LTE MAC, RLC, and PDCP

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  - Scheduling
  - HARQ
  - Power Control
  - Random Access
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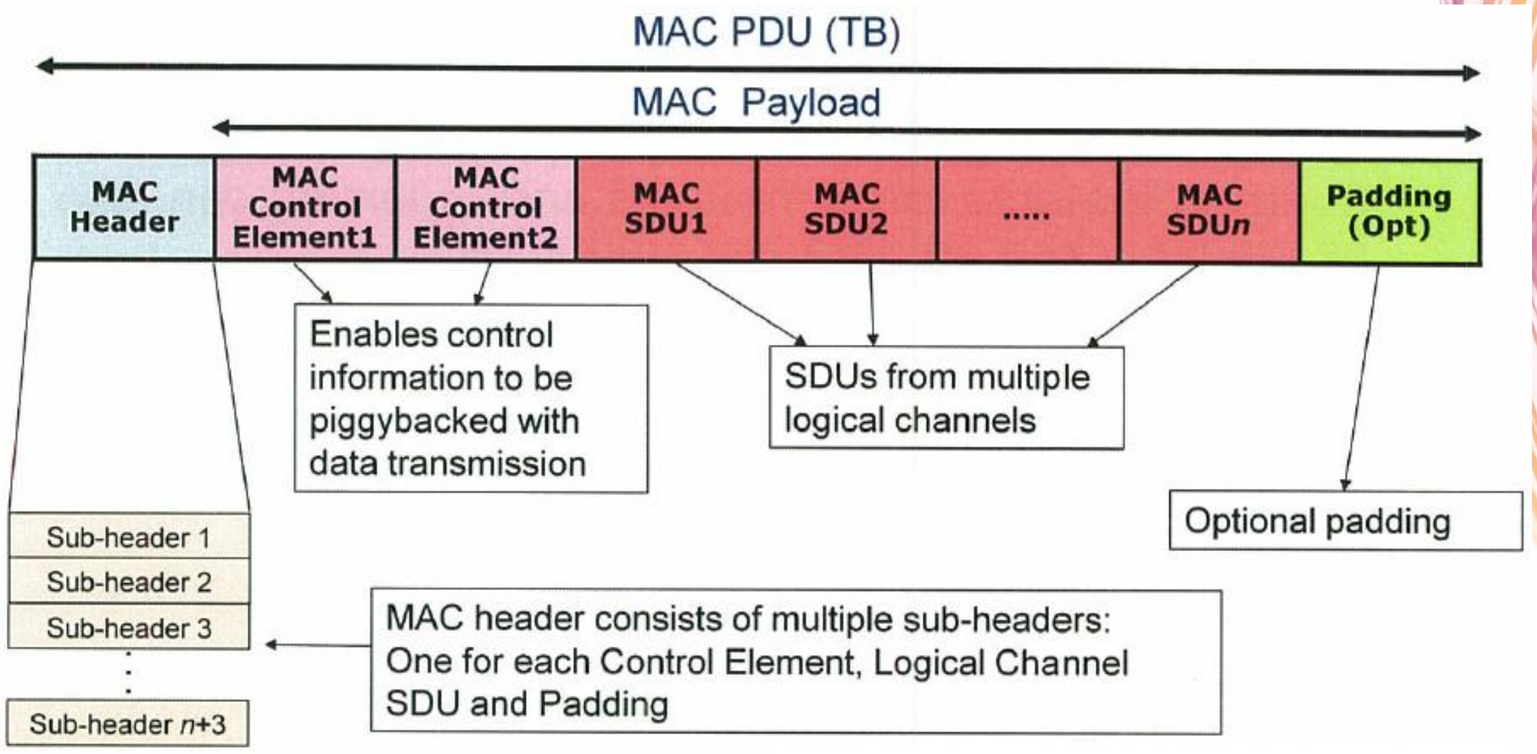
LTE MAC

MAC PDU for DL-SCH/UL-SCH

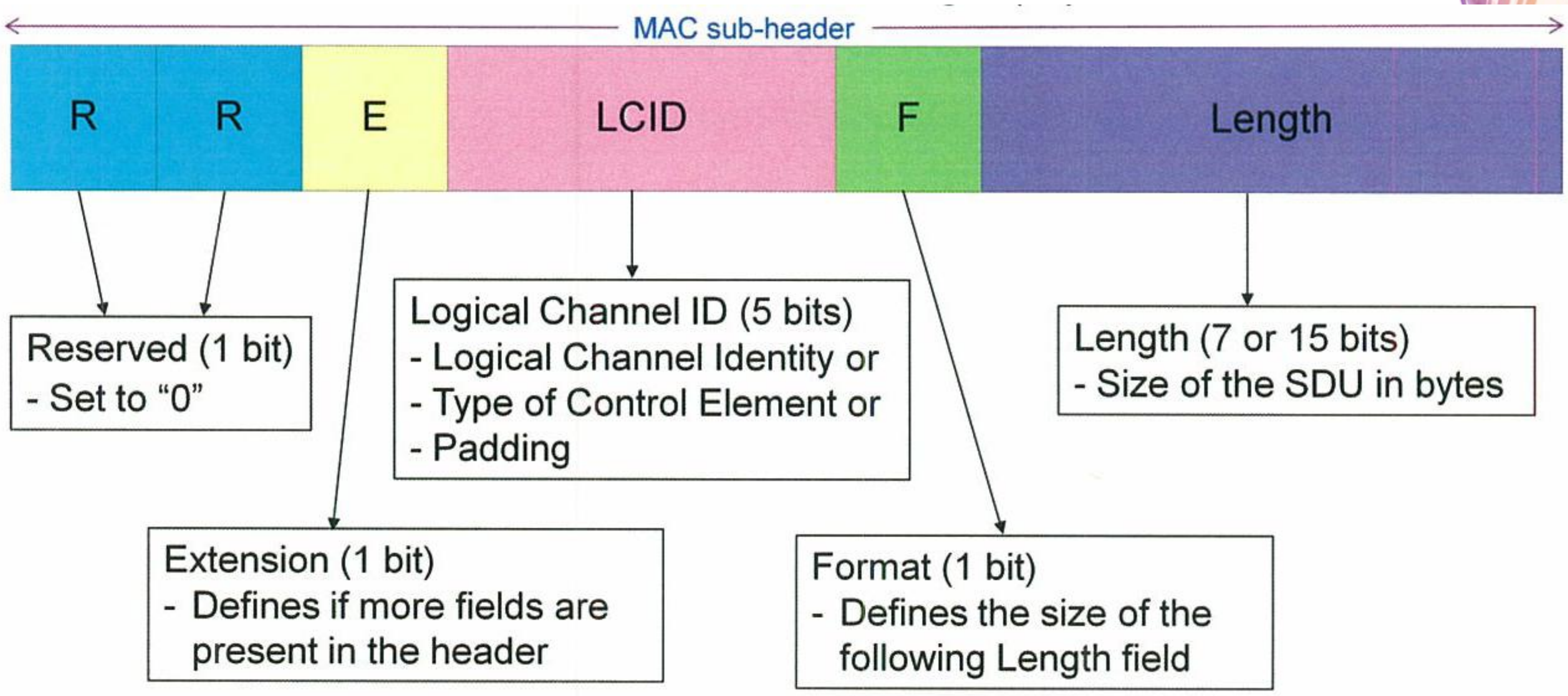
- Each MAC PDU corresponds to a single Transport Block (TB)
- There is one sub-header for each MAC Control Element in the PDU and each MAC SDU in the PDU



MAC Sub-header for DL-SCH/UL-SCH

MAC header consists of multiple sub-headers

- One sub-header for each Control Element, MAC PDU or Padding
- Each sub-header is 1 or 2, 3 bytes in length
  - [R/R/E/LCID]: Used for fixed length MAC SDUs and MAC Control Elements
  - [R/R/E/LDID/F/Length]: Used for variable length MAC SDUs



LCID (Logical Channel ID)

Values of LCID for DL-SCH

Index	LCID values
00000	CCCH
00001-01010	Identity of the logical channel
01011-11011	Reserved
11100	UE Contention Resolution Identity
11101	Timing Advance Command
11110	DRX Command
11111	Padding

Values of LCID for UL-SCH

Index	LCID values
00000	CCCH
00001-01010	Identity of the logical channel
01011-11001	Reserved
11010	Power Headroom Report
11011	C-RNTI
11100	Truncated BSR
11101	Short BSR
11110	Long BSR
11111	Padding

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MAC Control Element

Six Control Elements are defined

3 for DL

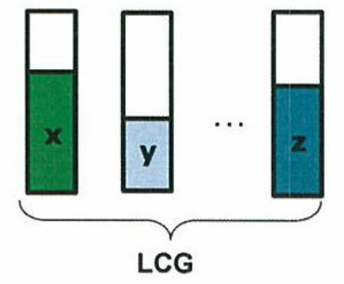
- Timing Alignment (8bits): Sent to provide initial and periodic time synchronization to the UE for UL
- DRX Command (8 bits): Initiates discontinuous reception mode at UE
- UE Contention Resolution Identity (48bits): Used during RACH procedure to resolve possible contention b/w multiple UEs trying to simultaneously access the network

3 for UL

- UE Buffer Status Reports (8 or 24bits): Reports UE buffer occupancy for UL scheduling
- UE Power Headroom (8 bits): Reports UE transmit power compared to maximum or if the UE is currently power limited
- C-RNTI (16 bits): Identifies a UE when sending information over CCCH

Buffer Status Report (BSR) CE

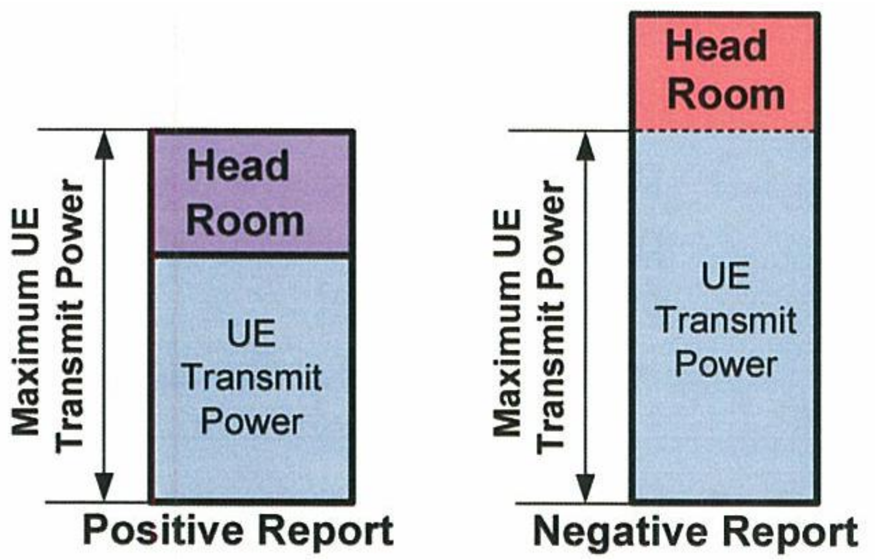
- Logical channels assigned to Logical Channel Groups (LCG)
  - Up to 4 groups can be defined
- BSR reports LCG buffer occupancy
- Two formats of report
  - Short and Truncated BSR: Report for one LCG
  - Long BSR: Report for all four LCGs
  - Report is a 6-bit value that indexes a size range in bytes.
- Regular BSRs are sent when
  - UL data becomes available for a logical channel with higher priority than the logical channels for which data exists in transmission buffer that has been already been reported.
  - A serving cell change occurs
  - A BSR retransmission timer expires and UL data is available
- Padding BSRs
  - If the size of the padding is greater than or equal to the size of BSR MAC CE, BSR MAC CE is sent instead of padding



