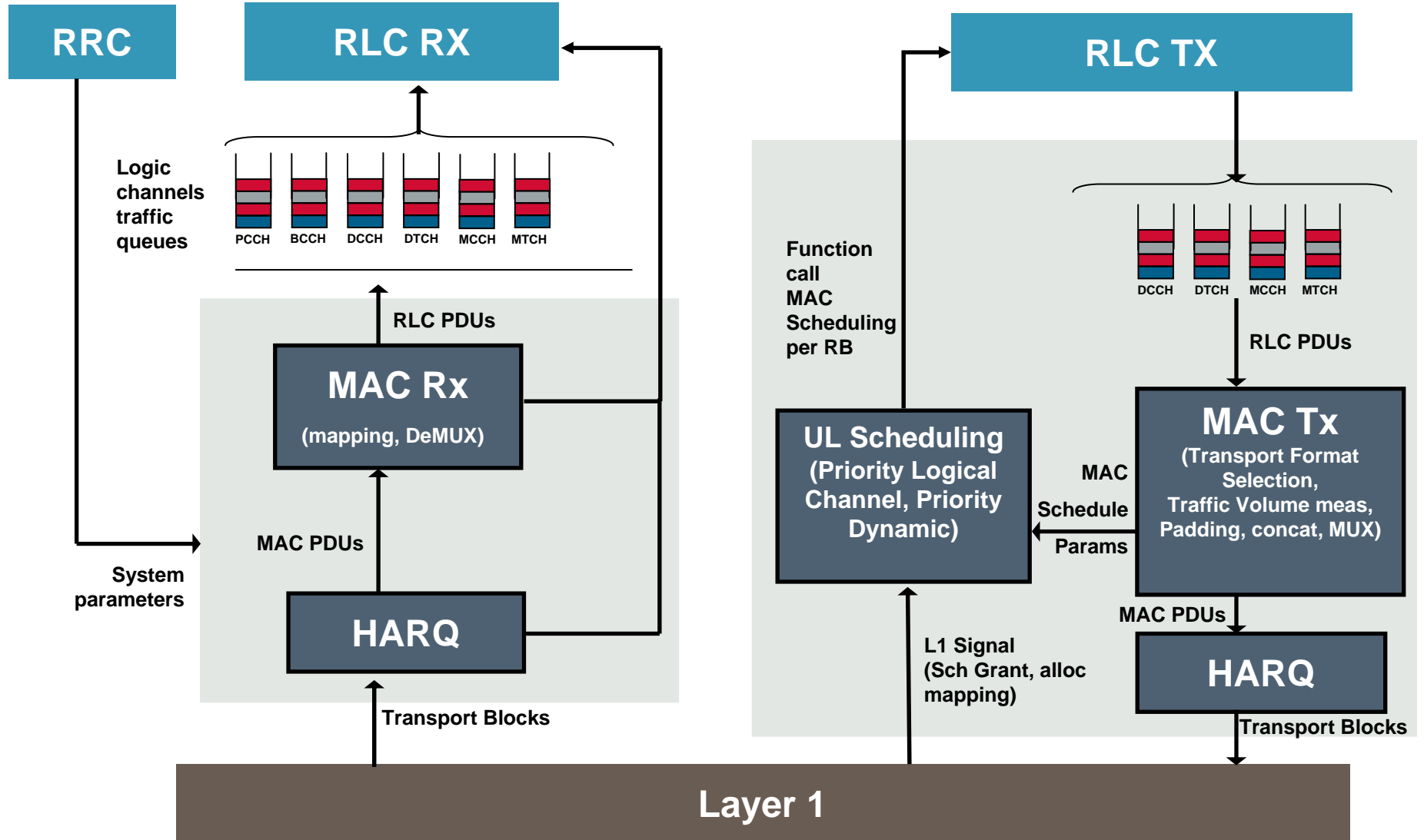
- Complex – highly optimized
- Continuous PHY transmission on downlink
- Fully scheduled operation
- Multiple logical channels carried over link



