# Introduction to Long-Term Evolution (LTE)

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# Outline

- Evolution for 3G
- Long Term Evolution (LTE)
  - Architecture, Protocol Stack, and Functionality
- Introduction to E-UTRAN
  - Protocol Stack, and Functionality
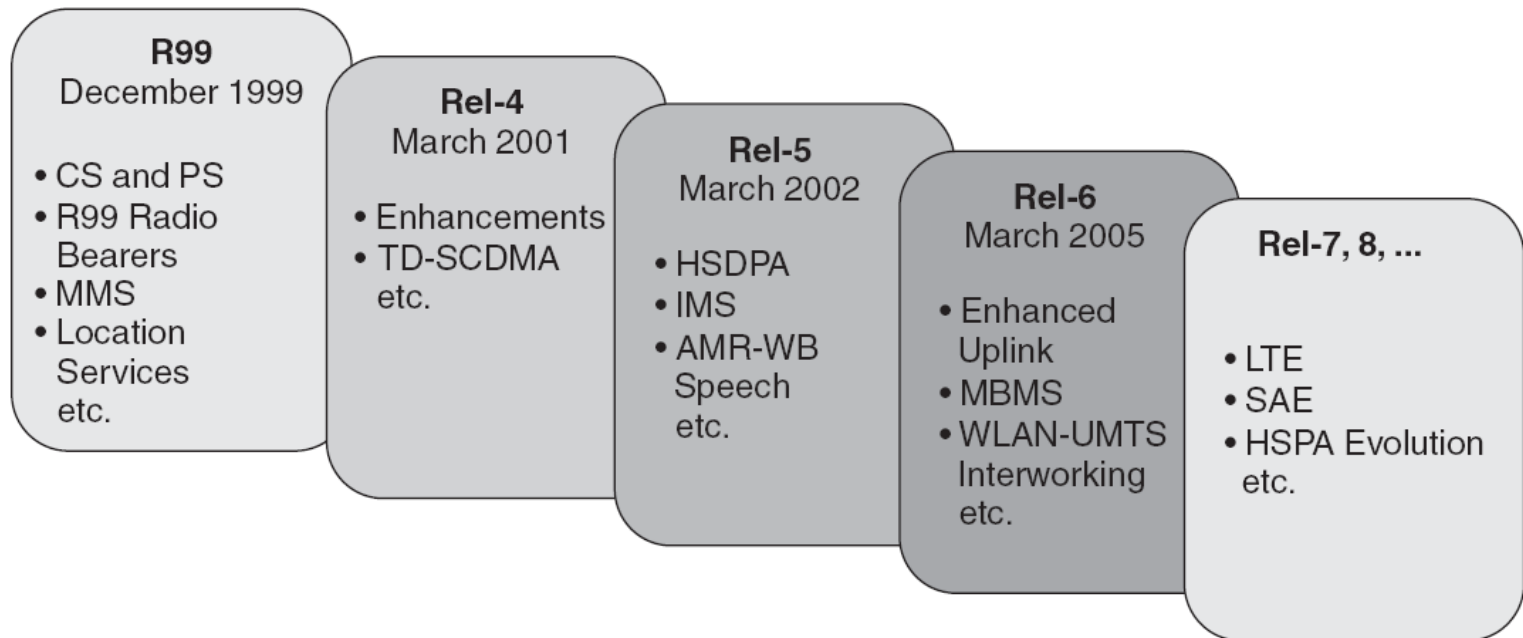
# Evolution for 3G
## Spectrum