UE Power Headroom (PHR) CE

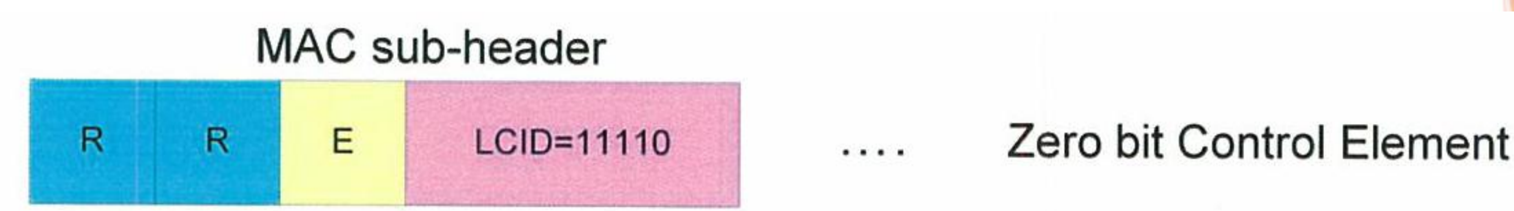
- Reports UE Power Headroom
- Ranges from -23dB to 40dB in steps of 1dB (6bits)
  - Positive values indicate the difference b/w the maximum UE transmit power and the current UE transmit power
  - Negative values indicate the difference b/w the maximum UE transmit power and the calculated UE transmit power

    → Negative value shows power assuming UE is "power limited" with the current grant



DRX Support

- Discontinuous Reception (DRX) can be implemented in the UE to save battery power
  - Discontinuous monitoring of PDCCH in DL
  - UE can turn off its receiver during periods of inactivity
  - Defined on a per UE basis, not per RB basis
- Two modes of entering DRX
  - Implicit transition based on timers
  - Explicit transition based on DRX command from the network via DRX Control Element



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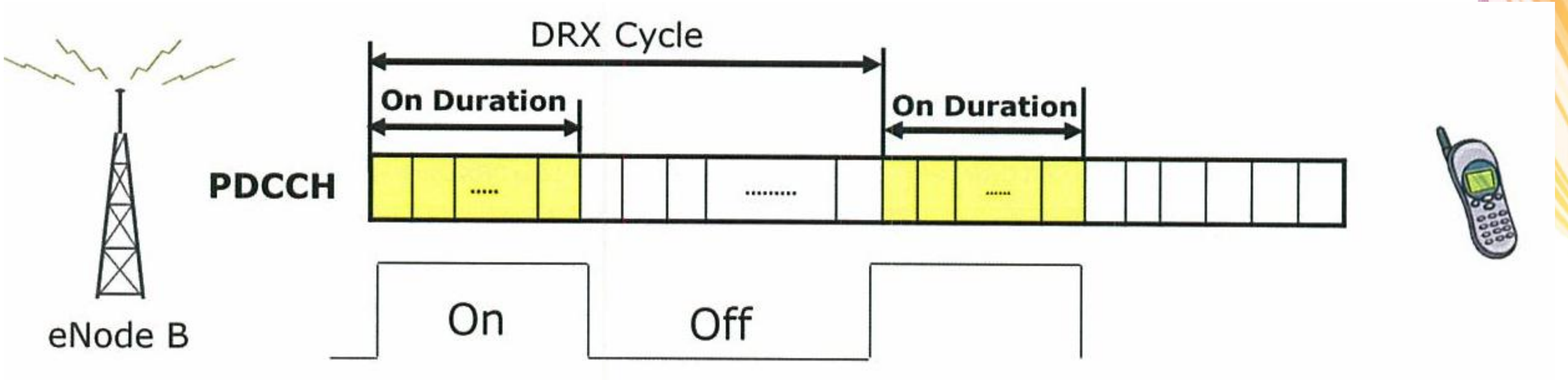
DRX Operation

- During DRX, UE maintains a DRX cycle that is defined as a number of subframes.
- UE monitors PDCCH for *on-duration* subframes (1~200 subframes) and may turn off its receiver for rest of the DRX cycle
- eNB does not schedule transmissions during off-period of the DRX cycle
- Two DRX cycles: Short and Long
  - UE starts with Short DRX cycle and transitions to long DRX cycle after the expiration of a timer



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RNTI

- ## RNTI Usage

RNTI	Usage	Transport Channel	Logical Channel
P-RNTI	Paging and System Information change notification	PCH	PCCH
SI-RNTI	Broadcast of System Information	DL-SCH	BCCH
RA-RNTI	Random Access Response	DL-SCH	N/A
Temporary C-RNTI	Contention Resolution (when no valid C-RNTI is available)	DL-SCH	CCCH
Temporary C-RNTI	Msg3 transmission	UL-SCH	CCCH, DCCH, DTCH
C-RNTI	Dynamically scheduled unicast transmission	DL-SCH, UL-SCH	DCCH, DTCH
C-RNTI	Triggering of PDCCH ordered random access	N/A	N/A
Semi-Persistent Scheduling C-RNTI	Semi-Persistently scheduled unicast transmission (activation, reactivation and retransmission)	DL-SCH, UL-SCH	DCCH, DTCH
Semi-Persistent Scheduling C-RNTI	Semi-Persistently scheduled unicast transmission (deactivation)	N/A	N/A
TPC-PUCCH-RNTI	Physical layer Uplink power control	N/A	N/A
TPC-PUSCH-RNTI	Physical layer Uplink power control	N/A	N/A

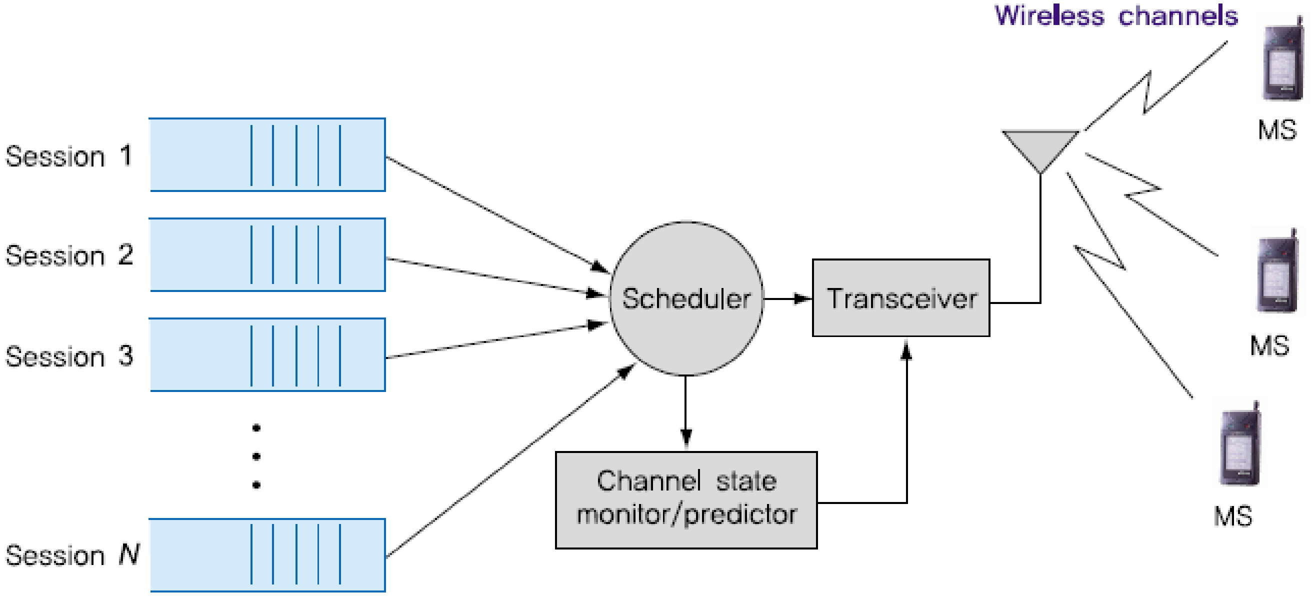
- ## RNTI Values

Value (hexa -decimal)	RNTI
0000	N/A
0001-003C	RA-RNTI, C-RNTI, Semi-Persistent Scheduling C-RNTI, Temporary C-RNTI, TPC-PUCCH-RNTI and TPC-PUSCH-RNTI (see note)
003D-FFF3	C-RNTI, Semi-Persistent Scheduling C-RNTI, Temporary C-RNTI, TPC-PUCCH-RNTI and TPC-PUSCH-RNTI
FFF4-FFFD	Reserved for future use
FFFE	P-RNTI
FFFF	SI-RNTI

Scheduling

Scheduling Overview

- Scheduling strategy is implementation-specific and not part of the 3GPP specifications.
- Most scheduling strategies need information about:
  - Channel condition
  - Buffer status and priorities of the different data flows
  - Interference situation in neighboring cells

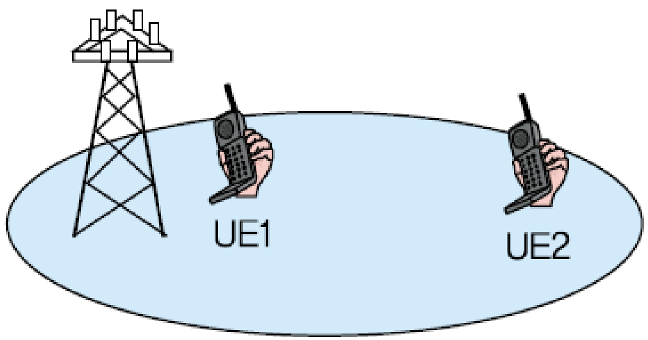


Scheduler Design Considerations

- Throughput
- Efficiency
- QoS Support
  - Different types and levels of QoS, respective for different service applications
  - Attributes such as bandwidth, delays, error rate and jitter
  - Need to serve each subscriber at a certain minimum QoS based on his/her Service Level Agreement (SLA)
- Fairness
  - Is a measure of customer satisfaction.
  - Neglecting subscribers unfairly in order to increase throughput may lead to high churn rates
- Others: Revenue, Marketing/Operational Strategies

Scheduling Schemes

- Fair throughput scheduler
- Fair time scheduler (Round Robin)
- Max C/I scheduler



Fair Throughput	UE1	UE1	UE2	UE2	UE2	UE2
Fair Time	UE1	UE2	UE1	UE2	UE1	UE2
C/I scheduling	UE1	UE1	UE1	UE1	UE2	UE2

Scheduling Schemes – cont'd

Proportional Fairness (PF) scheduler

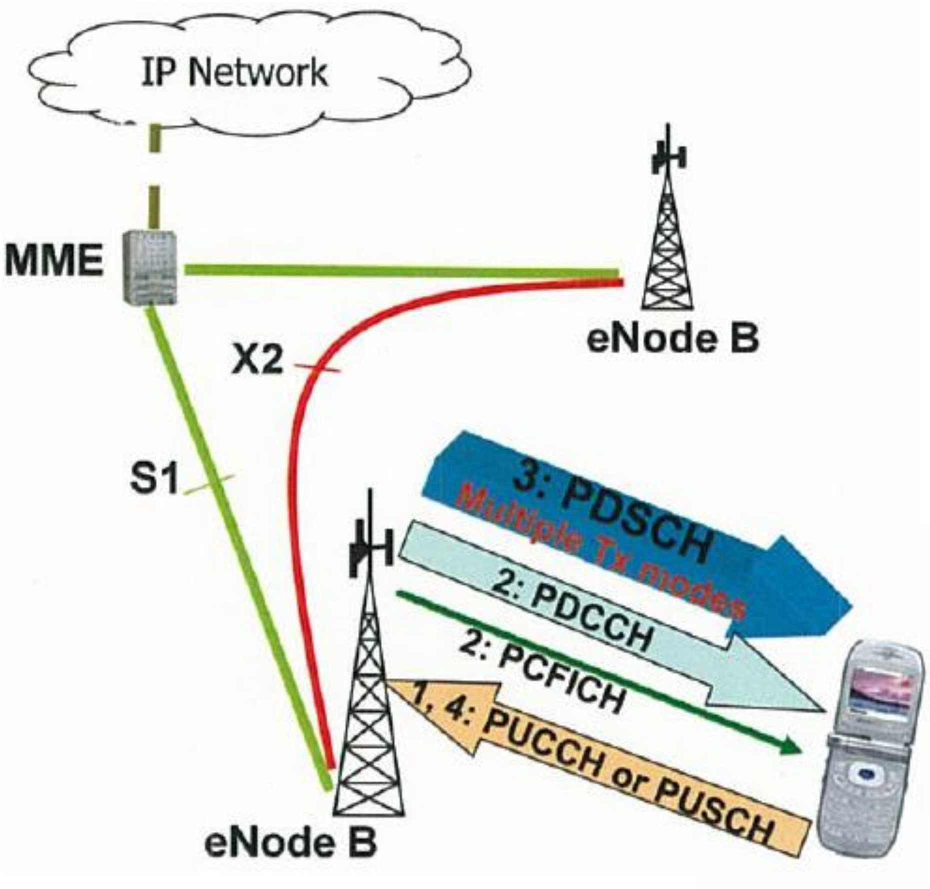
- Select a user *j* with biggest

$$\text{SM} = \frac{\textbf{(Channel condition)}}{\textbf{(Avg data rate user } j \textbf{ has received)}}$$

