3GPP LTE/5G Networks
- MAC Layer -

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Adapted from Prof. Sunghyun Choi's slides

NXC LAB

Contents

- LTE MAC Features
- LTE MAC Procedures
  - Scheduling
  - HARQ
  - Power Control
- RLC
- PDCP
- RRC
- Paging
- Handover

LTE Communication Channels

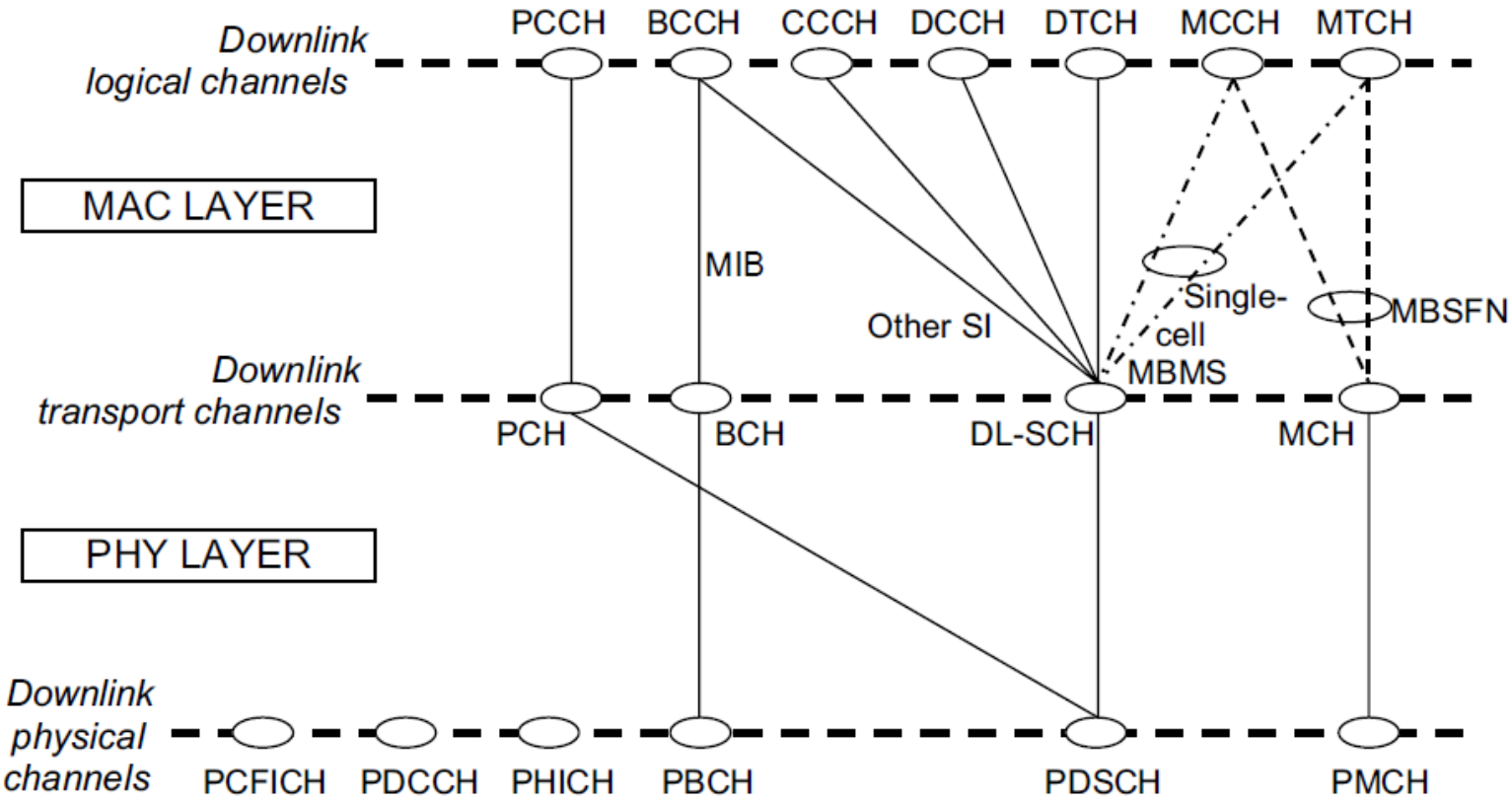
- Logical Channels
  - Define what type of information is transmitted over the air
  - e.g., traffic channels, control channels, system broadcast, etc.
  - Data and signaling messages are carried on logical channels between RLC and MAC

- Transport Channels
  - Define how is something transmitted over the air
  - e.g., what are encoding, interleaving options used to transmit data
  - ... between MAC and PHY

- Physical Channels
  - Define where is something transmitted over the air
  - e.g., first N symbols in the DL frame
  - ... below PHY