- International Telecommunication Union (ITU)
  - Identified the frequencies around 2GHz for International Mobile Telephony 2000 (IMT 2000)
- IMT 2000 spectrum allocation at 2GHz
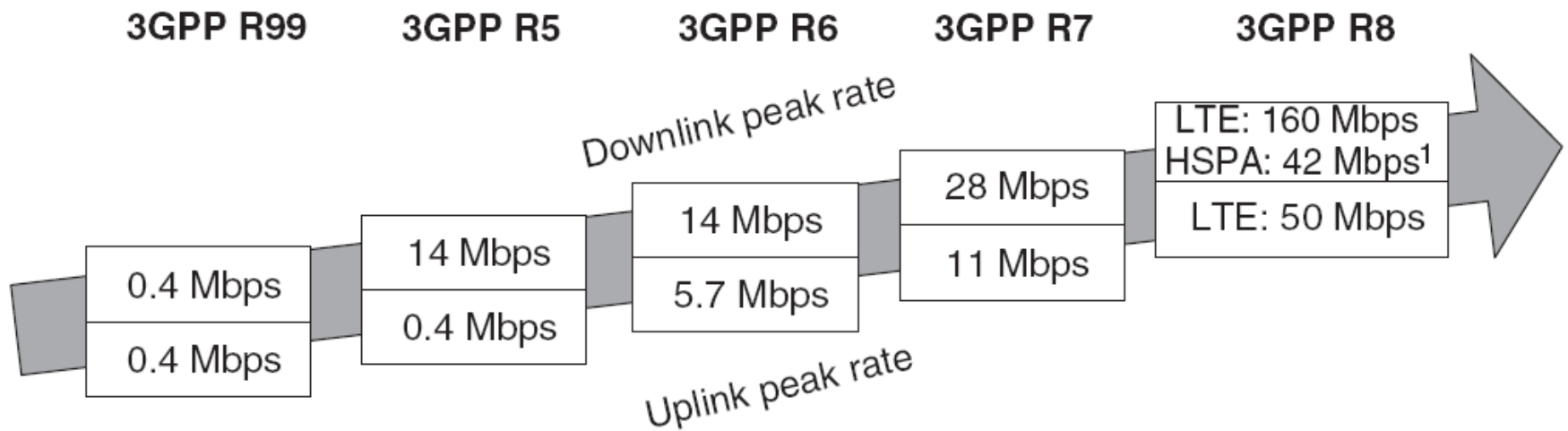  - LTE, WCDMA
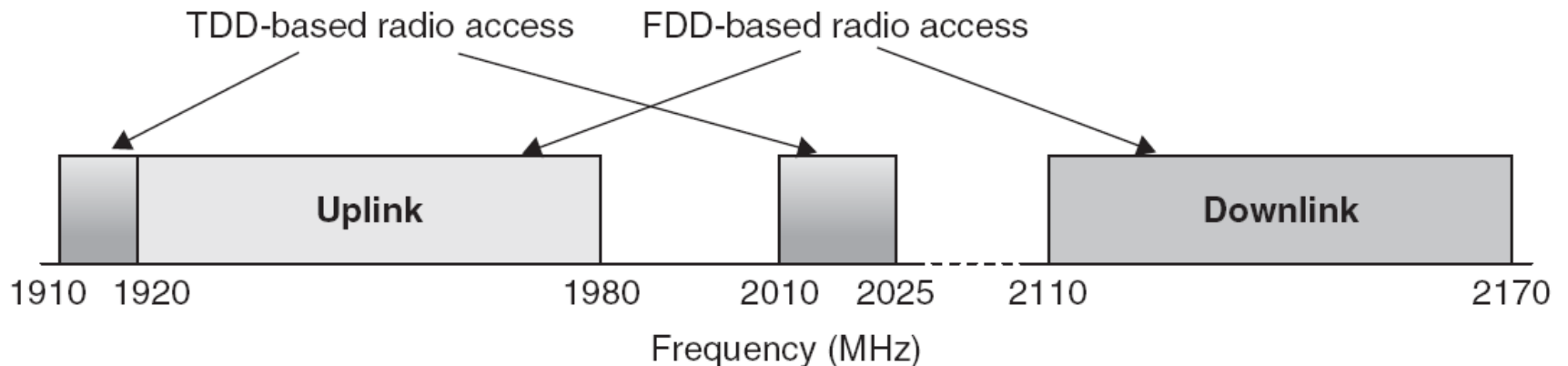
# Evolution for 3G
## Standardization

- Air Interface
  - UTRA-UTRAN Long Term Evolution (LTE) Study Item (TSG-RAN)
- Network Architecture
  - System Architecture Evolution (SAE) Study Item (TSG-SA)

**R99**
December 1999
- CS and PS
- R99 Radio Bearers
- MMS
- Location Services etc.

**Rel-4**
March 2001
- Enhancements
- TD-SCDMA etc.

**Rel-5**
March 2002
- HSDPA
- IMS
- AMR-WB Speech etc.

**Rel-6**
March 2005
- Enhanced Uplink
- MBMS
- WLAN-UMTS Interworking etc.

**Rel-7, 8, ...**
- LTE
- SAE
- HSPA Evolution etc.

# Evolution for 3G
## Peak Data Rate

| | 3GPP R99 | 3GPP R5 | 3GPP R6 | 3GPP R7 | 3GPP R8 |
|---|---|---|---|---|---|

Downlink peak rate

| | | | LTE: 160 Mbps |
|---|---|---|---|
| | | 28 Mbps | HSPA: 42 Mbps[1] |
| | 14 Mbps | 11 Mbps | LTE: 50 Mbps |
| | 5.7 Mbps | | |
| 14 Mbps | | | |
| 0.4 Mbps | | | |
| 0.4 Mbps | | | |

Uplink peak rate

[1]Assuming 2 × 2 MIMO together with 64QAM

# Requirements of LTE

- Objective:
  - To develop a framework for the evolution of the 3GPP radio-access technology towards a high-data-rate, low-latency and packet-optimized radio-access technology

| Metric | Requirement |
|---|---|
| Peak data rate | DL: 100Mbps (3 to 4 times to that of HSDPA)<br>UL: 50Mbps (2 to 3 times to that of HSUPA) |
| Mobility support | Up to 500kmph but optimized for low speeds from 0 to 15kmph |
| Control plane latency (Transition time to active state) | < 100ms (for idle to active) |
| User plane latency | < 5ms |
| Control plane capacity | > 200 users per cell |
| Coverage (Cell sizes) | 5 – 100km with slight degradation after 30km |
| Spectrum flexibility | 1.25, 2.5, 5, 10, 15, and 20MHz |