  – Numerator for "efficiency"
  – Denominator for "fairness"

- Adopted with modification for QoS in EVDO, EVDV, HSDPA packet scheduling

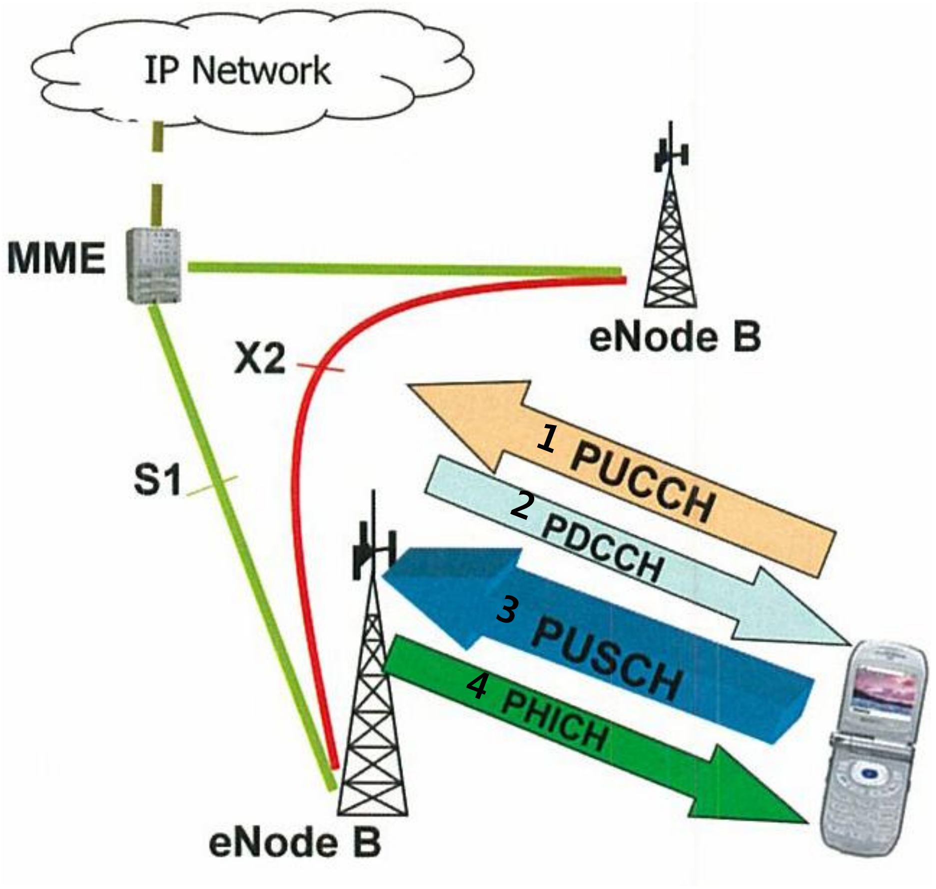
LTE DL Link Adaptation



1. UE reports CQI, PMI, RI in PUCCH (or PUSCH)
2. Scheduler at eNB dynamically allocated DL resources to the UE (PDCCH)
3. eNB sends user data in PDSCH
4. UE attempts to decode the received packet and sends ACK/NACK using PUCCH (or PUSCH)

* Qualcomm

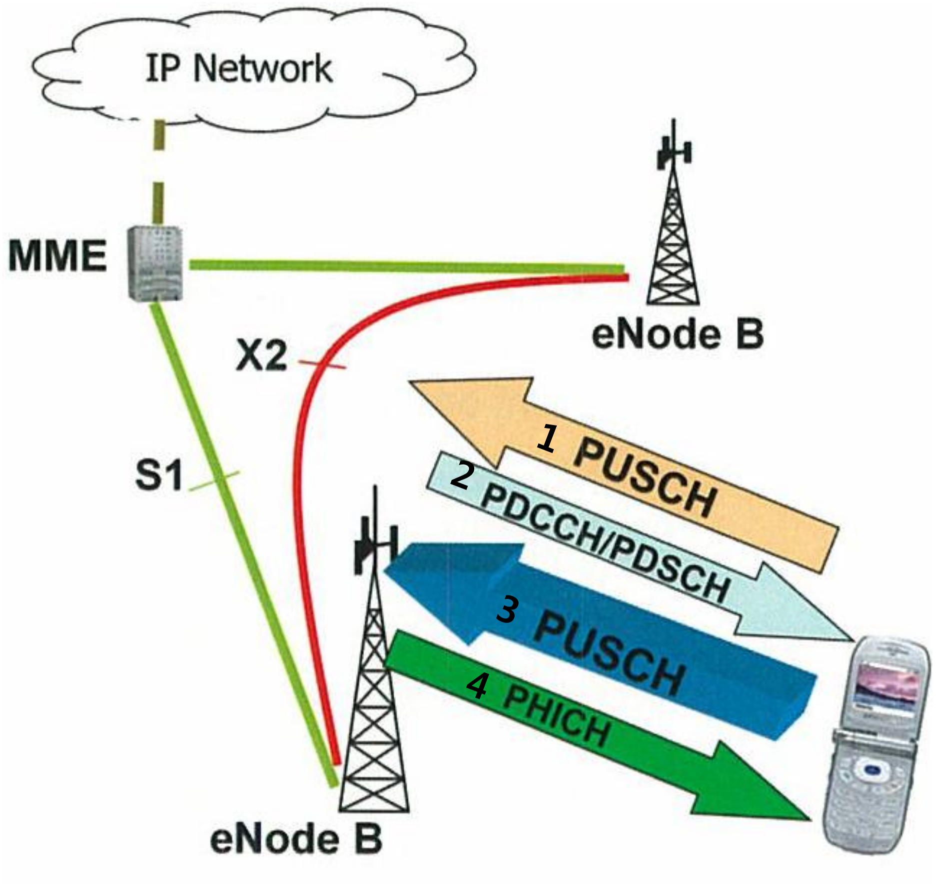
LTE UL Scheduling – w/o resource



1. If UE does not have UL-SCH resources, UE sends SR on PUCCH (In absence of PUCCH resources, UE must complete a RACH procedure to request UL-SCH resources.)
2. Scheduler at eNB allocates resources (PRBs and MCS to be used) to UE through “uplink grant” on PDCCH
3. UE sends user data on PUSCH
4. If eNB decodes the uplink data successfully, it sends ACK on PHICH

* Qualcomm

LTE UL Scheduling – modifying resource



1. UE sends BSR (Buffer Status Report) & PHR (Power Headroom Report) to network on PUSCH
2. Scheduler at eNB dynamically adjusts resources assigned to UE - Grant on PDCCH is adjusted
3. Based on the adjusted grant, UE sends user data on PUSCH
4. If eNB decodes the uplink data successfully, it toggles NDI (New Data Indicator) on PDCCH, and sends ACK on PHICH

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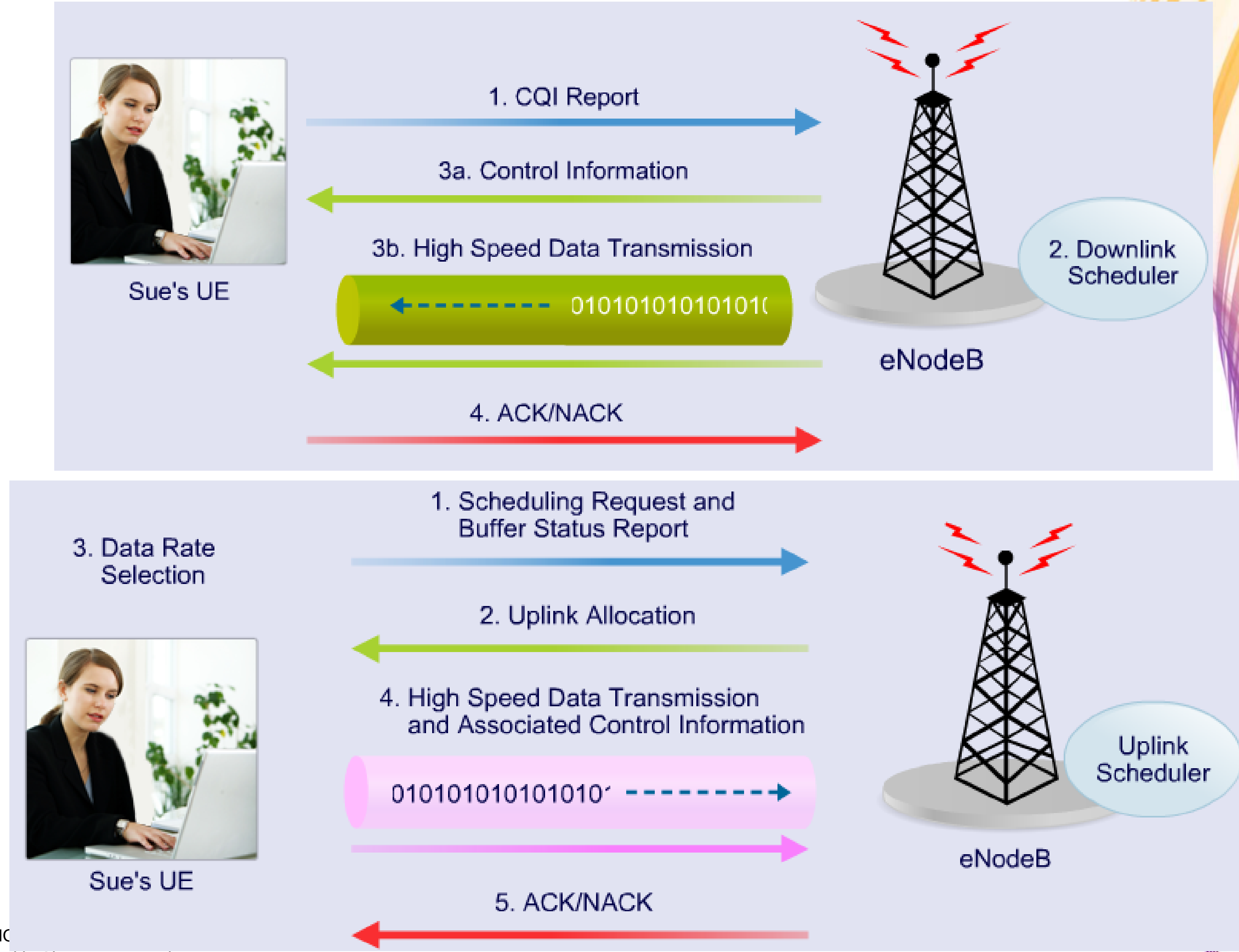
LTE DL/UL Data Transmission