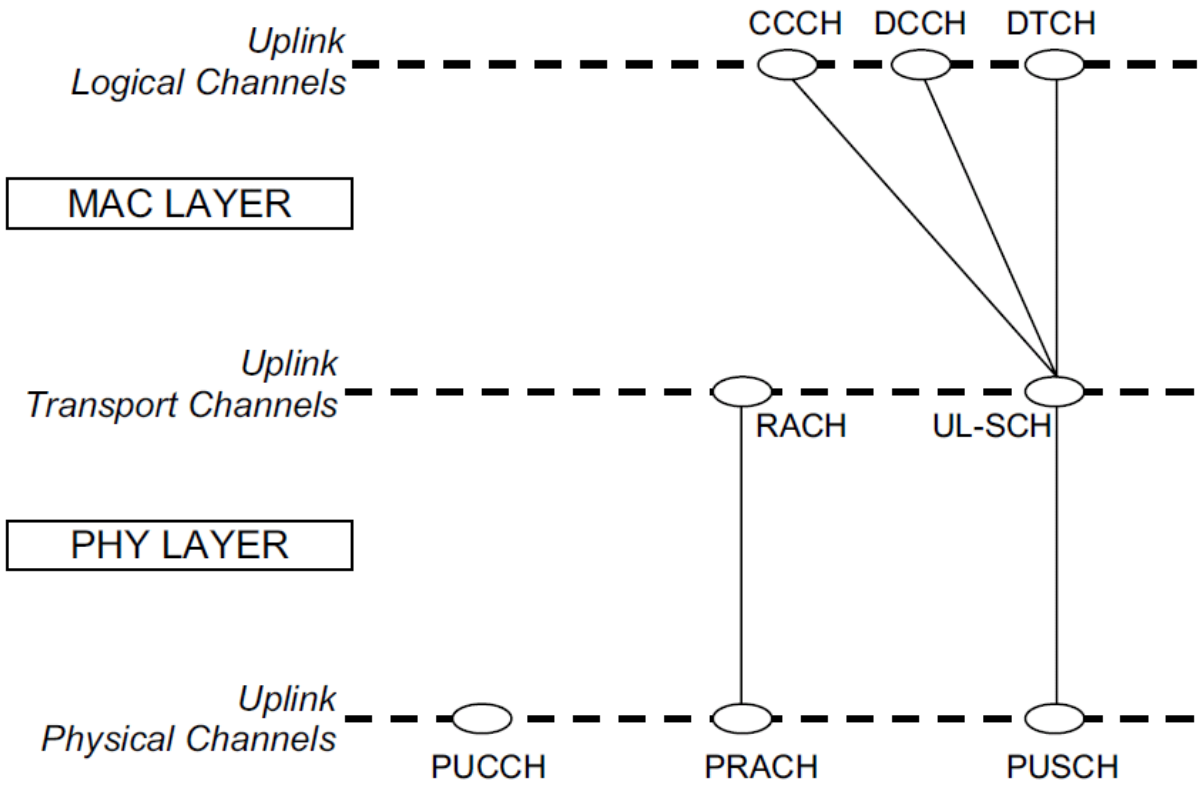
Downlink Channels

- Summary of downlink physical channels and mapping to higher layer



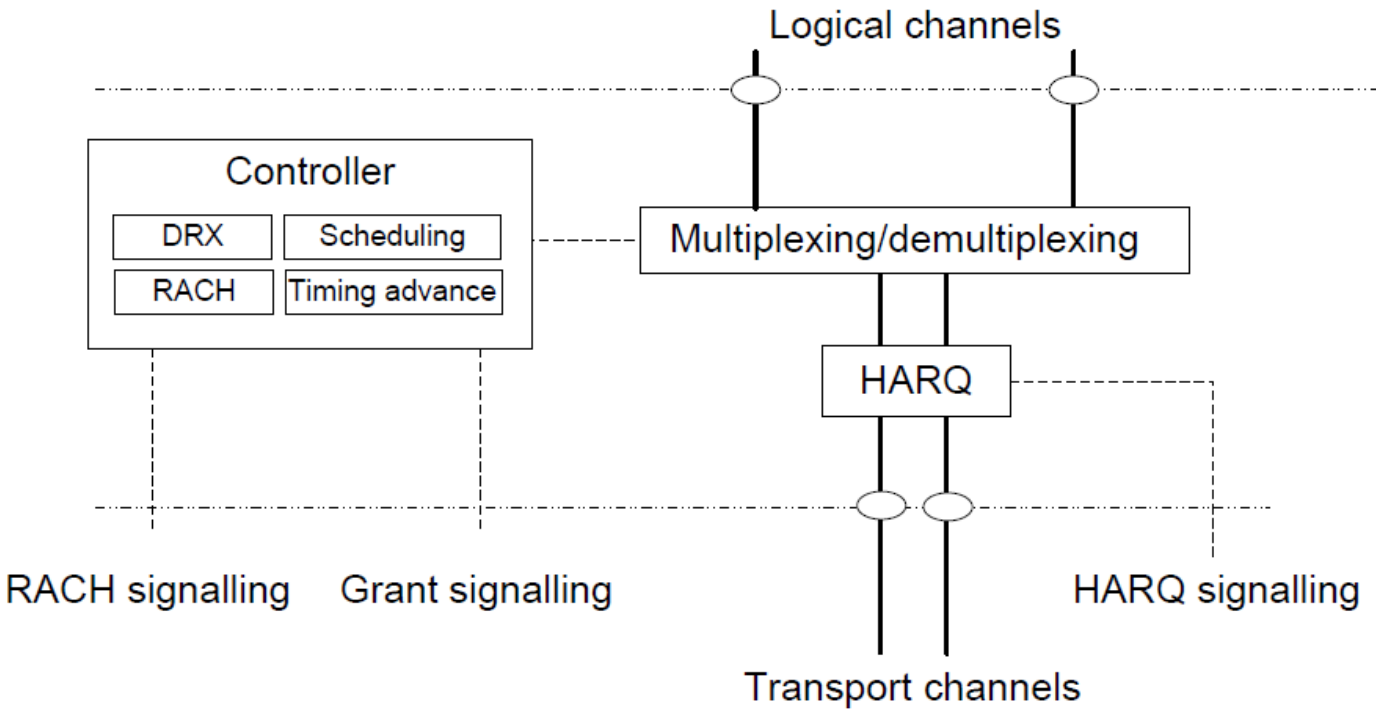
Uplink Channels

- Summary of uplink physical channels and mapping to higher layer



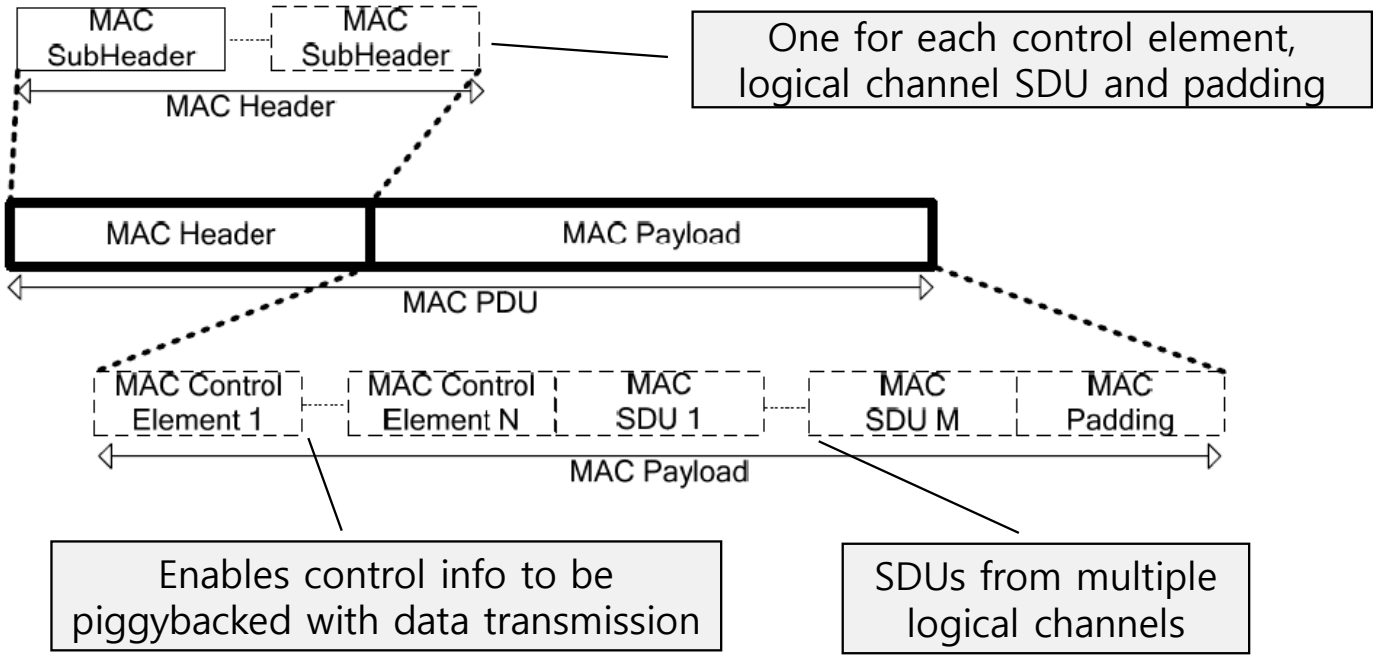
MAC Multiplexing

- MAC multiplexing allows data from multiple logical channels to be transmitted in a single MAC PDU (protocol data unit, MAC output) on the DL-SCH and UL-SCH
  - Priority of logical channels is considered during multiplexing



MAC PDU for DL-SCH/UL-SCH

- General MAC PDU format



- 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 (service data unit, MAC input) in the PDU

MAC Control Elements (MAC CE)

- 3 things for DL
  - Timing Advancement (8 bits): 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 (48 bits): Used during RACH procedure to resolve possible contention between multiple UEs trying to simultaneously access the network

- 3 things for UL
  - UE BSR (buffer status reports) (8 or 24 bits): 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 (Cell Radio Network Temporary Identifier) (16 bits): Identifies a UE when sending information over CCCH

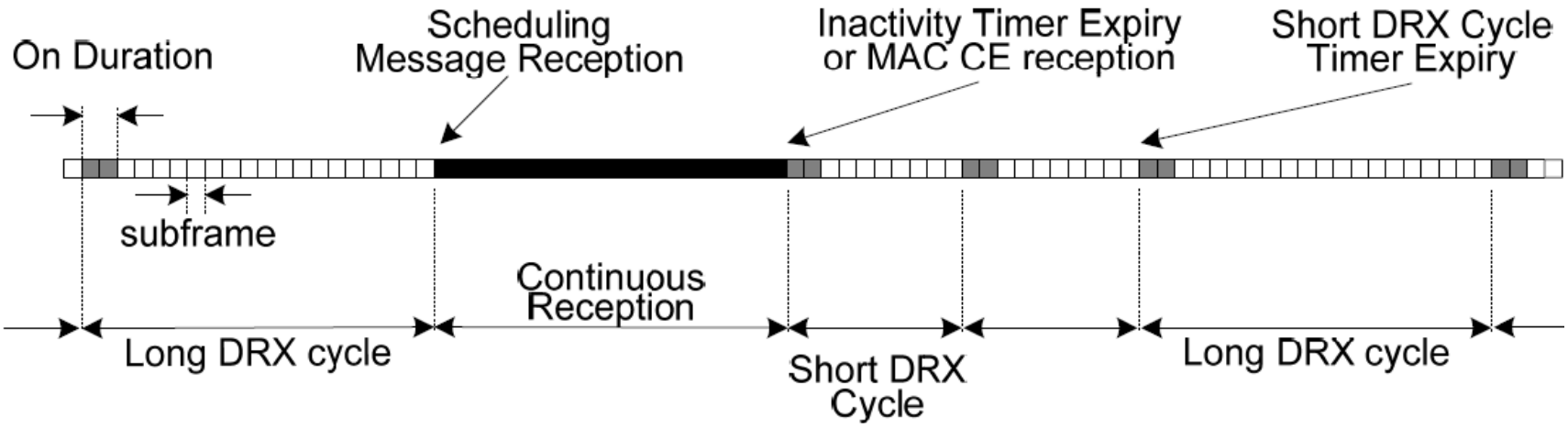
DRX Support

- 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

DRX Operation

- During DRX, UE maintains a DRX cycle (# 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
  - Two-level DRX procedures (short and long)
    - UE starts with Short DRX cycle and transitions to long DRX cycle after the expiration of a timer



DRX Operation

- Short DRX cycle is optional and targeted for applications which typically require relatively small transmissions of data at short but regular intervals (e.g., VoIP)

- Configuration
  - Short DRX cycle: 2-640 subframes
  - Long DRX cycle: 10-2560 subframes

- Handling VoIP can be done by setting
  - Short DRX cycle to 20 ms as the voice codec typically delivers a VoIP packet per 20 ms
  - Long DRX cycle is then used to handle longer periods of silence between talk spurts

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

UE Power Headroom Report (PHR) CE

- Reports UE Power Headroom
  - How much tx power left for a UE to use in addition to the power being used by current transmission
  - Used by eNB to estimate how much uplink bandwidth a UE can use for a specific subframe

- Ranges from -23 dB to 40 dB in steps of 1 dB (6 bits)
  - Negative values indicate the difference between max UE tx power and calculated UE transmit power
  - Negative value shows power assuming UE is “power limited” with the current grant

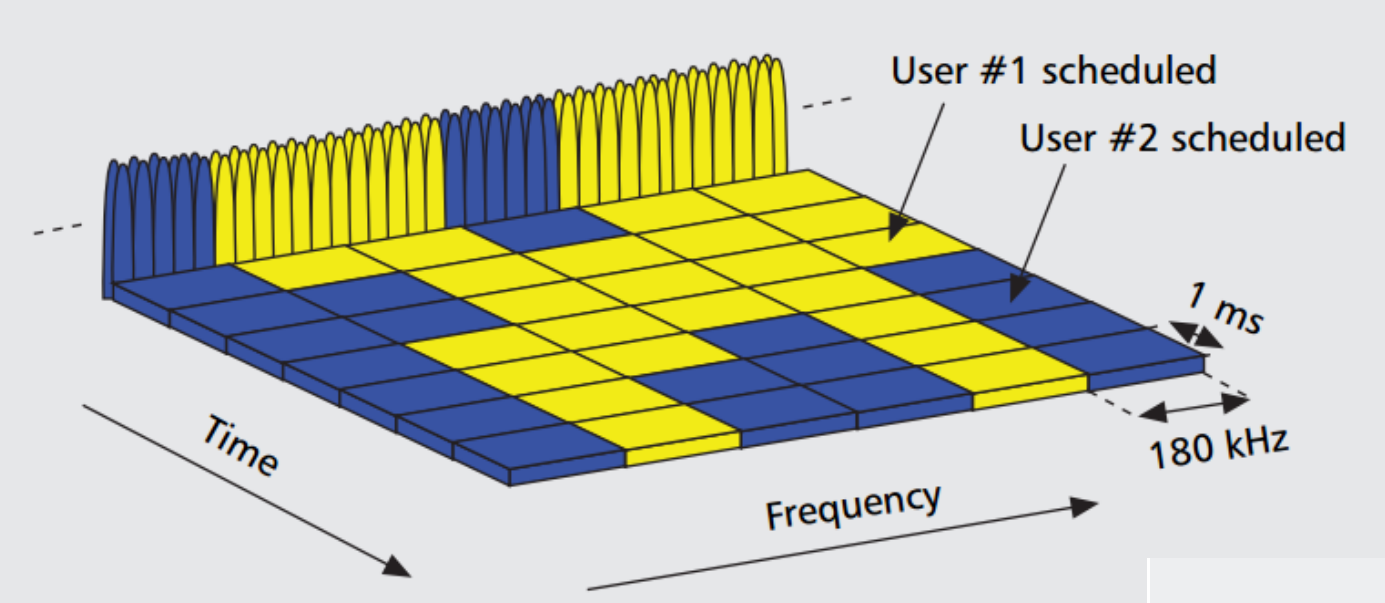
RNTI (Radio Network Temporary Identifier)