# LTE

Architecture and Protocol Stack

# EPS Architecture (1/2)
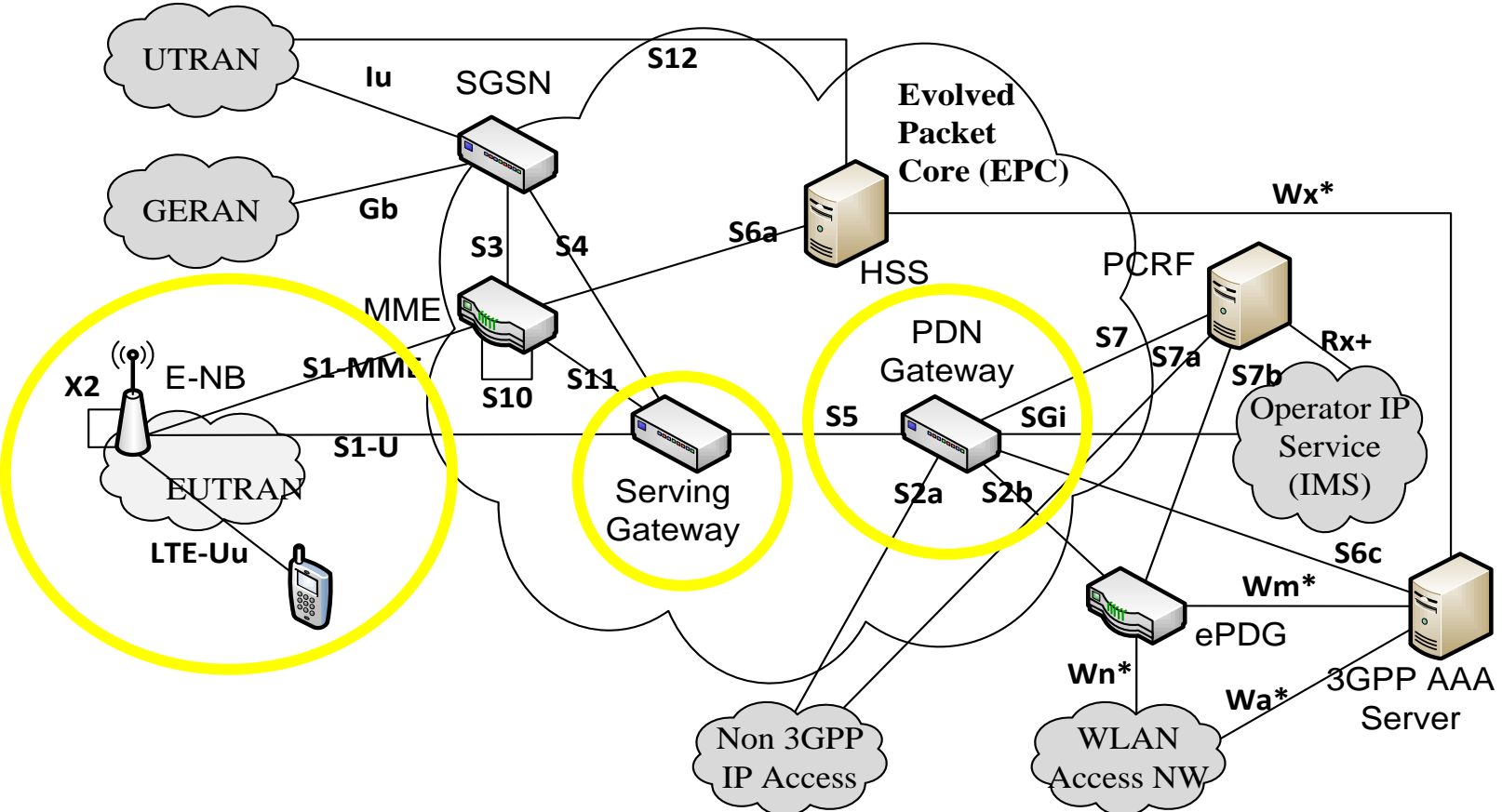


- Evolved Packet System (EPS) Architecture
  - EPS consists of LTE (Long Term Evolution), which is dedicated to the evolution of the radio interface, and SAE (System Architecture Evolution), which focuses on Core Network architecture evolution.
  - LTE → E-UTRAN
  - SAE → EPC (Evolved Packet Core)