LTE User Data Rate Control

- The instantaneous data rate for one UE in UL depends on
  - Modulation method
  - Channel coding rate applied
  - Frequency domain resource allocation (BW applied)
  - Time domain resource allocation
- The instantaneous data rate for one UE in DL depends on
  - Modulation
  - Channel coding rate applied
  - Frequency domain resource allocation (number of subcarriers applied)
  - Time domain resource allocation
  - Number of transmit antennas

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HARQ

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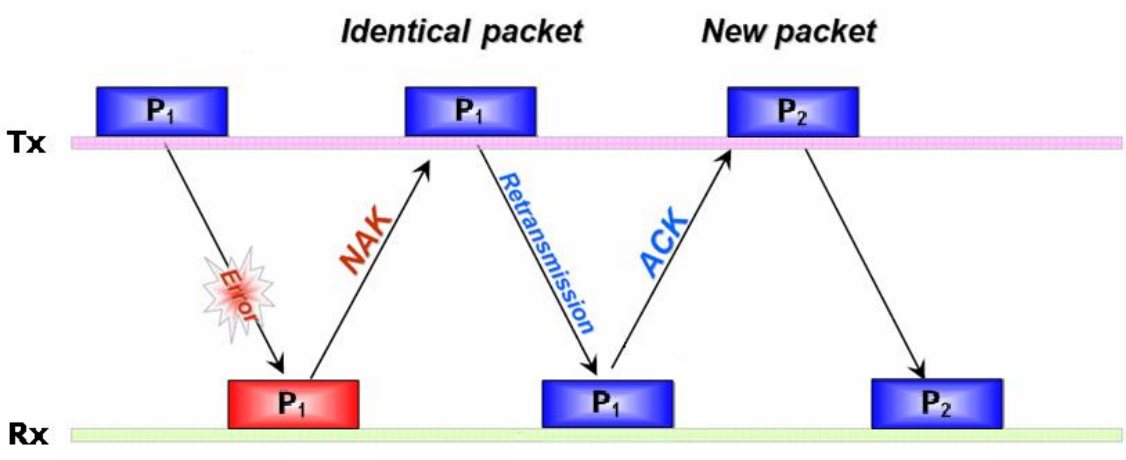
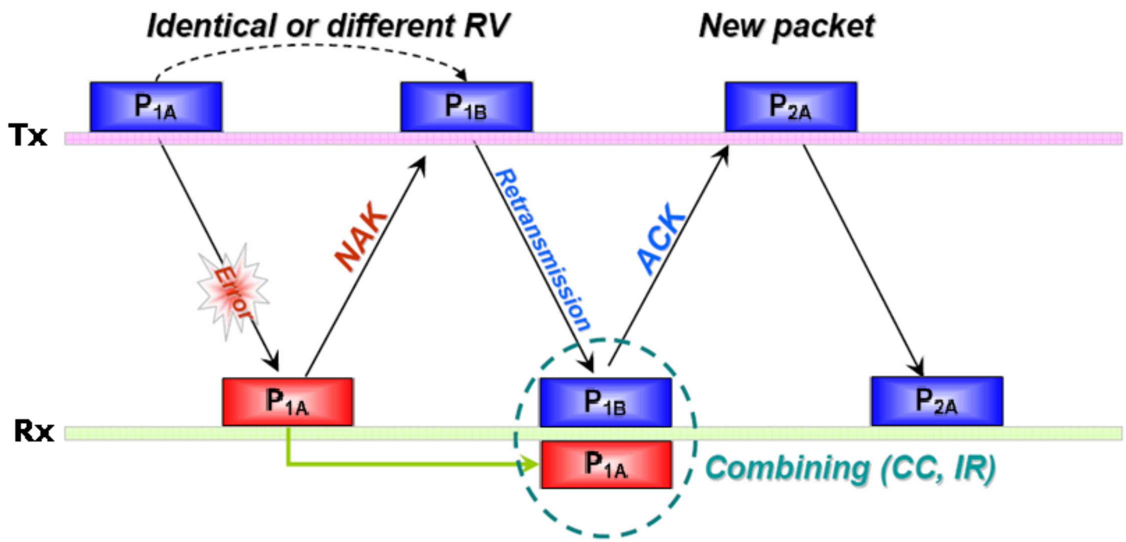
HARQ Principle



ARQ



HARQ

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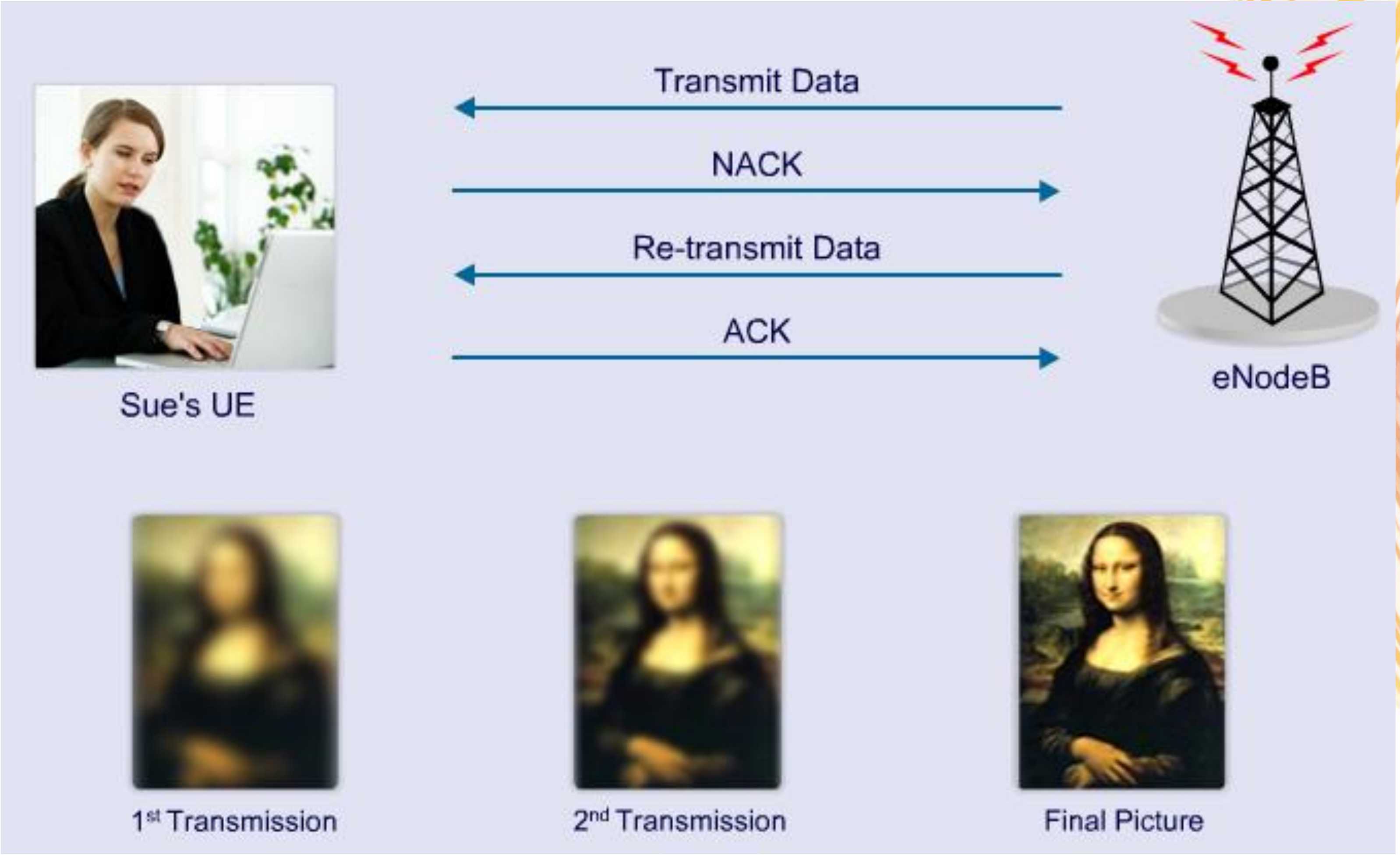
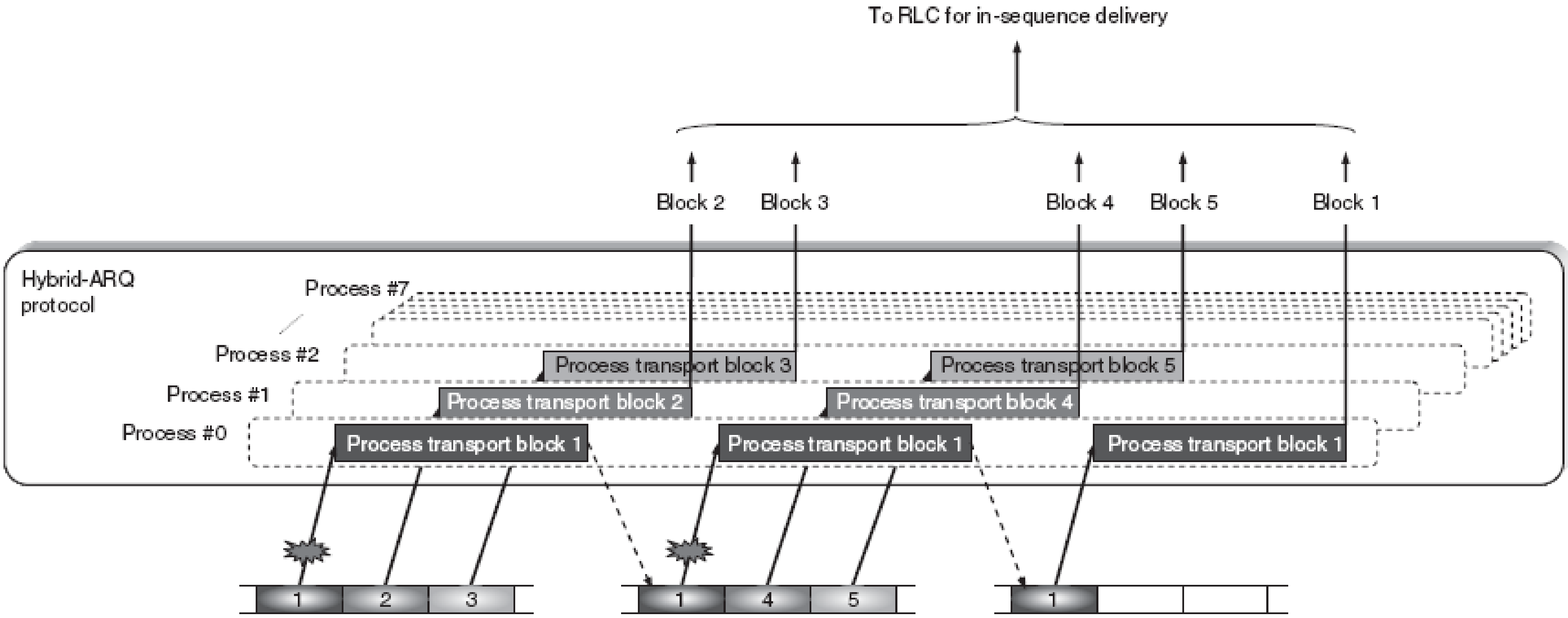
HARQ Principle



HARQ Overview

- HARQ is only supported for DL-SCH and UL-SCH
- Multiple (8) parallel stop-and-wait processes



DL HARQ

- Asynchronous protocol
  - DL retransmission may occur at any time after the initial transmission i.e., No fixed timing relationship b/w 'the time at which an ACK/NACK is received from the US' and 'the time when the retransmission takes place'
  - Explicit HARQ process number is used for indication
- Adaptive protocol
  - The frequency location and possibly the more detailed transmission format can be changed b/w transmissions
- Each retransmission needs the associated PDCCH
- In case of SM, each transport block has its own separate new-data indicator and redundancy-version indication.
- Synchronous ACK/NACK
  - A fixed timing relationship (n+4) b/w 'the time at which a DL packet is transmitted' and 'the time when the ACK/NACK from the UE is sent'