- Various RNTIs to identify UEs for various cases

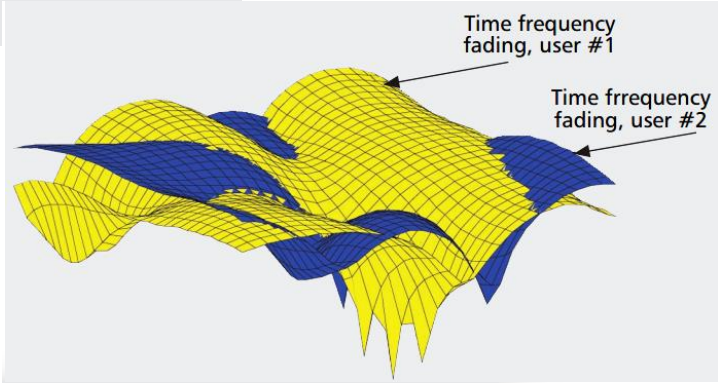
RNTI	Usage	Transport Channel	Logical Channel
P-RNTI	Paging and System Information change notification	PCH	PCCH
SI-RNTI	Broadcast of System Information	DL-SCH	BCCH
RA-RNTI	Random Access Response	DL-SCH	N/A
Temporary C-RNTI	Contention Resolution (when no valid C-RNTI is available)	DL-SCH	CCCH
Temporary C-RNTI	Msg3 transmission	UL-SCH	CCCH, DCCH, DTCH
C-RNTI	Dynamically scheduled unicast transmission	UL-SCH	DCCH, DTCH
C-RNTI	Dynamically scheduled unicast transmission	DL-SCH	CCCH, 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

Resource Allocation

- MAC scheduler allocates RBs to UEs



Reference: David Astely, et al. "LTE: the evolution of mobile broadband," IEEE Communications magazine (2009).

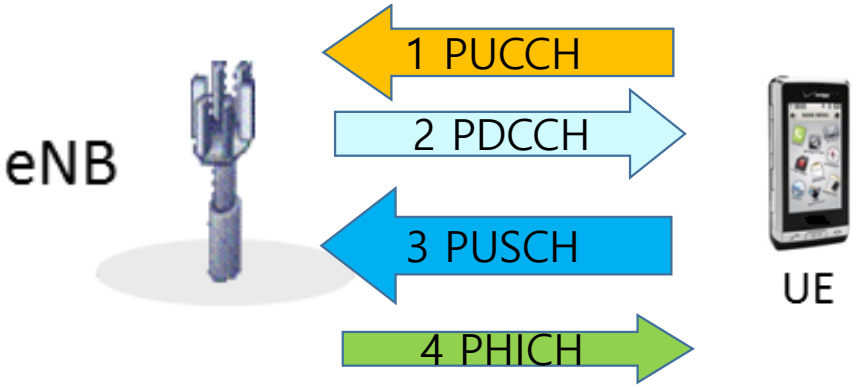


Scheduling

- Scheduling strategies need information about:
  - Channel condition
  - Buffer status and priorities of different data flows
  - Interference situation in neighboring cells

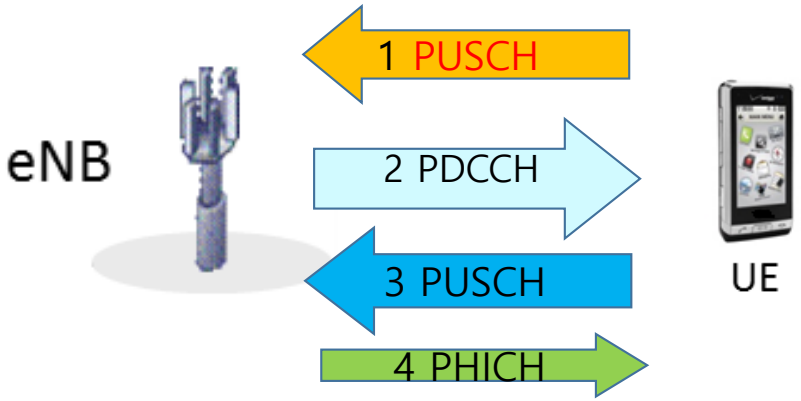
LTE UL Scheduling – w/o Resource

- 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



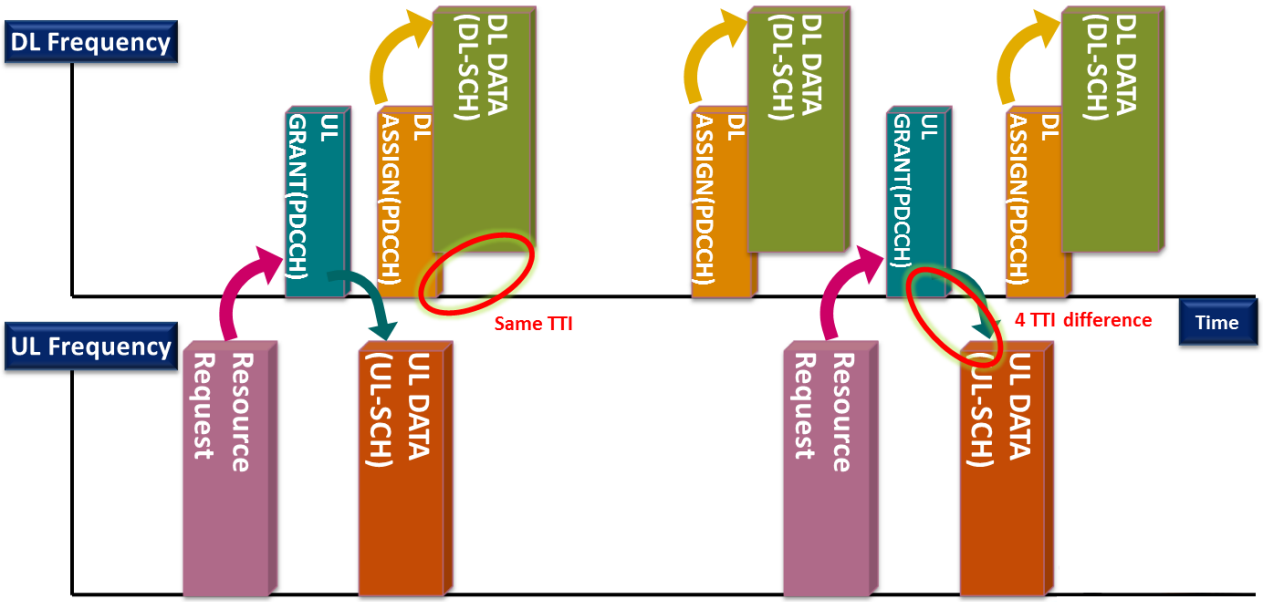
LTE UL Scheduling – Modifying Resource

- 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
- 3. Based on the adjusted grant, UE sends user data on PUSCH
- 4. If eNB decodes the uplink data successfully, it sends ACK on PHICH



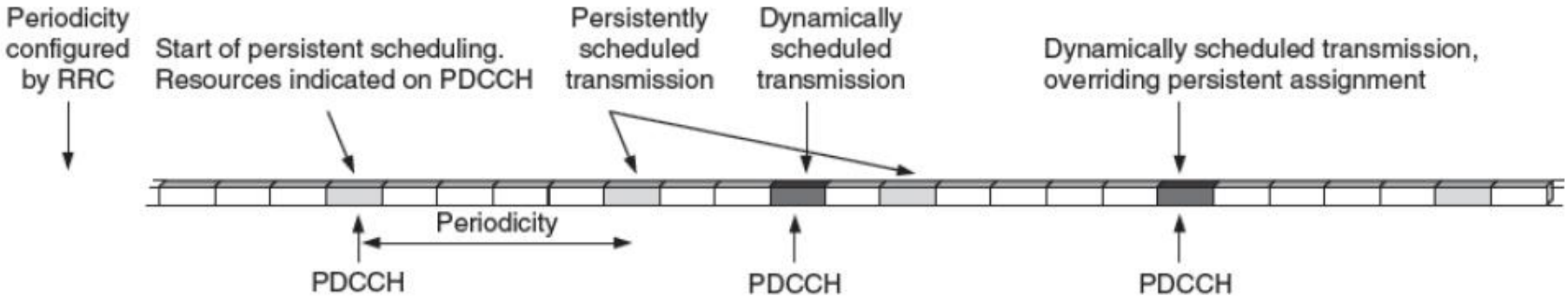
Dynamic vs. Semi-Persistent Scheduling

- Dynamic scheduling
  - PDCCH oriented
  - eNB in each 1 ms TTI sends scheduling information to the selected set of UEs, controlling the uplink and downlink transmission activity



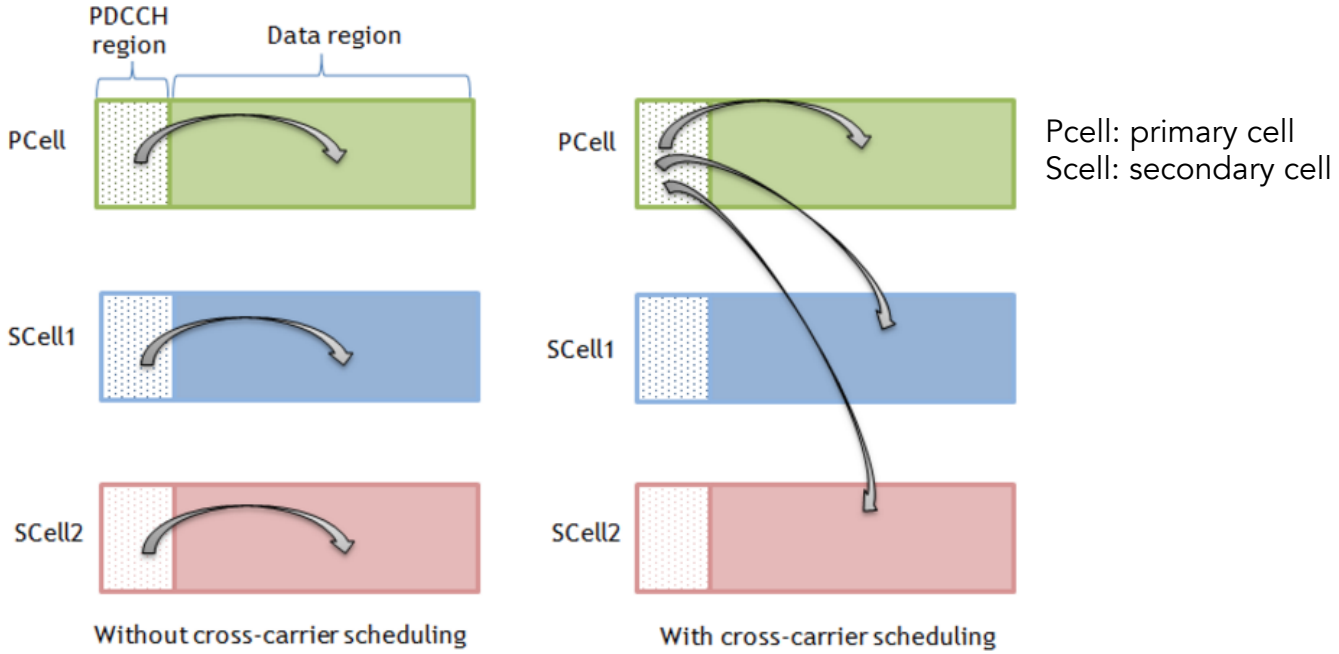
Dynamic vs. Semi-Persistent Scheduling

- Semi-persistent scheduling
  - With semi-persistent scheduling, UE is provided with the scheduling every n-th subframe until further notice.
  - For example, for VoIP, the scheduler can configure a periodicity of 20 ms
  - In case a dynamic scheduling command is detected, it takes **precedence** (priority) over the semi-persistent scheduling in that particular subframe