# EPS Architecture (2/2)
## Functional Entities

- Evolved Radio Access Network (eRAN)
  - Consists of the eNodeB (eNB)
  - Offers Radio Resource Control (RRC) functionality
  - Radio Resource Management, admission control, scheduling, ciphering/deciphering of user and control plane data, and compression/decompression in DL/UL user plane packet headers
- Serving Gateway (SGW)
  - Routes and forwards user data packets
  - Acts as the mobility anchor for the user plane
    - During inter-eNB handovers
    - Between LTE and other 3GPP technologies
  - Pages idle state UE when DL data arrives for the UE
- Packet Data Network Gateway (PDN GW)
  - Provides connectivity to the UE to external packet data networks
  - A UE may have simultaneous connectivity with more than one PDN GW
  - Performs policy enforcement, packet filtering, and charge support
  - Acts as mobility anchor between 3GPP and no-3GPP technologies
- Mobility Management Entity (MME)
  - Manages and stores UE contexts
    - UE/user identities, UE mobility state, user security parameters
  - Paging message distribution
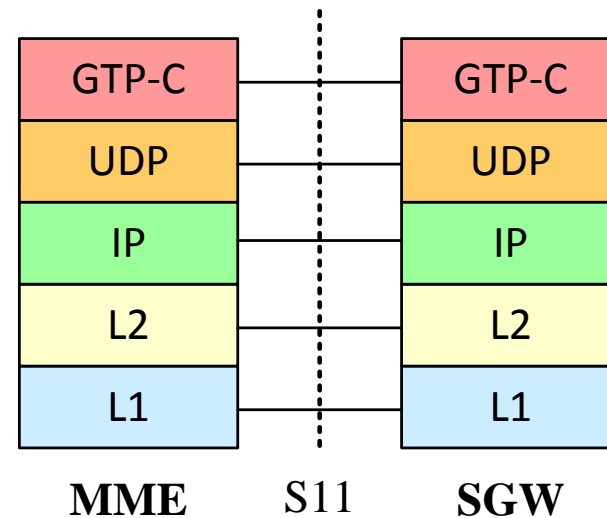
# Protocol Stack & Interface
## Control Plane

- LTE-Uu

- S1-MME
  - Reference point for the control plane protocol between E-UTRAN and MME. It uses Stream Control Transmission Protocol (SCTP) as the transport protocol
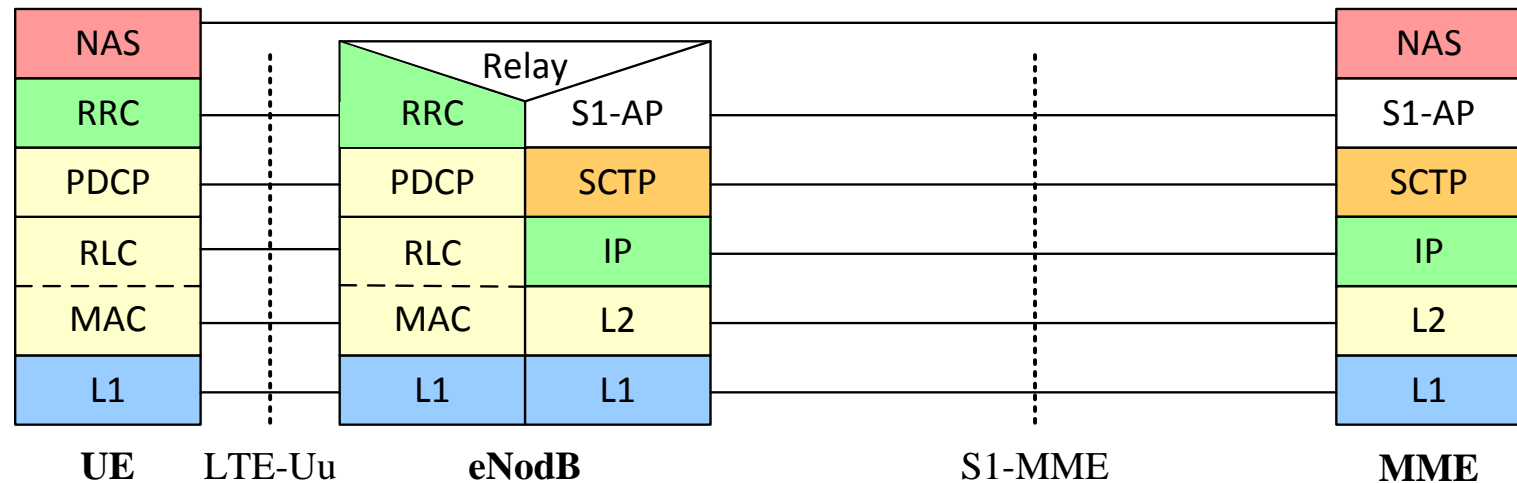
# Protocol Stack & Interface
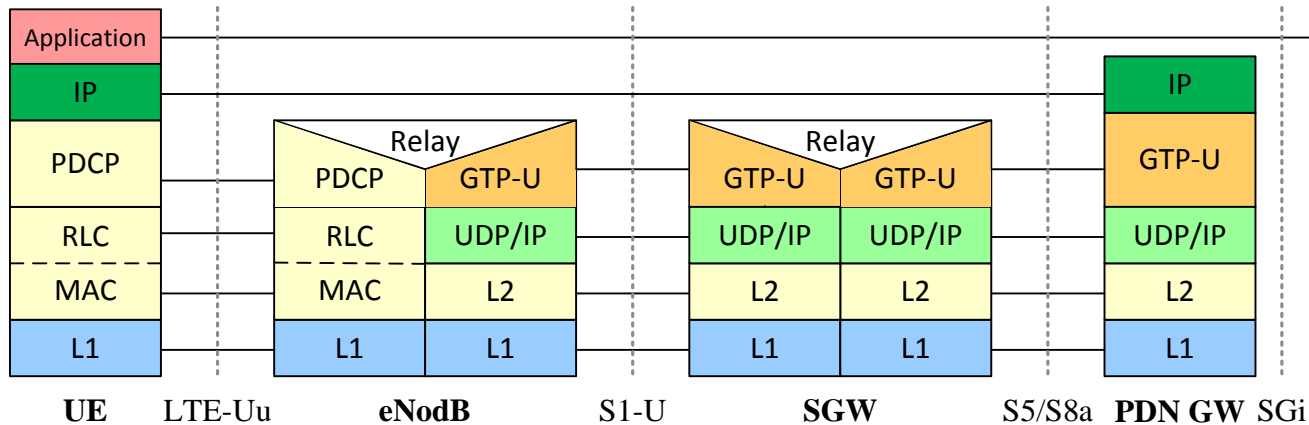## Control Plane