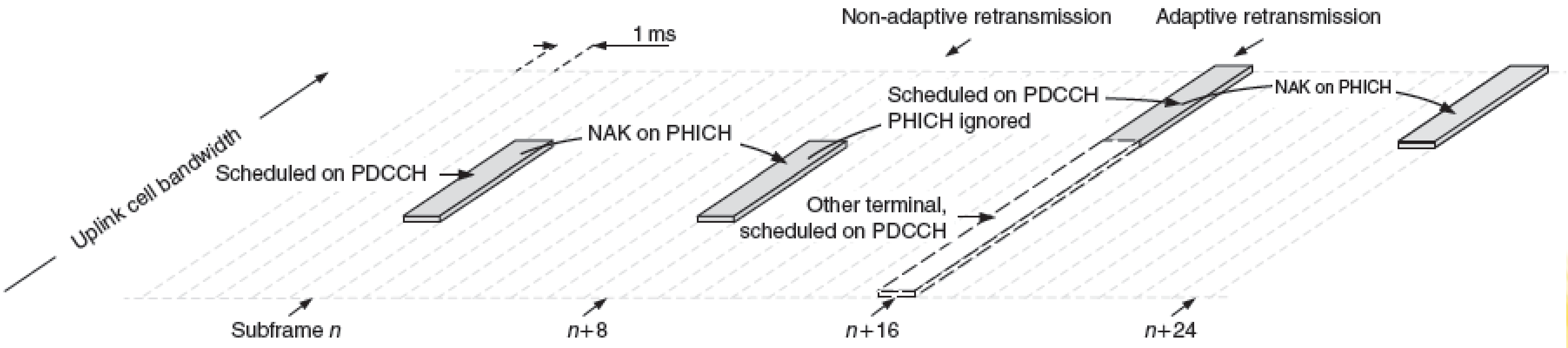
UL HARQ

- Synchronous protocol
  - Retransmission occurs at a pre-defined time after the initial transmission
  - The process number can be implicitly derived
- Non-adaptive protocol, "typically"
  - Retransmission must occur at the same frequency resources and with the same transmission format as the initial transmission
- Adaptive retransmission are sometimes needed
  - to avoid fragmenting the uplink frequency resource
  - to avoid collisions with random-access resources

PHICH feedback seen by the UE	PDCCH seen by the UE	UE behavior
ACK	-	No retransmission, keep data in UE HARQ buffer and a PDCCH grant is required to verify success & resume retransmissions or new transmission
NACK	-	Non-adaptive retransmission using same PUSCH resource as the last transmission
ACK or NACK	New Transmission	New transmission following PDCCH
ACK or NACK	Retransmission	Adaptive Retransmission – PDCCH can modify MCS, RV or RB

HARQ Procedure Example

Non-adaptive and adaptive HARQ procedure example in UL

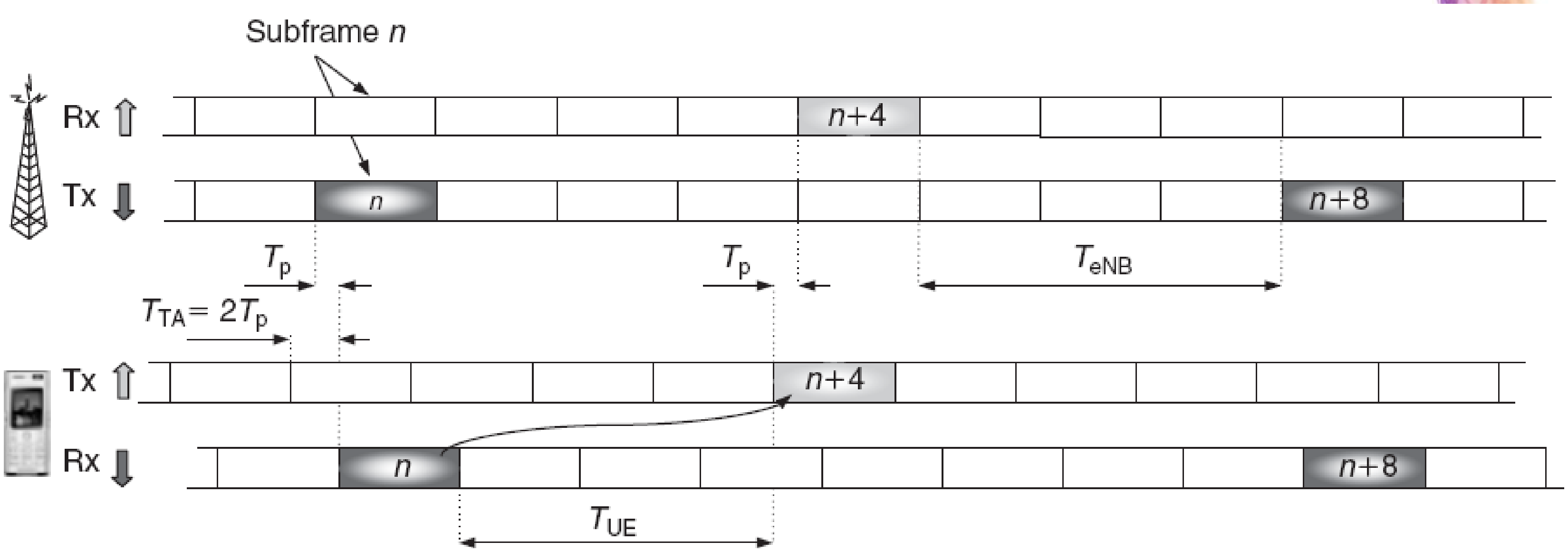


HARQ Timing

- Timing relation b/w downlink data in subframe *n* and uplink HARQ acknowledgement in subframe *n*+4 for FDD is as in the figure below
- Upon reception of HARQ acknowledgement, eNB can, if needed, retransmit the downlink data in subframe n+8

  → 8 HARQ processes are used

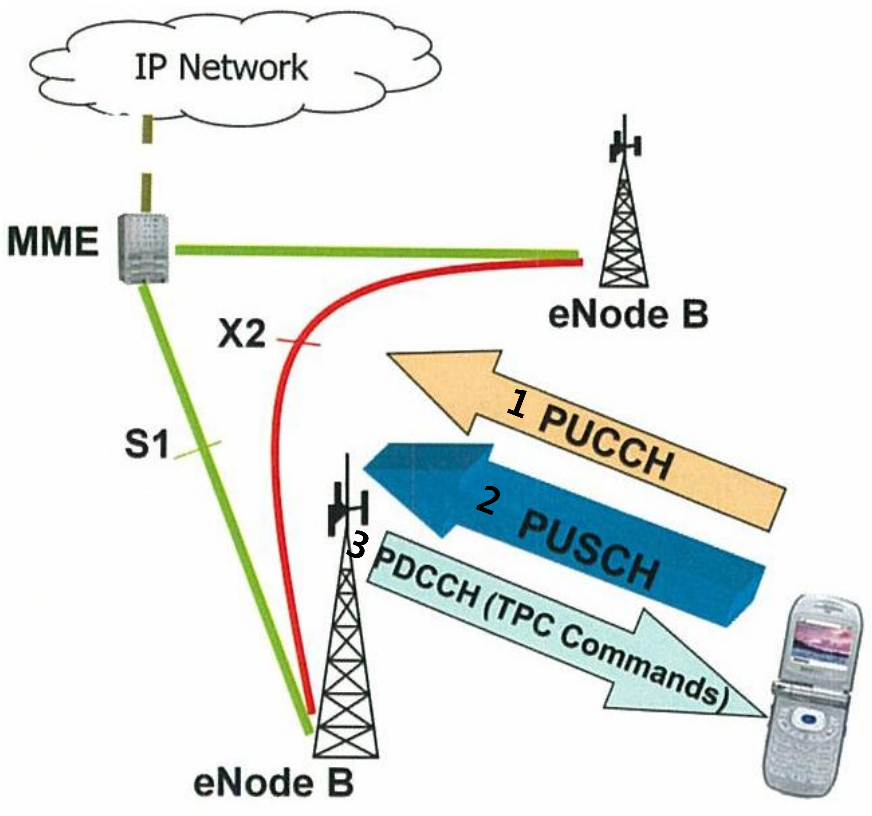
  → HARQ round-trip time is 8ms



~2.3ms
(assuming timing advance of 0.67ms)

Power Control

UL Closed Loop Power Control



1. UE transmits PUCCH or PUSCH
2. Serving eNB monitors link quality
3. Serving eNB sends TPC as part of DCI (Downlink Control Information) on PDCCH
4. UE adjusts transmit power levels of PUCCH or PUSCH.
5. Repeat

* Qualcomm

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PUSCH Power Control

$$P_{\mathrm{PUSCH}}(i)=\min\{P_{\mathrm{CMAX}},10\log_{10}(M_{\mathrm{PUSCH}}(i))+P_{\mathrm{O\_PUSCH}}(j)+\alpha(j)\cdot PL+\Delta_{\mathrm{TF}}(i)+f(i)\}\ \ [\mathrm{dBm}]$$

- $M_{\mathrm{PUSCH}}(i)$: the bandwidth of the PUSCH resource assignment expressed in number of resource blocks valid for subframe *i*
- $P_{\mathrm{O\_PUSCH}}(j)$: a parameter composed of the sum of a cell specific nominal component $P_{\mathrm{O\_NOMINAL\_PUSCH}}(j)$ and a UE specific component $P_{\mathrm{O\_UE\_PUSCH}}(j)$ provided by higher layers
- $\alpha \in \{0, 0.4, 0.5, 0.6, 0.7, 0.8, 0.9, 1\}$: a 3-bit cell specific parameter provided by higher layers
- PL*:* the downlink path-loss estimate calculated in the UE in dB
- $\Delta_{\mathrm{TF}}(i)=10\log_{10}((2^{MPR\cdot K_S}-1)\beta_{offset}^{PUSCH})$: it reflects the fact that different SINR is required for different modulation schemes and coding rates used for the PUSCH transmission
- $f(i)$: the term reflects TPC

More on $f(i)$

Accumulative

$$f(i) = f(i-1) + \delta_{PUSCH}(i - K_{PUSCH})$$

Absolute command

$$f(i) = \delta_{\mathrm{PUSCH}}(i - K_{\mathrm{PUSCH}})$$

δ_{PUSCH} is a UE specific correction value, also referred to as a TPC command and is included in PDCCH with DCI format 0 or jointly coded with other TPC commands in PDCCH with DCI format 3/3A whose CRC parity bits are scrambled with TPC-PUSCH-RNTI

PUCCH Power Control

$$P_{\mathrm{PUCCH}}(i) = \min\left\{P_{\mathrm{CMAX}}, P_{0\_\mathrm{PUCCH}} + PL + h\left(n_{CQI}, n_{HARQ}\right) + \Delta_{\mathrm{F\_PUCCH}}(F) + g(i)\right\} \quad [\mathrm{dBm}]$$

- $P_{\mathrm{O\_PUCCH}}(j)$: a parameter composed of the sum of a cell specific nominal component $P_{\mathrm{O\_NOMINAL\_PUCCH}}(j)$ and a UE specific component $P_{\mathrm{O\_UE\_PUCCH}}(j)$ provided by higher layers
- PL: the downlink path-loss estimate calculated in the UE in dB
- $h\left(n_{CQI}, n_{HARQ}\right)$: a PUCCH format dependent value, where n_{CQI} corresponds to the number of information bits for the channel quality information and n_{HARQ} is the number of HARQ bits
- $\Delta_{\mathrm{F\_PUCCH}}(F)$: a value corresponds to a PUCCH format (F) relative to PUCCH format 1a
- $g(i)$: the term reflects TPC

$$g(i) = g(i-1) + \sum_{m=0}^{M-1} \delta_{PUCCH}(i - k_m)$$ … M=1, k_0=4 for FDD