Cross-Carrier Scheduling

- Scheduling across multiple CCs with CA
- Cross-carrier scheduling strength
  - Simplify to decode PDCCH
  - Minimize ICI (inter-cell interference) in Heterogeneous Network (HetNet)
    - HetNet indicates the use of multiple types of access nodes (e.g., macrocells, picocells, and femtocells) in a wireless network.

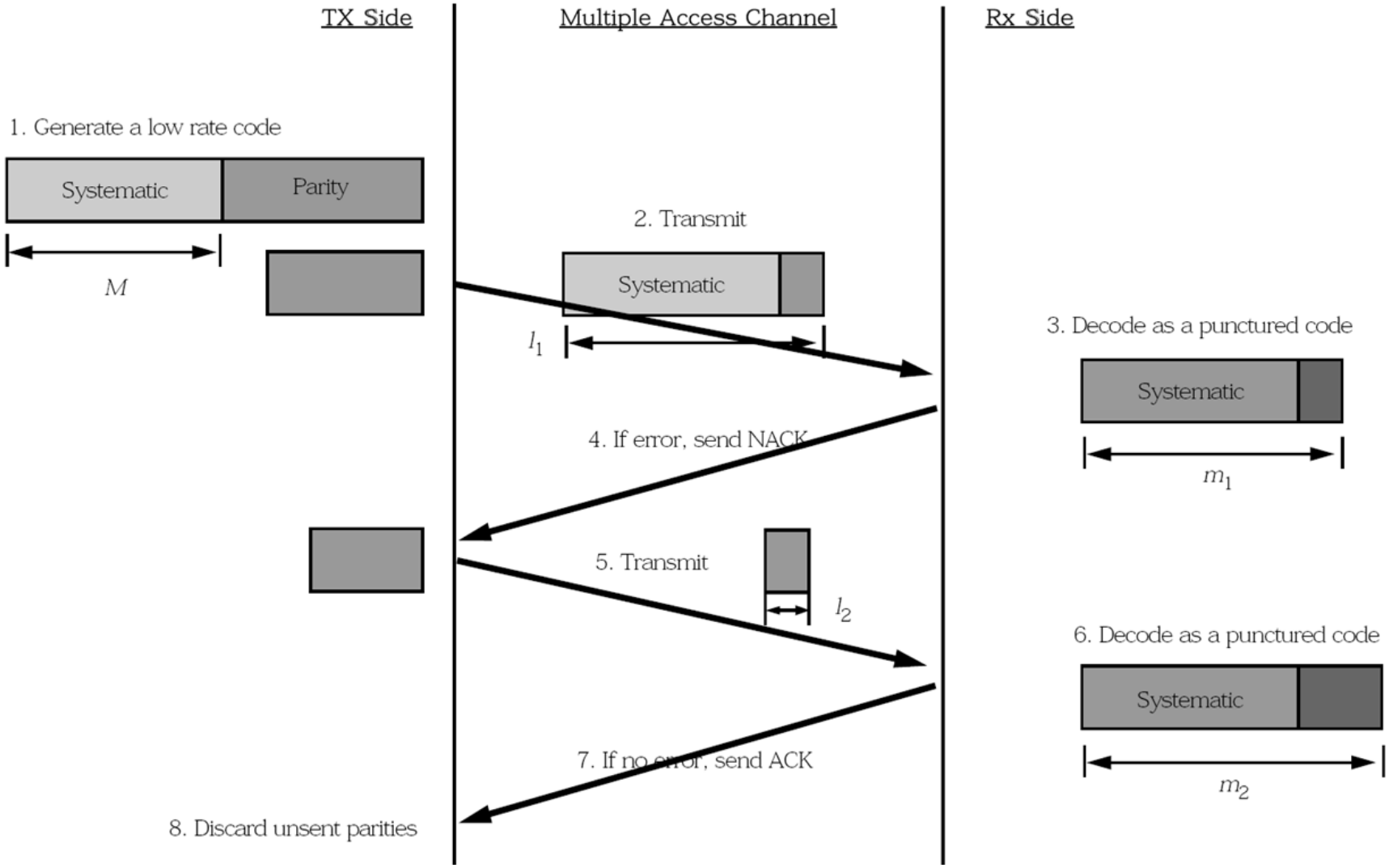


Hybrid ARQ (HARQ)

- CC (Chase Combining) HARQ
  - Retransmit the same information with original transmission
  - Combine the original and retransmitted version in soft state (i.e., before decoding)
  - Obtain SINR gain via MRC (Maximum Ratio Combining)

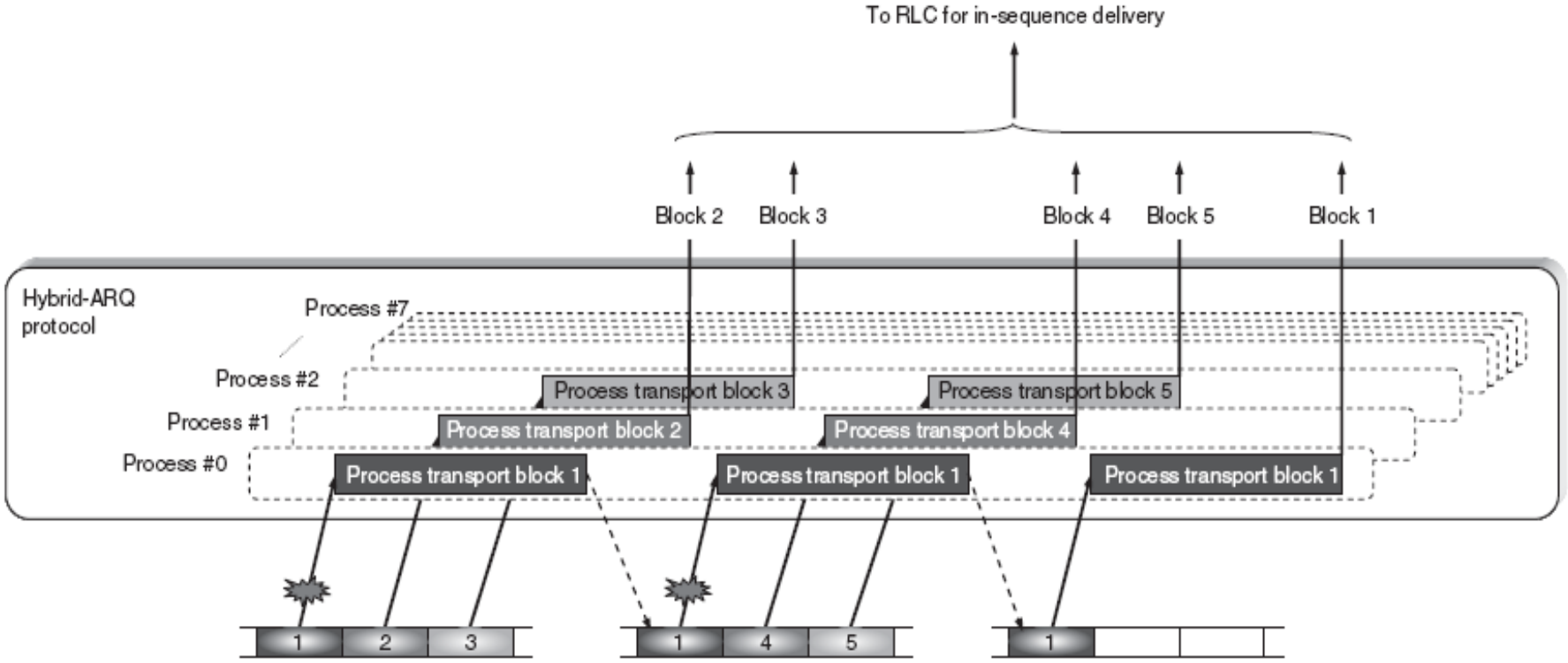
- IR (Incremental Redundancy) HARQ
  - Using rate compatible punctured code, e.g., RCPC (Rate Compatible Punctured Convolutional), RCPT (Rate Compatible Punctured Turbo) codes
  - Retransmit only a part of redundancy bits, not information bits
  - Obtain time diversity similar to chase combining, and additional coding gain