- S11 (MME-SGW)
  - GPRS Tunnelling Protocol for the control plane (GTP-C)
  - Has the same protocol stack as
    - S10 (MME-MME)
    - S5 or S8a (SGW-PGW)
    - S4 (SGSN-SGW)
    - S3 (SGSN-MME)

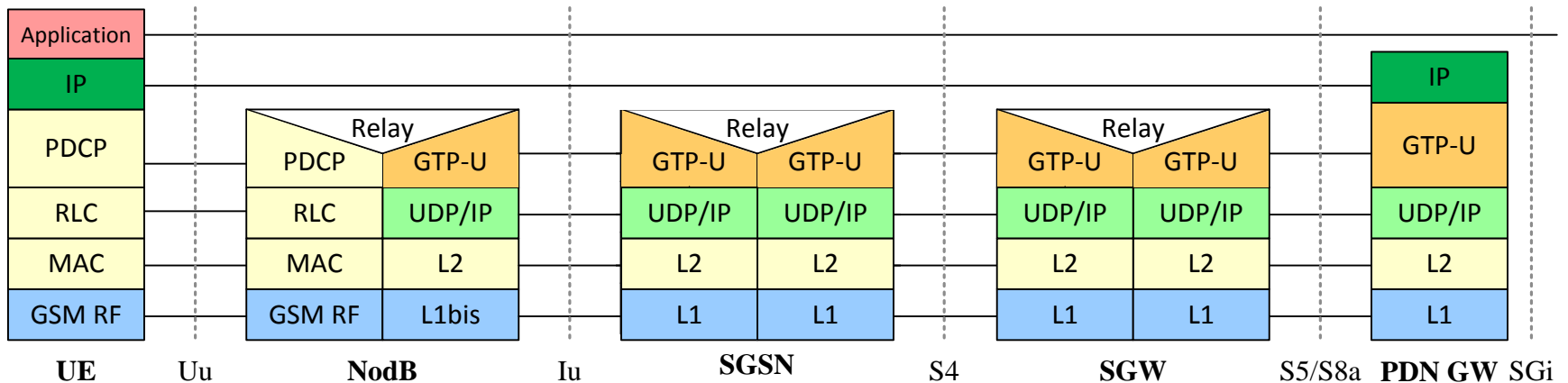| MME | | SGW |
|---|---|---|
| GTP-C | | GTP-C |
| UDP | | UDP |
| IP | | IP |
| L2 | | L2 |
| L1 | | L1 |
| **MME** | S11 | **SGW** |