SRS Power Control

$$P_{\mathrm{SRS}}(i) = \min\{P_{\mathrm{CMAX}},\ P_{\mathrm{SRS\_OFFSET}} + 10\log_{10}(M_{\mathrm{SRS}}) + P_{\mathrm{O\_PUSCH}}(j) + \alpha(j)\cdot PL + f(i)\}\quad [\mathrm{dBm}]$$

- $P_{\mathrm{SRS\_OFFSET}}$: a 4-bit UE specific parameter semi-statically configured by higher layers
- M_{SRS}: the bandwidth of the SRS transmission in subframe *i* expressed in number of resource blocks

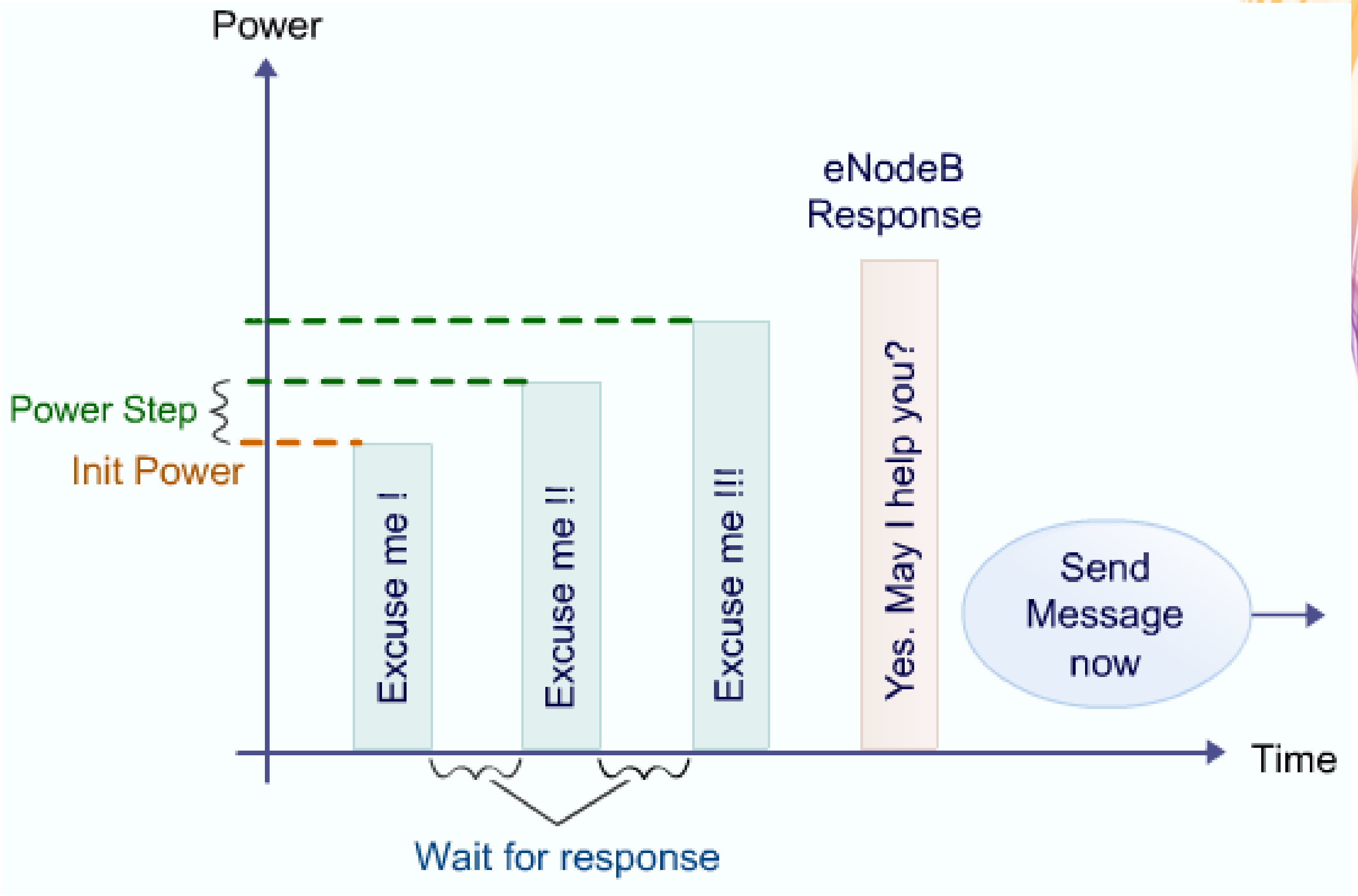
Random Access

Random Access

- Objectives of random access
  - Get unique UE identity (C-RNTI)
  - Timing correction information for uplink
- 5 Events invoking RA procedure
  - <u>Initial access</u> from RRC_IDLE
  - RRC Connection Re-establishment procedure
  - <u>Handover</u> requiring RA procedure
  - DL data arrival during RRC_CONNECTED requiring RA procedure when UL synchronization status is "non-synchronised"
  - UL data arrival during RRC_CONNECTED requiring RA procedure when UL synchronization status is "non-synchronised" or there is no PUCCH resources for SR
- Random Access channel characteristics
  - Contention-based transmission & Non-contention-based transmission (e.g. handover)
  - Signal structure to support full coverage
  - <u>Small preamble to lower overhead</u> (as in WCDMA)
  - RA attempts are done in pre-defined time/frequency resources.

    → <u>PRACH orthogonal to PUSCH/PUCCH</u> (different from WCDMA PRACH)

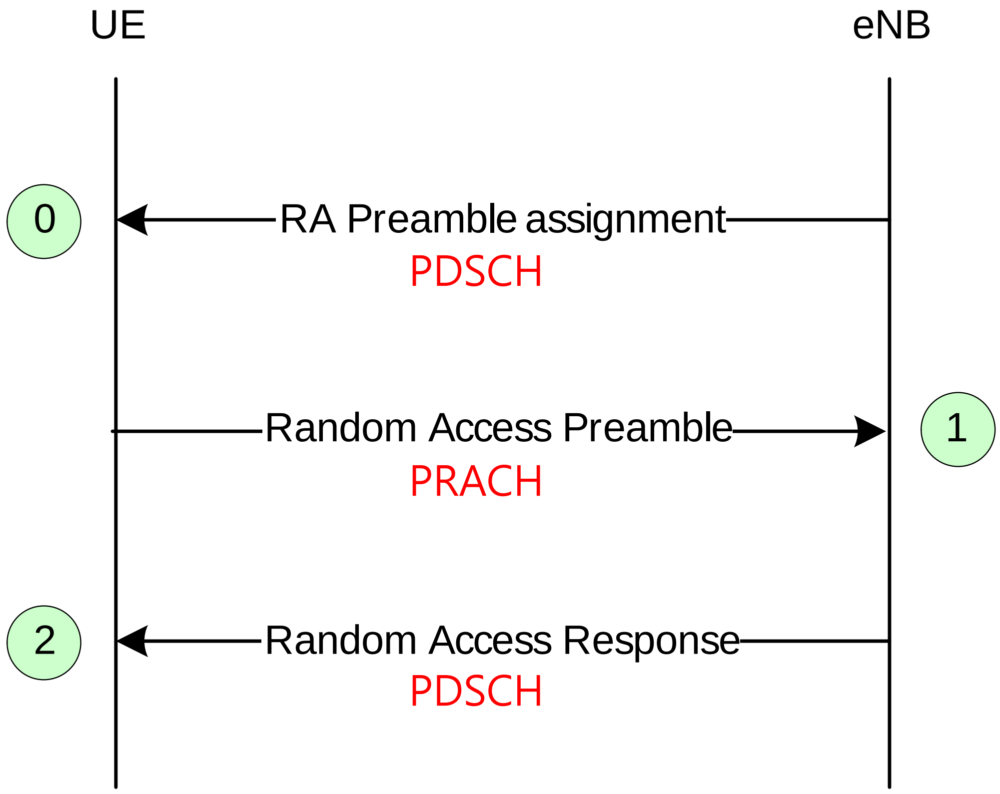
Access “Preamble” Transmission



Random Access Types

- Non-contention-based (Contention-free) Random Access
  - PDCCH or RRC indicates a RA preamble and PRACH resource (PRB) for UE to send signaling or data on PUSCH
- Contention-based Random Access
  - UE selects a RA preamble and PRACH resource to send signaling or data on PUSCH
  - There is probability that multiple UEs in the cell could pick the same preamble signature and the eNB would assign the same PRB to both UEs for UL transmission of message/data
  - Contention resolution is needed

Non-contention-based Random Access



Non-contention-based Random Access

0) Random Access Preamble assignment (and PRACH resource (PRB)) via dedicated signalling in DL:

   Signalled via:

   - HO command generated by target eNB and sent via source eNB for handover;
   - PDCCH in case of DL data arrival.

1) Random Access Preamble on RACH in uplink:

   UE transmits the assigned non-contention Random Access Preamble.

   'Power Ramp (with time backoff)' can be applied until preamble is received.

   - The amount of power increase is defined in specification

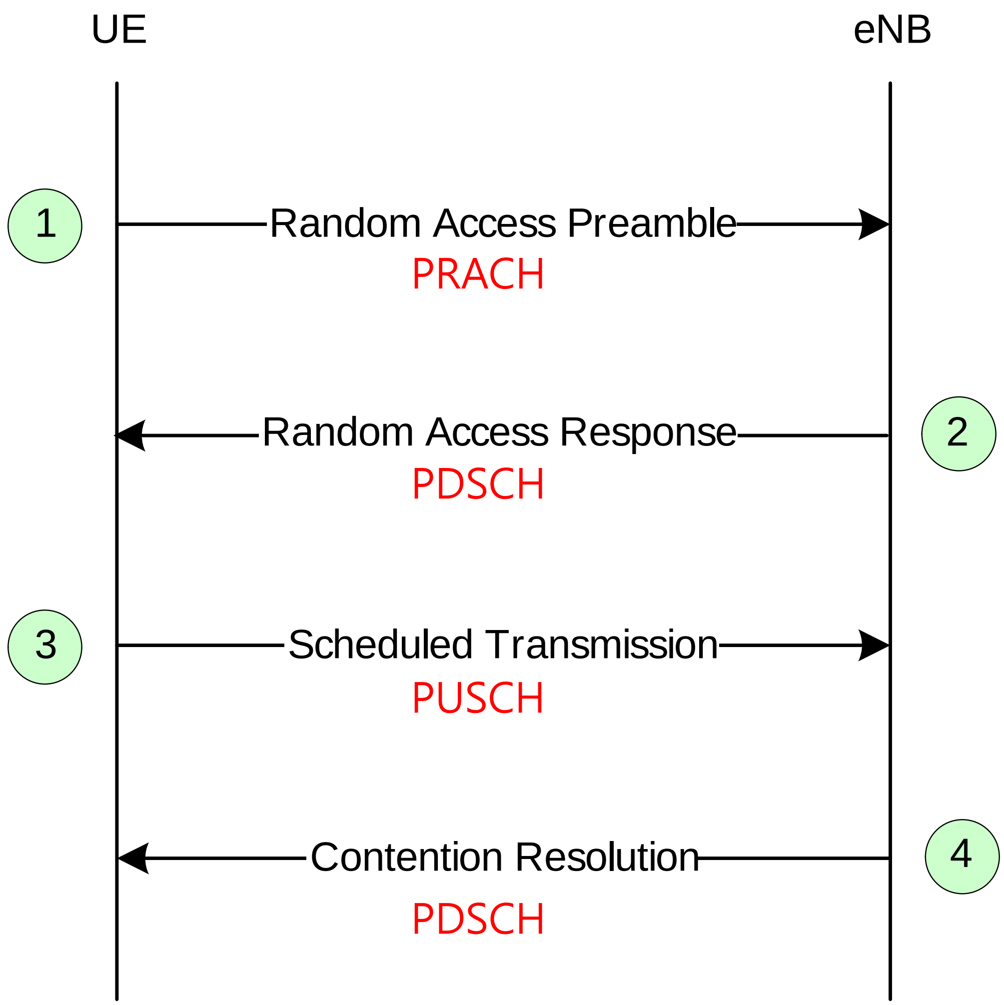
2) eNB sends a transmission on PDCCH identified using RA-RNTI

   Actual RAR (Random Access Response) is on PDSCH pointed by PDCCH w/ RA-RNTI

   - No HARQ
   - RAR includes RA preamble ID

   If UE finds the same RA preamble ID in RAR, UE consider RA was successful.