Example of IR ARQ



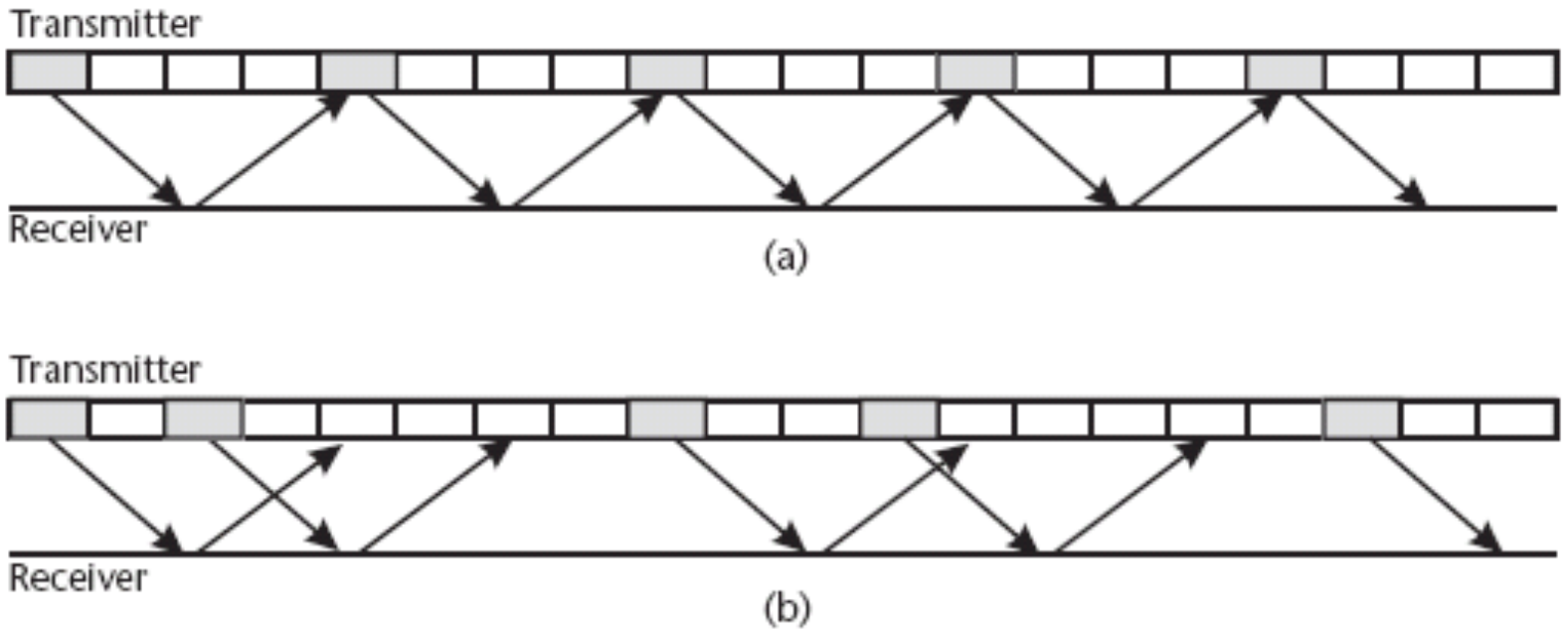
HARQ Overview

- HARQ is only supported for DL-SCH and UL-SCH
- Multiple (up to 8) parallel stop-and-wait processes
- Up to 4 (re)transmissions per packet



Synchronous vs. Asynchronous HARQ

- Illustration of timing for HARQ:
  - (a) SHARQ (synchronous)
  - (b) AHARQ (asynchronous)



DL HARQ

- Asynchronous protocol
  - DL retransmission may occur at any time after the initial transmission
- Adaptive protocol
  - The frequency location and possibly the more detailed transmission format can be changed between transmissions
- Synchronous ACK/NACK
  - A fixed timing relationship (n+4) between “the time at which a DL packet is transmitted” and “the time when the ACK/NACK from the UE is sent”

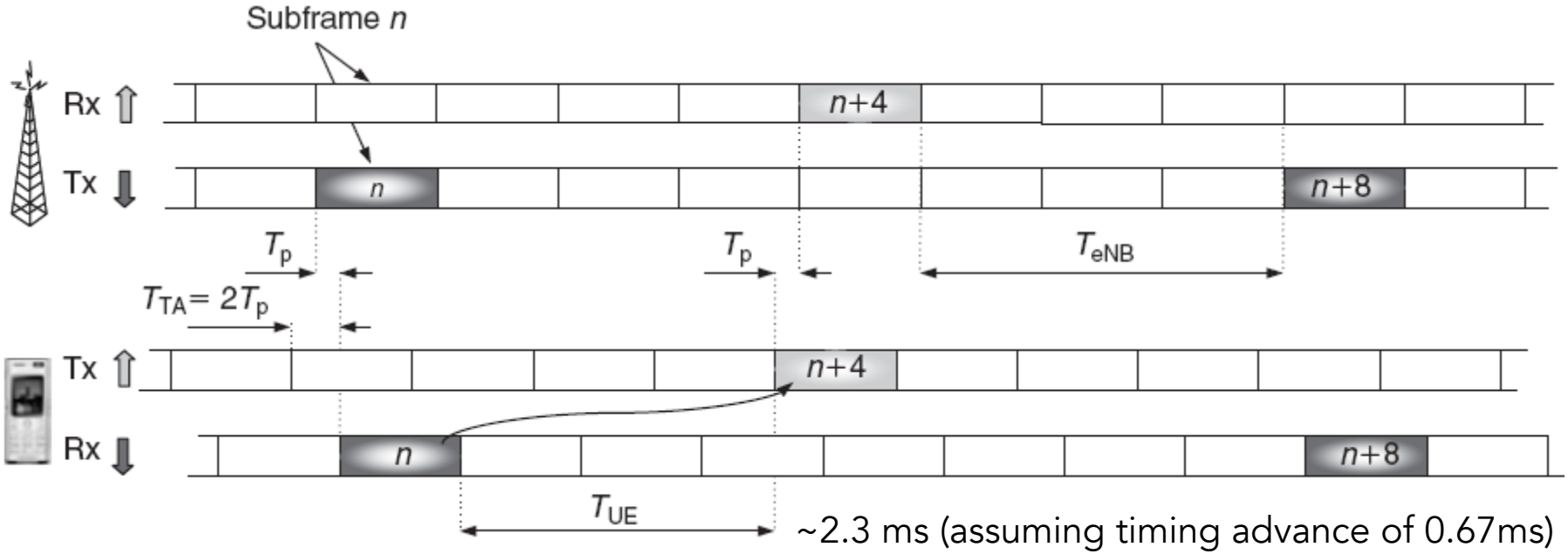
UL HARQ

- Synchronous protocol
  - Retransmission occurs at a pre-defined time after the initial transmission
- 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

HARQ Timing

- Downlink data in subframe n and uplink HARQ ACK in subframe n+4 for FDD as shown in the figure below
- Upon reception of HARQ ACK, eNB can, if needed, retransmit the downlink data in subframe n+8

  → HARQ round-trip time is 8 ms (typical, but can vary)



UE Power Control

- Total transmit power setting (in dBm)

$$\text{UE transmit power} = \underbrace{P_0 + \alpha \cdot \text{PL}}_{\substack{\text{basic open-loop} \\ \text{operating point}}} + \underbrace{\Delta_{\text{TF}} + f(\Delta_{\text{TPC}})}_{\text{dynamic offset}} + \underbrace{10 \log_{10} M}_{\text{bandwidth factor}}$$

  - Range: [-41, 23] dBm

- Basic open-loop operating point
  - P : target received power (base level) 0
    PL: path-loss estimate
    α: path-loss compensation factor (0 ~ 1)
  - The fractional path-loss compensation factor can be seen as a tool to trade off the cell-edge data rate against the total uplink capacity (~inter-cell interference)

UE Power Control

- Bandwidth factor
  - M: the number of allocated RBs
- Dynamic offset
  - A component dependent on the MCS: Δ_{TF} (can be set to 0)
  - Practical limitation of the system and receiver (**BPRE**: Bits Per RE)

$$\Delta_{\mathrm{TF}} = 10\log(2^{k\cdot \mathrm{BPRE}} - 1)\cdot \beta_{\mathrm{offset}}$$

  - Explicit Transmitter Power Control (TPC) commands: $f(\Delta_{TPC})$
    - Signaled via PDCCH
    - Accumulative TPC commands {−1, +1} dB or {−1, 0, +1, +3} dB
    - Absolute TPC commands {−4, −1, +1, +4} dB

RLC Functions

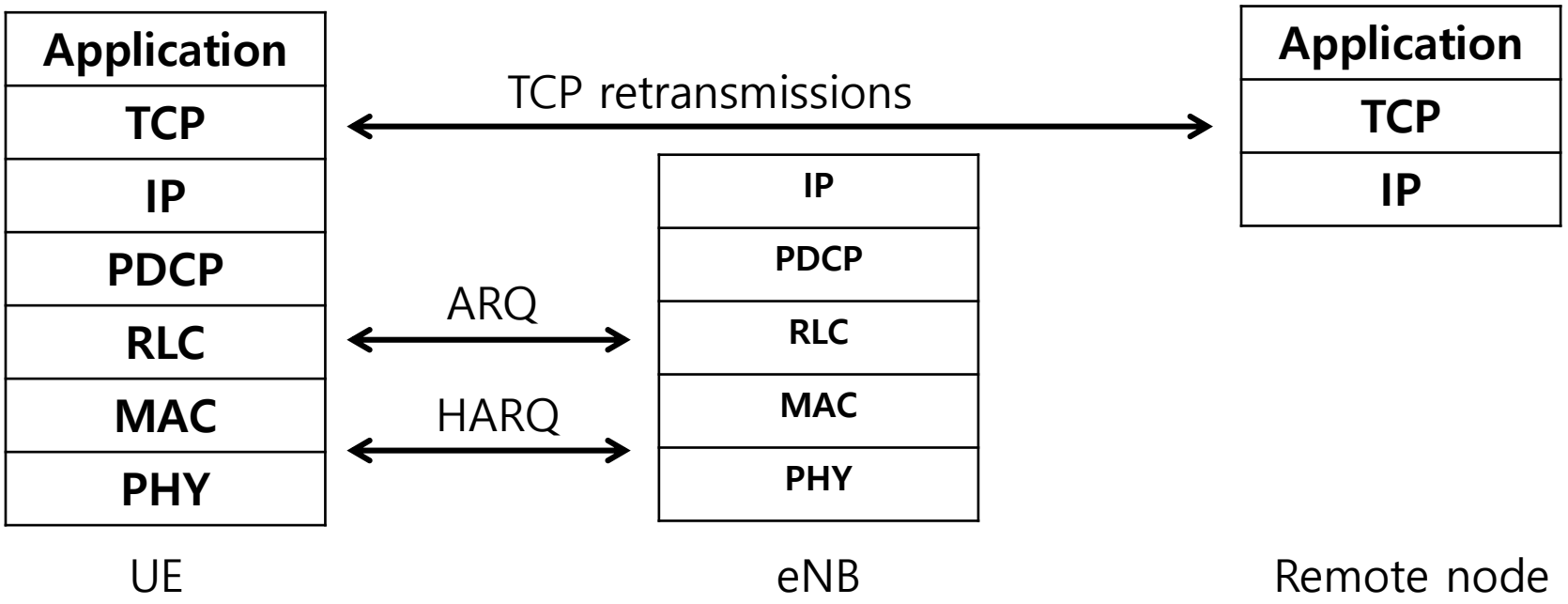
- Transfer of upper layer PDUs
  - Signaling Radio Bearer (SRB) from RRC
  - Radio Bearer (RB) from PDCP
- Error correction through ARQ
- Concatenation, segmentation, and reassembly of SDUs
- Re-segmentation of RLC PDUs
- In-sequence delivery of upper layer PDUs
- Duplicate detection
- Protocol error 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
  - Used for broadcast channels such as BCCH, CCCH, and PCCH, where the information should reach multiple users
- Unacknowledged mode (UM)
  - Supports segmentation/reassembly and in-sequence delivery, but not retransmissions
  - Used when error free delivery is not required
  - e.g., for MCCH and MTCH using MBSFN and for VoIP
- **Acknowledged mode (AM)**
  - Main mode of operation for TCP/IP packet data transmission on DL-SCH
  - **Segmentation/reassembly, in-sequence delivery and retransmissions of erroneous data are all supported**