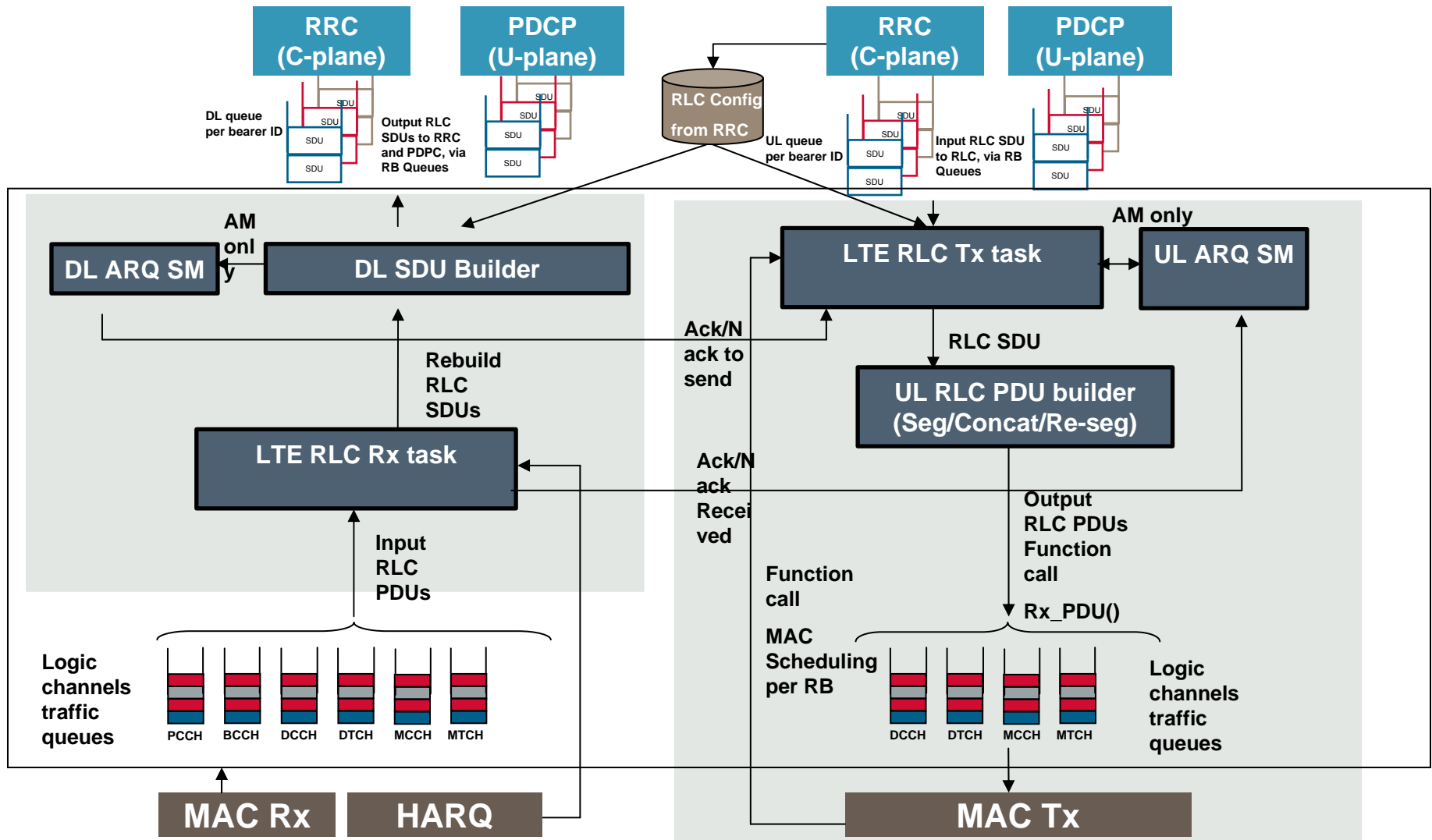


Functional view of the stack

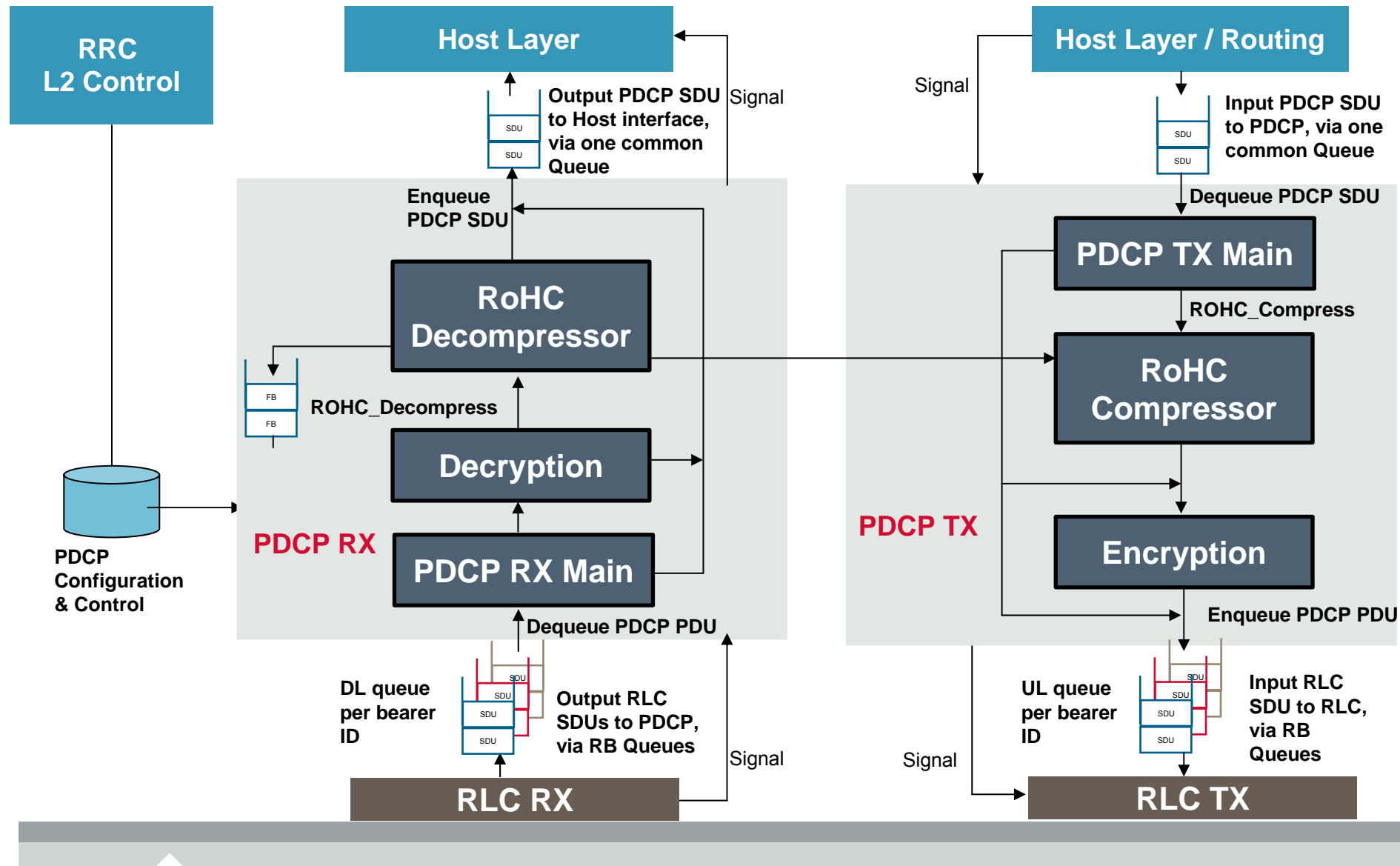
MAC Data Flow Functional Blocks



RLC Data Flow Functional Blocks



PDCP Data Flow Functional Blocks



RRC Functional Blocks