Contention-based Random Access



Random Access Procedures

Step 1: Random-access preamble transmission

- The network broadcasts info to all UEs in which time-frequency resources random-access preamble transmission is allowed (i.e., PRACH resources in SIB 2)
- In each cell, there are 64 preamble sequences available
  - Two subsets (Preamble set #0 and set #1) as well as 'preambles for contention-free access'
- A UE randomly selects one sequence in one of the subsets.
- Transmission of random-access preamble for eNB to estimate the UE transmission timing.
- *Only the first step uses physical-layer processing specifically designed for RA*
- If UE has been requested to perform a contention-free random access (e.g. handover to a new cell), the preamble to use is explicitly indicated from eNB
- For FDD, there is at most one random-access region per subframe
- 'Power Ramp (with time backoff)' can be applied until preamble is received

Random Access Procedures

Step 2: Random-access response

- After eNB detects the preamble, it sends a transmission on PDCCH identified using RA-RNTI.
- Actual RAR is on PDSCH pointed by PDCCH w/ RA-RNTI
- Message contains:
  - Index of the random-access preamble sequences detected at the network
  - The timing correction calculated at the network
  - A scheduling grant for Step 3
  - A temporary identity, TC-RNTI, used for the following steps
- Collision when multiple UEs using the same preamble at the same time at Step 1. In this case, multiple UEs will react upon the same downlink response message and collision occurs.

Random Access Procedures – cont'd

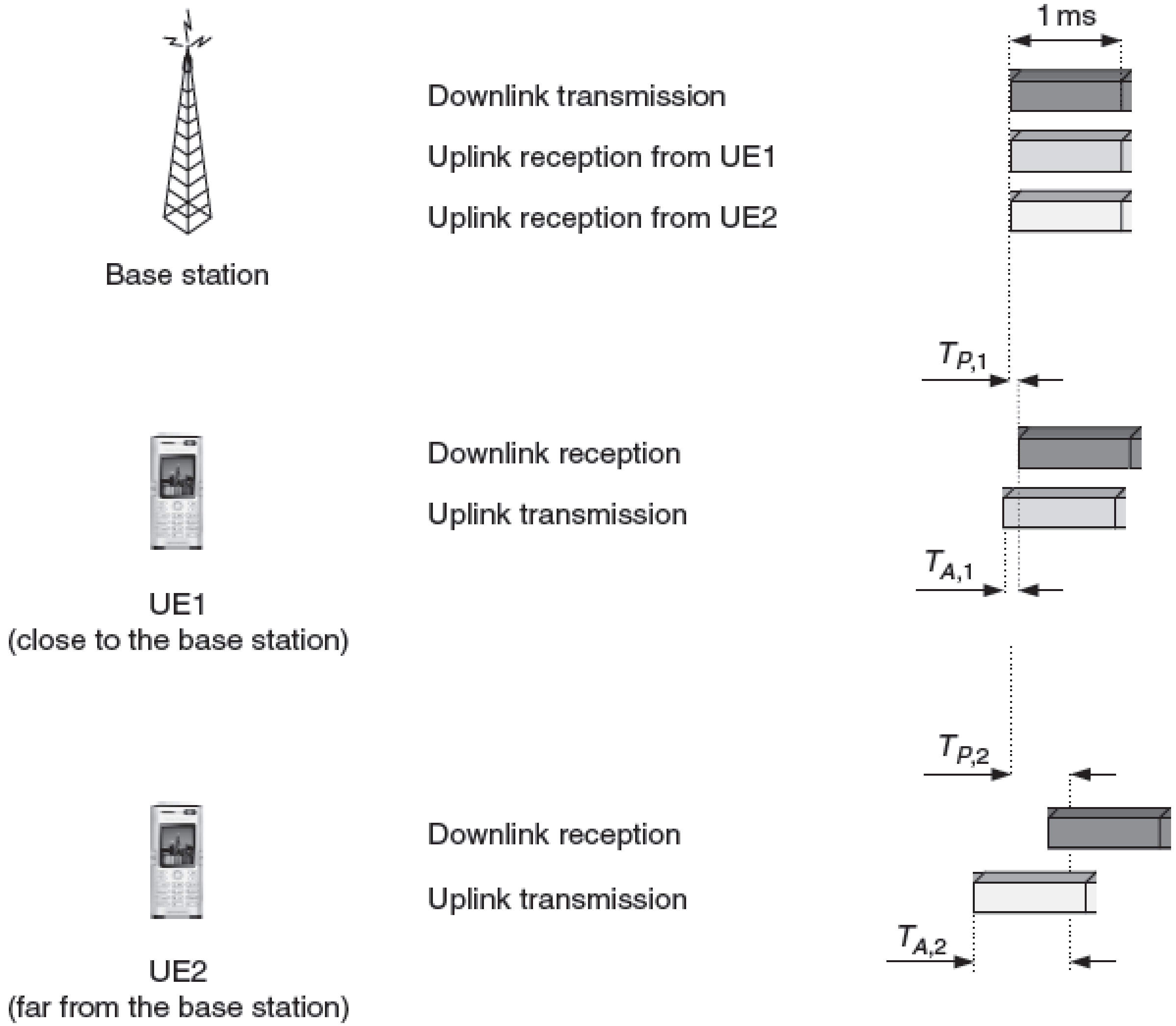
Step 3: Terminal identification

- UE adjusts timing per timing correction info provided at Step 2.
- UE starts a contention resolution timer.
- Each UE will transmit its unique UL CCCH SDU on UL-SCH
- Transmitting the uplink message in the same manner as scheduled uplink data.
  - Flexibility on grant size and modulation scheme
  - It allows to use HARQ to enhance the receiving performance

Step 4: Contention resolution

- eNB will only receive UL-SCH from UE whose time adjustment was suitable
- Then, eNB sends a PDCCH with a TC-RNTI originally included in RAR and then the Contention Resolution message on PDSCH where a Contention Resolution ID which matches the CCCH SDU of only one of the UEs is included
- Each UE receiving the downlink message will compare the Contention Resolution ID
- Only one UE which observes a match b/w the ID received in Step 4 and the ID (CCCH SDU) used in Step 3 will declare the random-access procedure successful.
- The timer will expire for the other UEs for them to restart the RA process

Timing Advance



LTE RLC

RLC Functions

- Transfer of Upper Layer PDUs
  - Signaling Radio Bearer (SRB) from RRC
  - Radio Bearer (RB) from PDCP
- Error Correction through ARQ
- Concatenation, Segmentation and Reassembly of SDUs
- Re-segmentation of RLC PDUs
- In-Sequence delivery of Upper Layer PDUs
- Duplicate Detection
- Protocol Error Detection and Recovery

RLC Modes

Transparent mode (TM)

- RLC is completely transparent and is in essence bypassed.
- No retransmissions, no segmentation/reassembly, and no in-sequence delivery.
- This configuration is used for broadcast channels such as BCCH, CCCH, and PCCH where the information should reach multiple users.
- The size of these messages are selected such that all intended terminals are reached with a high probability. Hence, no need for segmentation to handle varying channel conditions, nor retransmissions to provide error-free data transmission.
- Retransmissions are not possible for these channels as there is no possibility for the terminal to feed back status reports as no uplink has been established.

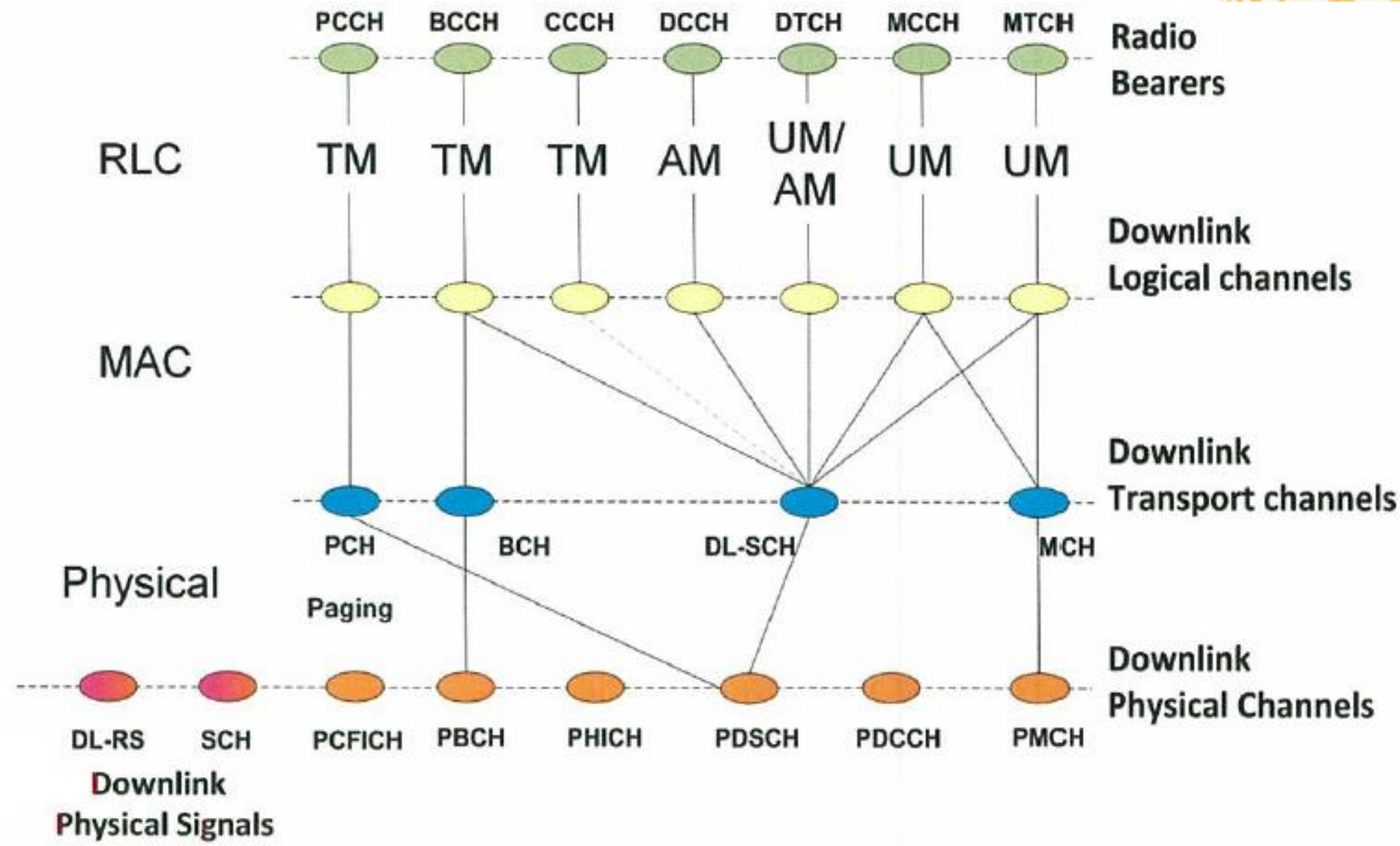
Unacknowledged mode (UM)

- Supports segmentation/reassembly and in-sequence delivery, but not retransmissions.
- This mode is used when error free delivery is not required, for example for MCCH and MTCH using MBSFN and for VoIP.