Retransmission in LTE

- MAC HARQ: up to 4 (re)transmissions per packet
- RLC ARQ allows more retransmissions and in-sequence delivery



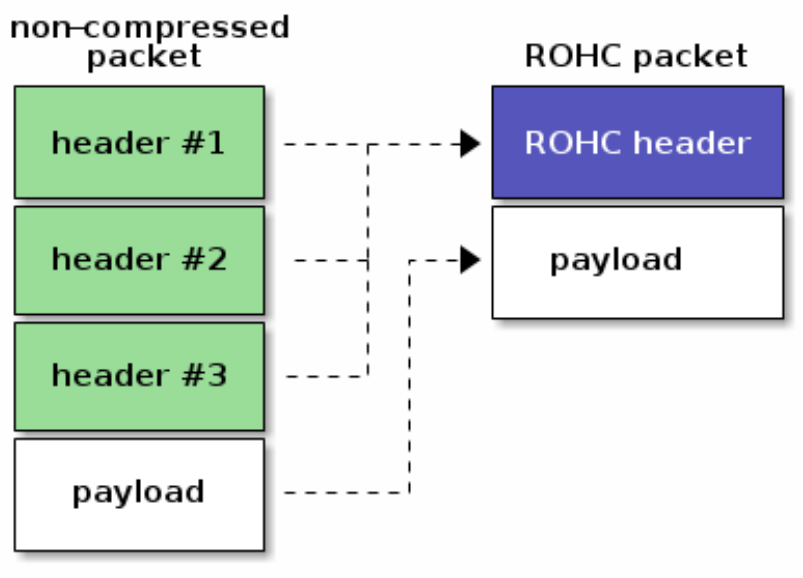
PDCP Functions

- Transfer of User Plane and Control Plane data to and from upper layers
- Security functions, e.g., ciphering for User and Control Plane bearers and integrity protection for Control Plane bearers
- Header compression services via Robust Header Compression (ROHC) to improve the efficiency of over the air transmissions

- In-order delivery of packets and duplicate detection services to upper layers after handovers
  - After handover, source eNB transfers unacknowledged packets to target eNB when operating in RLC AM
  - Target eNB forwards packets from source eNB to UE

Robust Header Compression (ROHC)

- It aims at reducing bandwidth usage on network links with limited capacity
- It defines a lossless compression scheme for network headers
- The ROHC protocol can compress IPv4, IPv6, UDP, UDP-Lite, ESP, RTP, and TCP headers

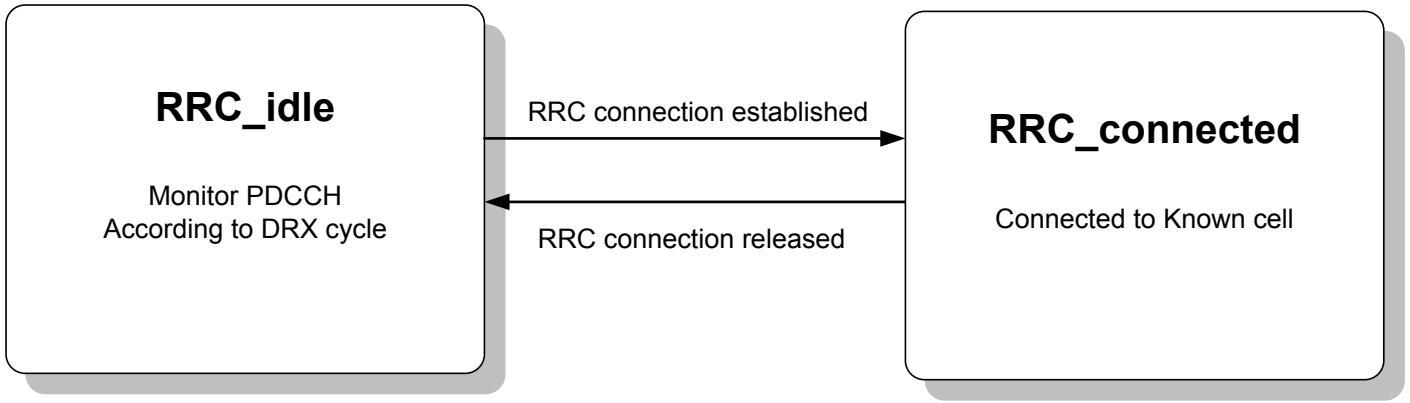


RRC Functions

- Broadcast of system information (eNB)
- Including NAS common interface
- Paging (eNB)
- Establishment/Release of RRC connection between UE and E-UTRAN
  - Connection Management (eNB)
  - Handover (UE)
  - UE cell selection and reselection
  - UE measurement reporting

RRC State Transition

- RRC-Idle
  - Monitors a paging channel to detect incoming traffic
  - Performs neighboring cell measurements and cell (re)selection
- RRC-Connected
  - Transfer of unicast data to/from UE
  - Network controlled mobility such as Handover
  - Performs neighboring cell measurements and reporting
  - Provides channel quality and feedback information



RRC_Idle

- PLMN (Public Land Mobile Network) selection
- DRX configured by NAS
- Broadcast of system information
- Paging
- Cell re-selection mobility
- UE shall have been allocated an ID which uniquely identifies the UE in a tracking area
- No RRC context stored in eNB

RRC_Connected

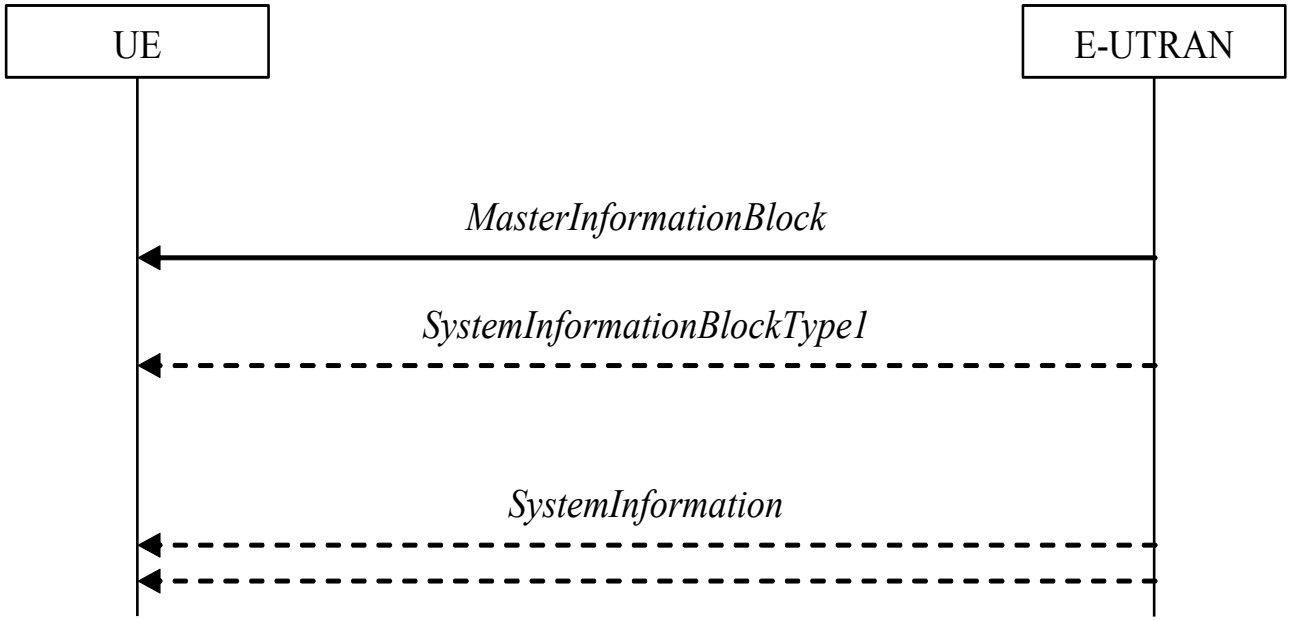
- UE has an E-UTRAN-RRC connection and context in E-UTRAN
  - Network can transmit and/or receive data to/from UE
  - UE monitors control signaling channel
- UE also reports channel quality information and feedback information to eNB
  - Neighbor cell measurements
- DRX period can be configured according to UE activity level for UE power saving and efficient resource utilization

System Information

- MIB (Master Information Block) defines the most essential physical layer information of the cell required to receive further system information
  - Cell bandwidth, SFN (System Frame Number), etc.
- SIB1 (System Information Block) contains information relevant when evaluating if a UE is allowed to access a cell and defines the scheduling of other system information blocks
  - PLMN-Identitylist, TrackingAreaCode, SIB-MappingInfo, etc.
- SIB2 contains common and shared channel information
  - RACH configuration, PUSCH configuration, PCCH configuration, SRS configuration, PDSCH configuration, UE timers, etc.