# Protocol Stack & Interface
## User Plane

- UE - PGW user plane with E-UTRAN
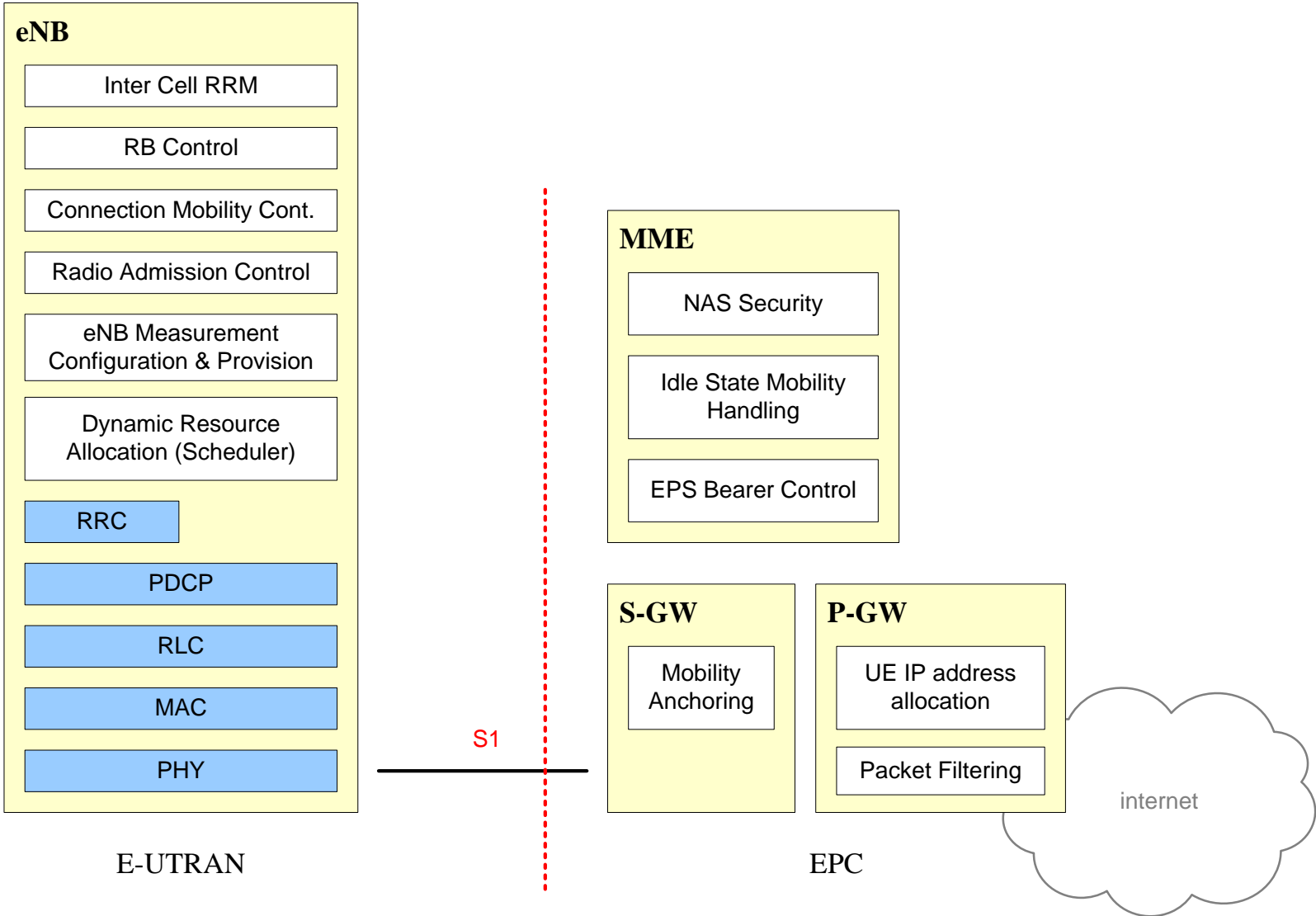


- UE - PGW user plane with 3G access via the S4 interface

# E-UTRAN

Protocol Stack, Functionality

# Protocol for E-UTRAN

## eNB

Inter Cell RRM

RB Control

Connection Mobility Cont.

Radio Admission Control

eNB Measurement Configuration & Provision

Dynamic Resource Allocation (Scheduler)

RRC

PDCP

RLC

MAC

PHY

E-UTRAN

## MME

NAS Security

Idle State Mobility Handling

EPS Bearer Control

## S-GW

Mobility Anchoring

## P-GW

UE IP address allocation

Packet Filtering

S1

internet

EPC

# S1 Interface

- The S1 control plane interface (S1-MME)
  - The SCTP layer provides the guaranteed delivery of application layer messages.
  - The transport network layer is built on IP transport, similarly to the user plane but for the reliable transport of signalling messages SCTP is added on top of IP.
  - The application layer signalling protocol is referred to as S1-AP (S1 Application Protocol).