Acknowledged mode (AM)

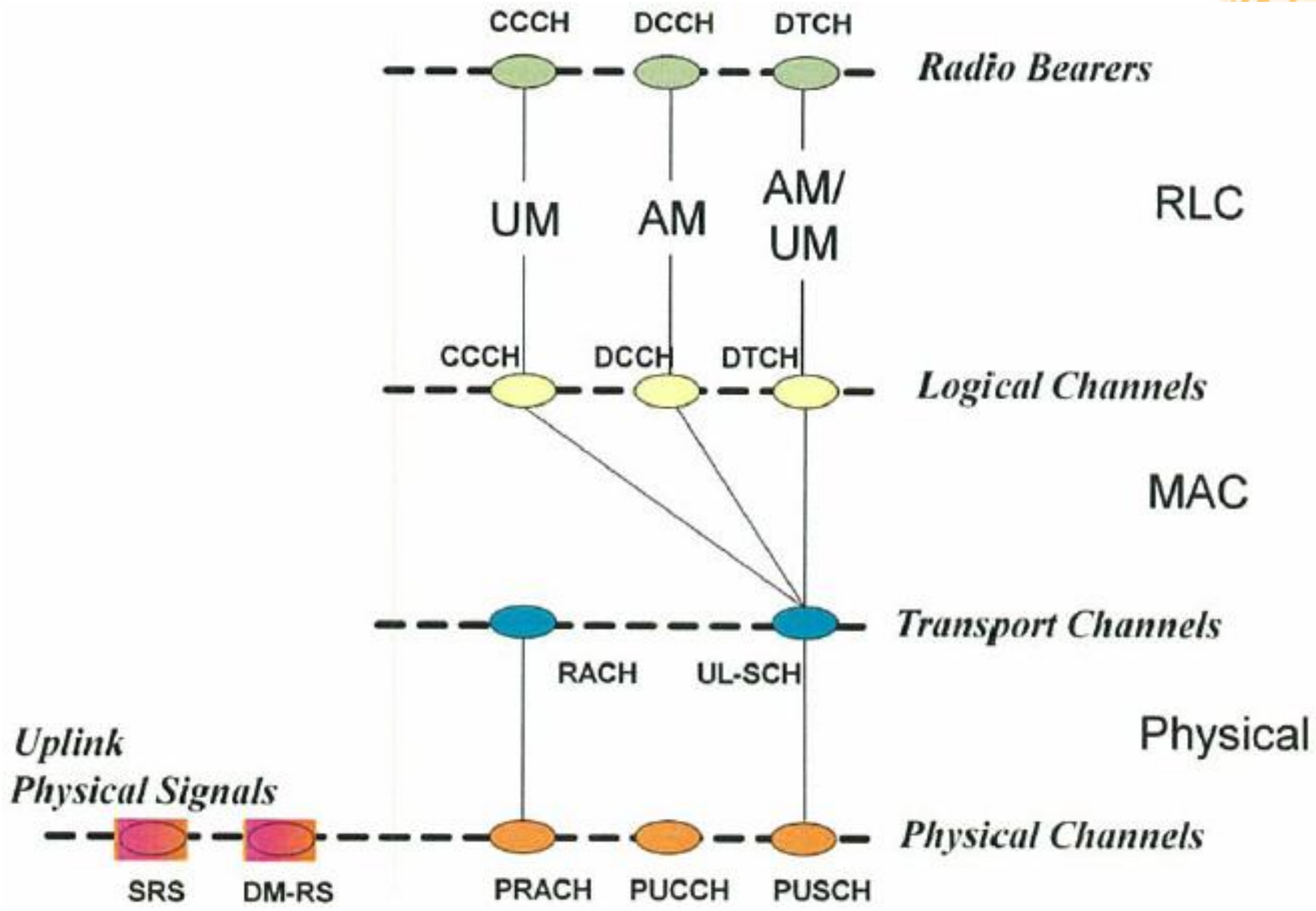
- Main mode of operation for TCP/IP packet data transmission on the DL-SCH.
- Segmentation/reassembly, in-sequence delivery and retransmissions of erroneous data are all supported.

RLC Mode for DL Logical Channels



* Qualcomm

RLC Mode for UL Logical Channels



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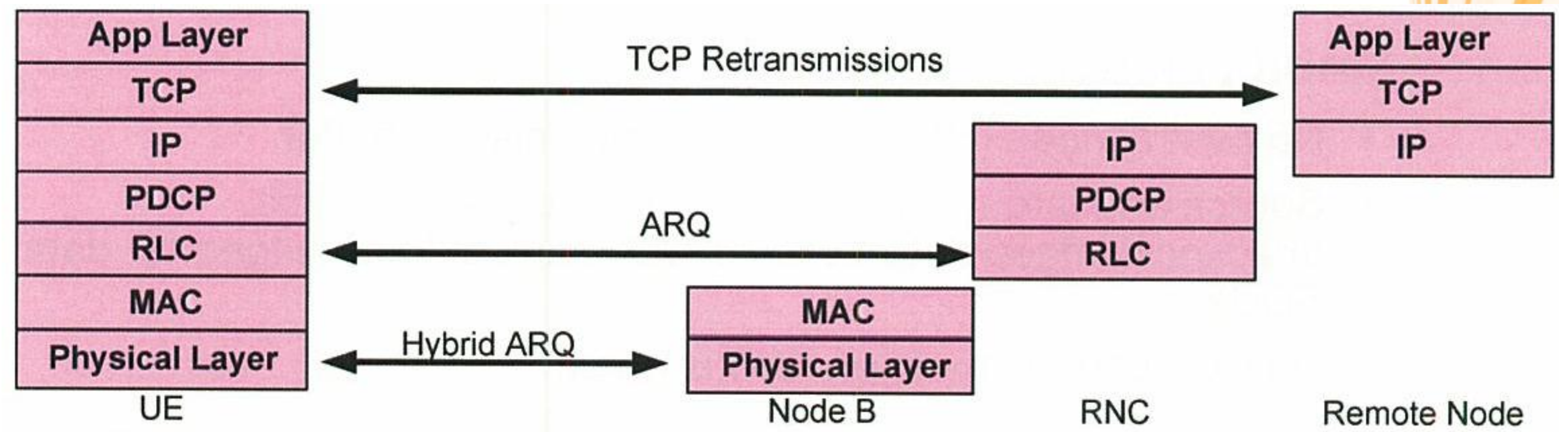
Difference b/w LTE and HSPA

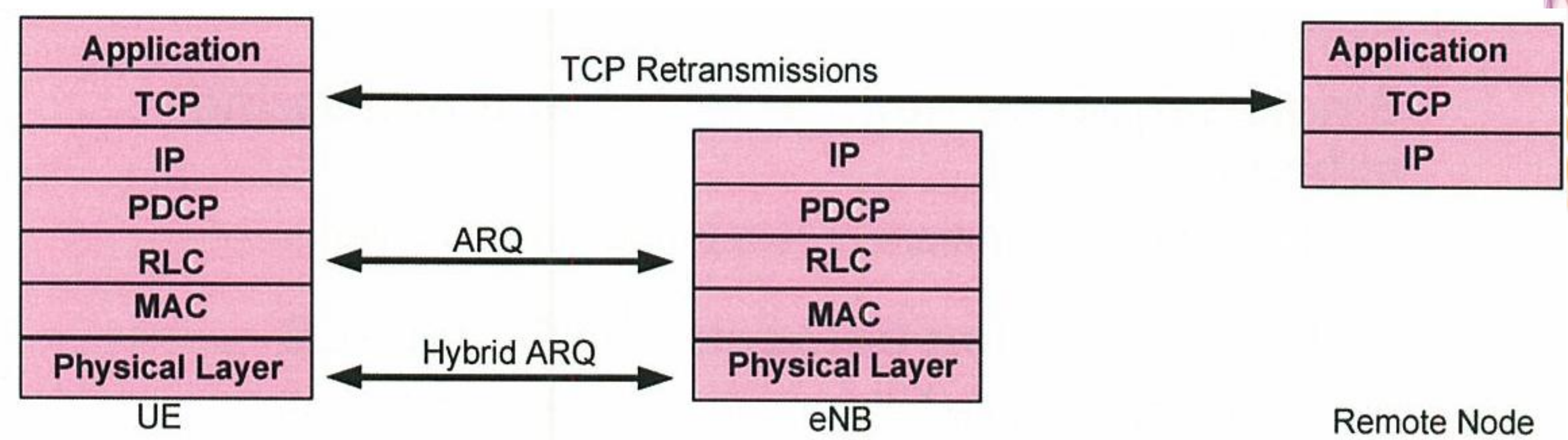
LTE RLC	HSPA RLC
RLC located in eNB	RLC located in RNC
Flexible RLC PDU sizes to match underlying PHY layer capacity	RLC PDU sizes are semi-statically configured by RRC layer (except for R7 and beyond)
Re-segmentation of RLC PDUs during retransmission to match PHY layer capacity	Re-segmentation for retransmissions not allowed
No ciphering at RLC layer (performed at PDCP layer)	Ciphering supported for UM and AM modes
Transparent mode for common signaling channels only	Sometimes, even the traffic channels as well as signaling should use transparent mode

Retransmissions in HSPA and LTE

HSPA



LTE



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LTE PDCP

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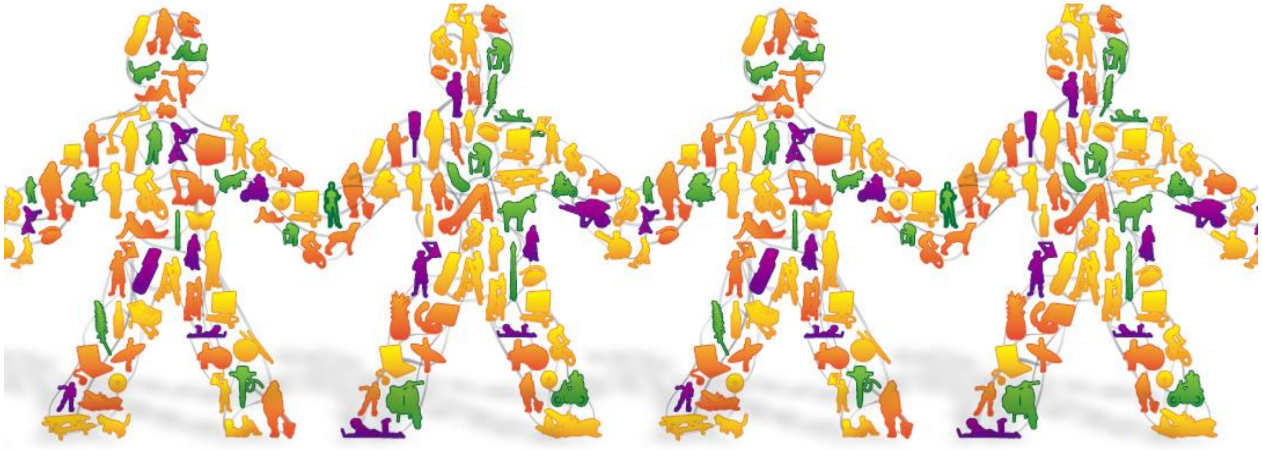
PDCP Functions

- Transfers User Plane and Control Plane data to and from upper layers. It receives SDUs from upper layers and sends PDUs to the lower layers. In the other direction, it receives PDUs from the lower layers and sends SDUs to upper layers.
- Is responsible for *security functions*. It applies ciphering for User and Control Plane bearers, if configured. It may also perform integrity protection for Control Plane bearers, if configured.
- Performs *header compression* services to improve the efficiency of over the air transmissions. The header compression is based on Robust Header Compression (ROHC).
- Is responsible for *in-order delivery* of packets and *duplicate detection* services to upper layers after handovers. After handover, the source eNB transfers unacknowledged packets to target eNB when operating in RLC AM. The target eNB forwards packets from the source eNB to the UE.



Thank you !

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