System Information

- System information acquisition procedure to acquire system information that is broadcasted by the E-UTRAN
- The procedure applies to UEs in both RRC-Idle and in RRC-Connected

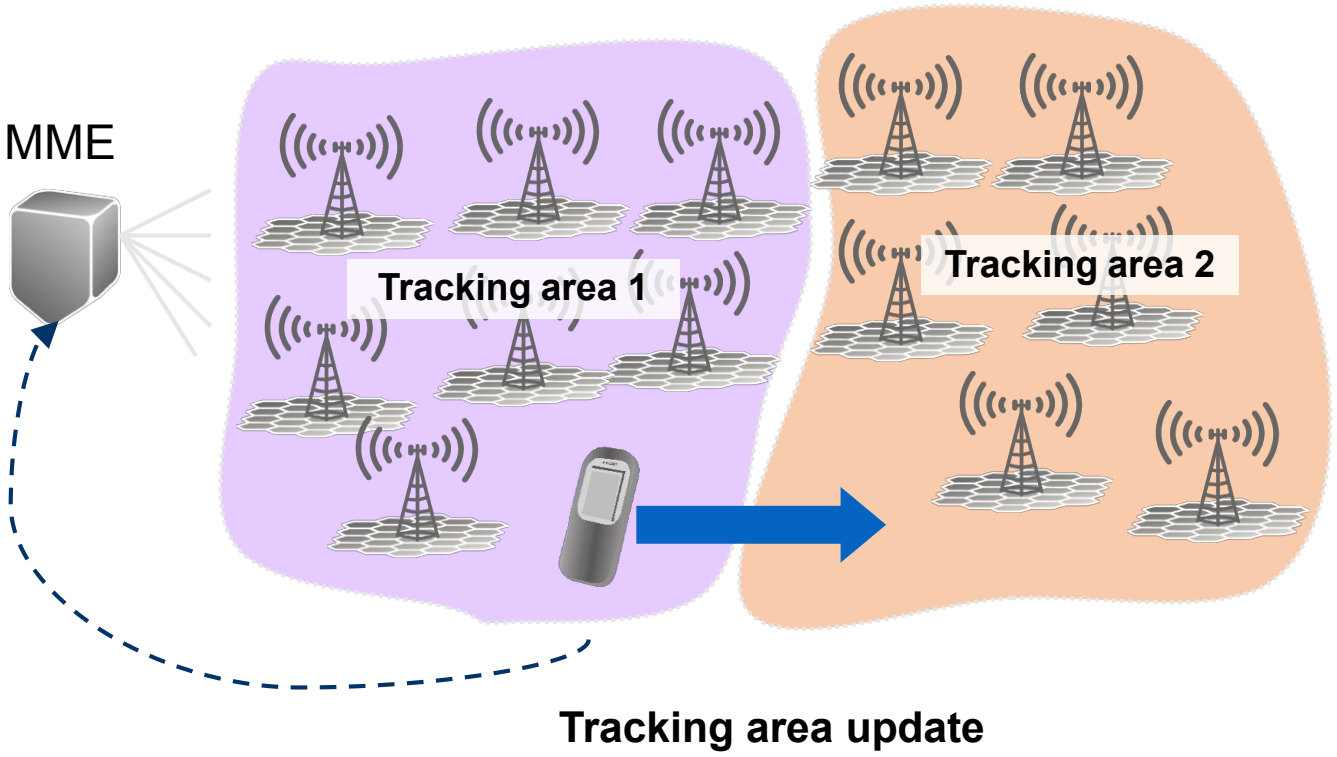


Paging

- The purpose of paging procedure
  - To transmit paging information to a UE in RRC-Idle
  - To inform UEs in RRC-Idle and UEs in RRC-Connected about a system information change
  - To inform UEs in RRC-Idle of incoming traffic
  - To inform UEs in RRC-Idle and RRC-Connected of incoming warning messages

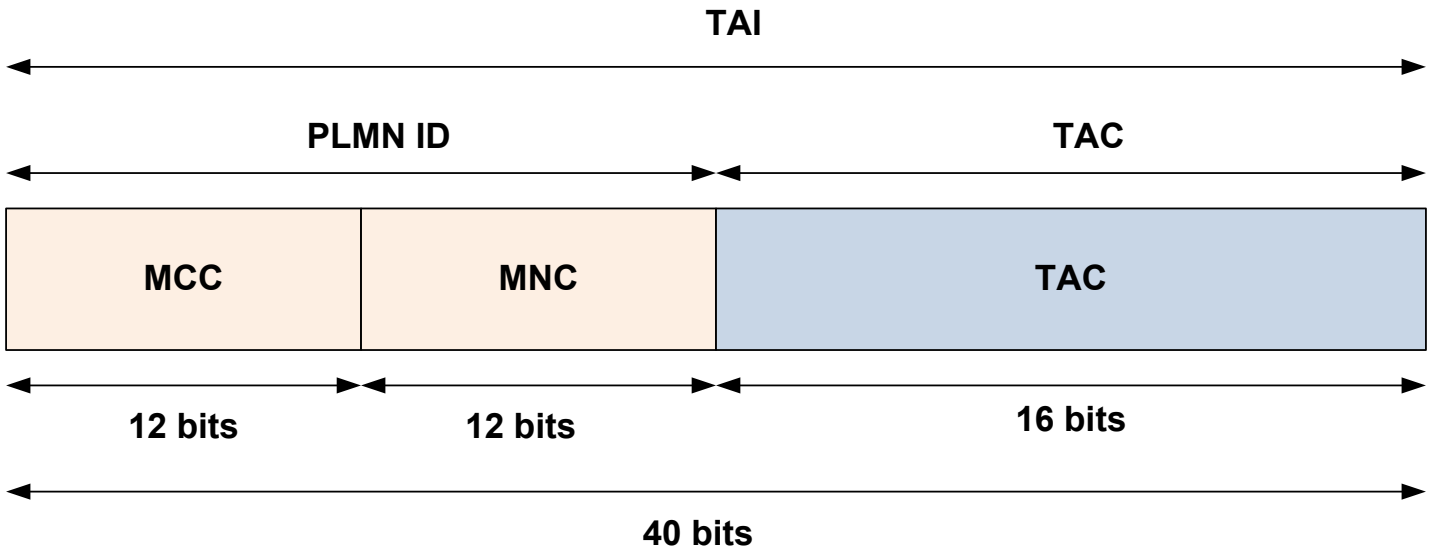
LTE Tracking Area

- When UE is in RRC-Idle, MME knows UE location with Tracking Area accuracy



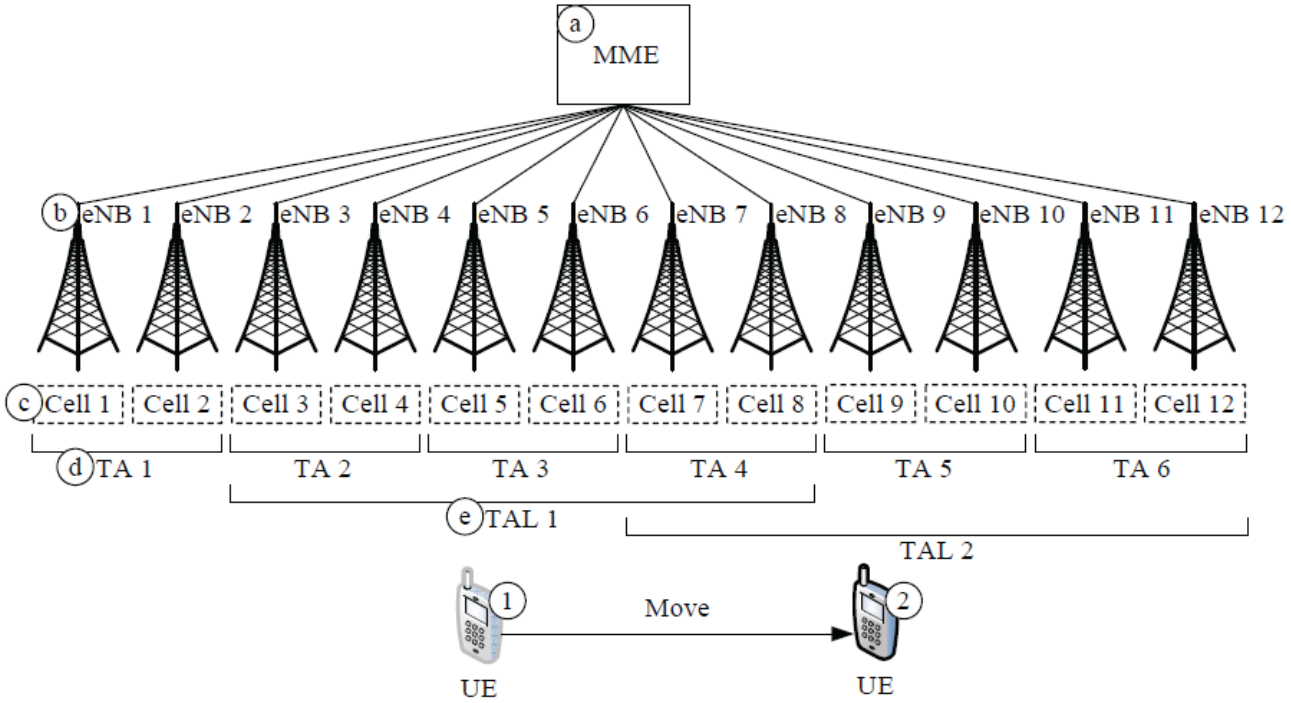
Tracking Area Identity (TAI)

- MCC (Mobile Country Code): defined in ITU E.212 ("Land Mobile Numbering Plan") for use in identifying mobile stations in wireless telephone networks, particularly GSM and UMTS networks (e.g., Korea 450)
- MNC (Mobile Network Code): identify a mobile phone operator/carrier using the GSM/LTE, CDMA, UMTS (e.g., KT 02, SKT 11, LGU 06)
- TAC (Tracking Area Code): is used to uniquely identify a Tracking Area