S1-AP

SCTP

IP

Data link layer

Physical layer
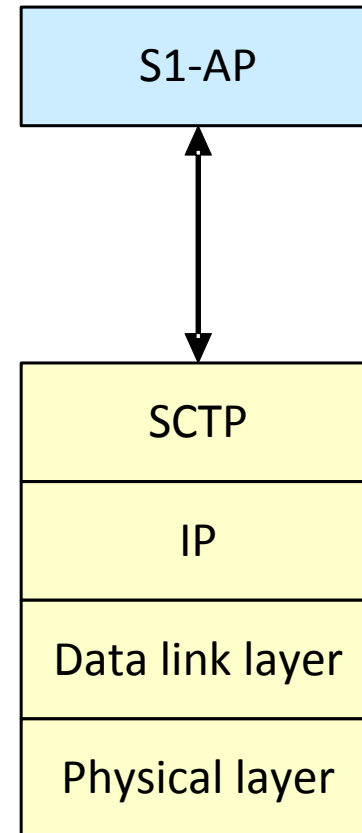
# S1 Interface

- ## S1 User Interface
  - Provides non guaranteed delivery of user plane PDUs between the eNB and the S-GW.
  - The transport network layer is built on IP transport and GTP-U is used on top of UDP/IP to carry the user plane PDUs between the eNB and the S-GW.

| User plane PDUs |
|---|

| GTP-U |
|---|
| UDP |
| IP |
| Data link layer |
| Physical layer |
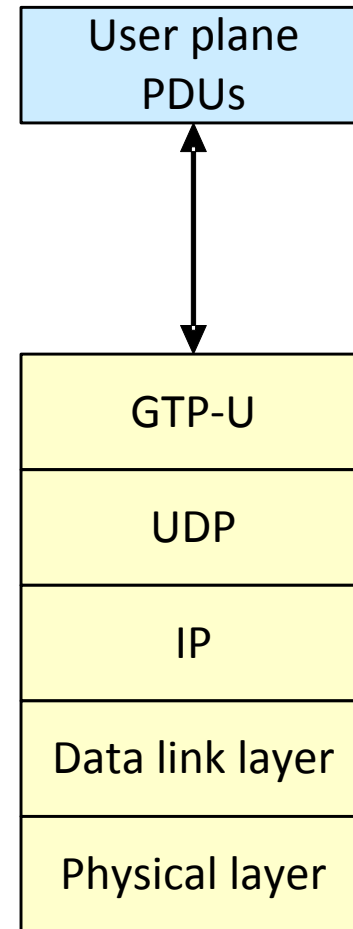
# S1 Interface
## Functions

- EPS Bearer Service Management function:
  - Setup, modify, release.
- Mobility Functions for UEs in EMM-CONNECTED:
  - Intra-LTE Handover
  - Inter-3GPP-RAT Handover.
- S1 Paging function
- NAS Signalling Transport function
- S1-interface management functions
  - Error indication and Reset
- Initial Context Setup Function
  - supports the establishment of the necessary overall initial UE Context in the eNB to enable fast Idle-to-Active transition.
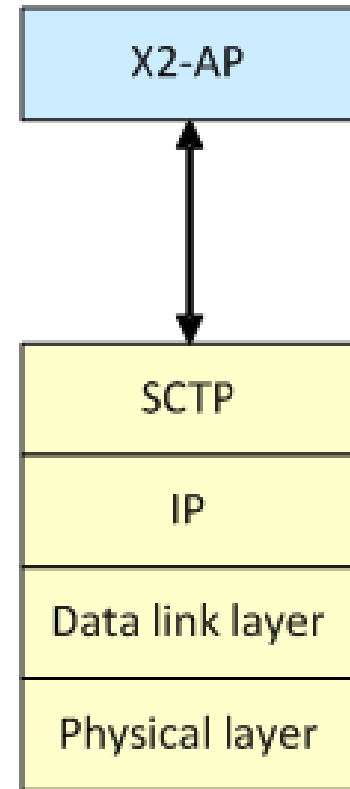
# X2 Interface