Paging

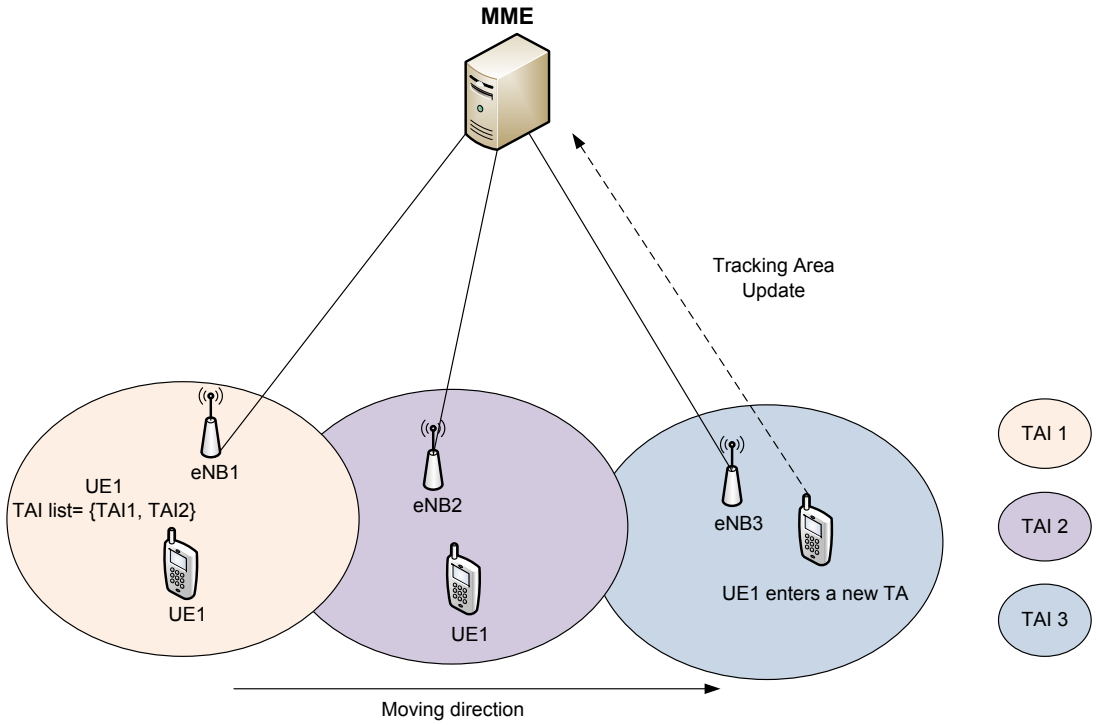
- Cells are grouped into Tracking Areas
- TAI (Tracking Area Identity) is used to uniquely identify a Tracking Area
- TAs are further grouped into TAI list (TAL)



LTE Mobility Management Architecture

Tracking Area Update

- Tracking Area is a logical concept of an area where a UE can move around without location update
- UE detects it has entered a new TA that is not in the list of TAIs, then the UE triggers Tracking Area update to the network (as it does for mobile IP)

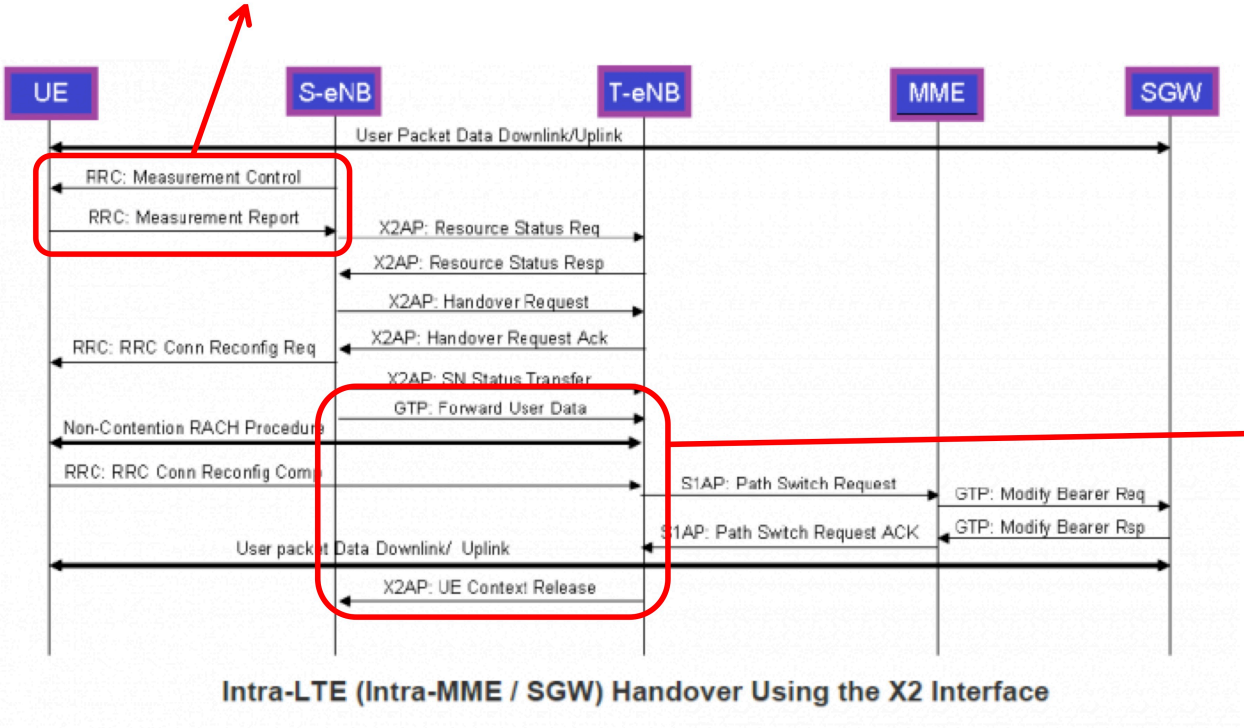


Handover (HO)

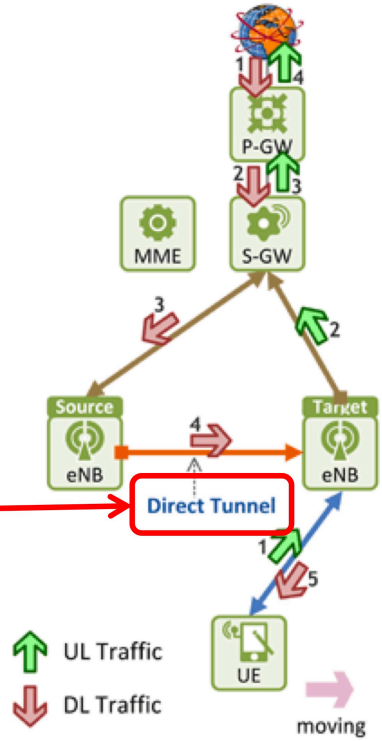
- UE-assisted network-controlled HO in RRC-Connected state
  - With HO preparation signaling in E-UTRAN
  - Part of HO command comes from target eNB and is transparently forwarded to UE by source eNB
  - To prepare HO, source eNB passes all necessary information to target eNB (e.g., RRC context)
- UE accesses target cell via RACH
  - Contention-free procedure using a dedicated RACH preamble
  - Contention-based procedure if dedicated RACH preambles are not available

Intra-LTE Handover via X2 Interface

- UE to send a Measurement Report upon triggering event (e.g., when a neighboring cell's signal strength becomes higher than that of the serving cell)



Intra-LTE (Intra-MME / SGW) Handover Using the X2 Interface

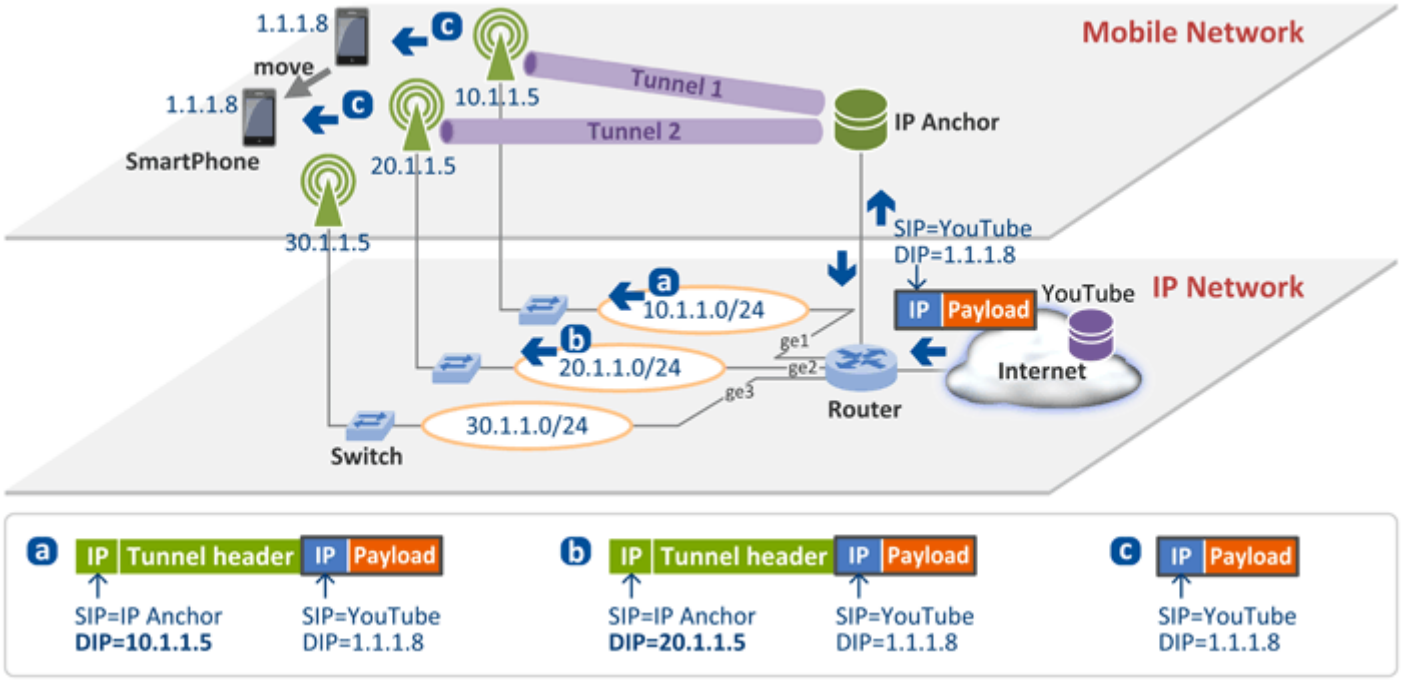


Data Forwarding via Direct Tunnel over X2 Interface during HO

Source: http://tech.queryhome.com/47283/handovers-in-lte-part-1
http://www.netmanias.com/ko/post/blog/5423/lte-handover-x2-handover-s1-handover/lte-x2-based-handover-s1-based-handover

Tunneling after Handover

- UE can continue to use the same IP address after handover by switching to a new tunnel



GTP after Handover

- When UE is mobile, the IP address remains same and packets are still forwarded since tunneling is provided between PGW and eNB via SGW
- GTP tunnel between S-GW and eNB is switched during handover
- GTP tunnel between S-GW and P-GW is able to remain the same