- Architecture
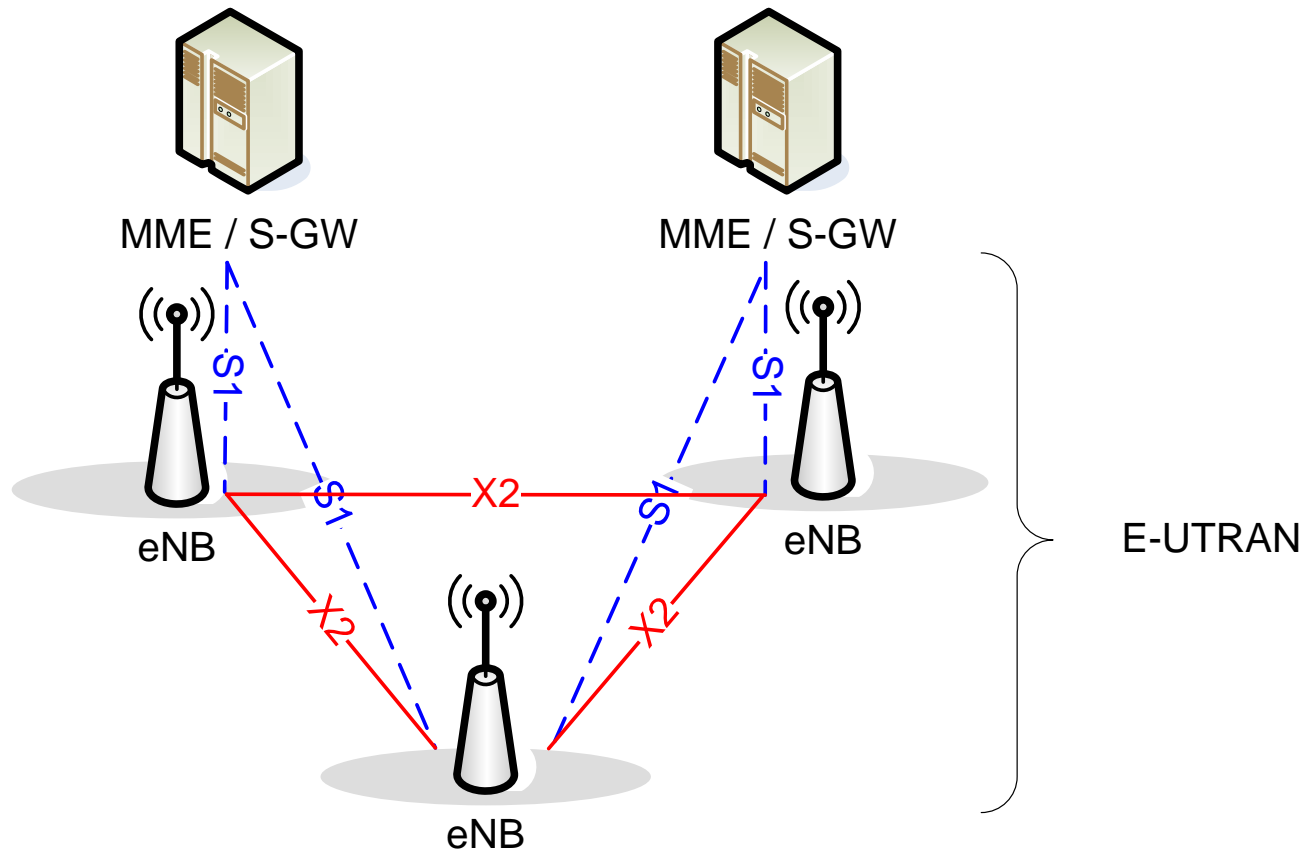
# X2 Interface

- The X2 control plane interface (X2-CP)
  - The transport network layer is built on SCTP on top of IP.
  - The application layer signalling protocol is referred to as X2-AP (X2 Application Protocol).
- Functions
  - Intra LTE-Access-System Mobility Support for UE in EMM-CONNECTED:
    - Context transfer from source eNB to target eNB;
    - Control of user plane tunnels between source eNB and target eNB;
    - Handover cancellation.
  - Uplink Load Management;
  - General X2 management and error handling functions:
    - Error indication.

X2-AP

SCTP

IP

Data link layer

Physical layer

# X2 Interface

- X2 user plane interface (X2-U)
  - The X2-U interface provides non guaranteed delivery of user plane PDUs between eNBs.
  - The transport network layer is built on IP transport and GTP-U is used on top of UDP/IP to carry the user plane PDUs.
- The X2-U interface protocol stack is identical to the S1-U protocol stack.

| User plane PDUs |
|---|

| GTP-U |
|---|
| UDP |
| IP |
| Data link layer |
| Physical layer |
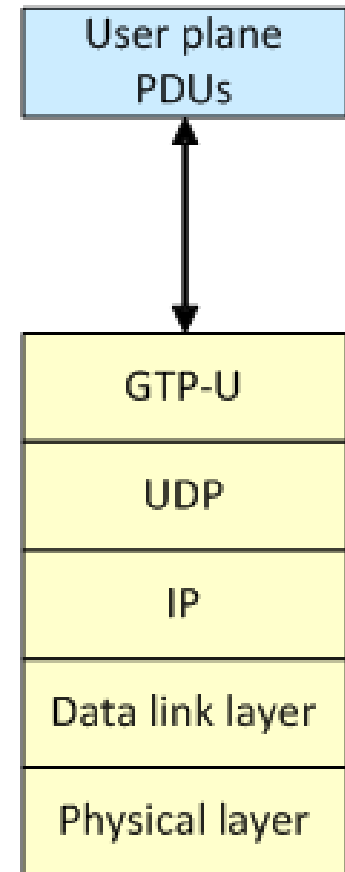
# E-UTRAN Layer 1

- The physical layer performs the following main functions:
  - Error detection on transport channel;
  - Support for Hybrid ARQ;
  - Power weighting;
  - Physical channel modulation/demodulation & link adaptation;
  - Frequency and time synchronization;
  - Physical layer mapping;
  - Support for handover
  - Support for multi-stream transmission and reception (MIMO)



Data Streams · MIMO - TX processing · MIMO Channel · MIMO - RX processing
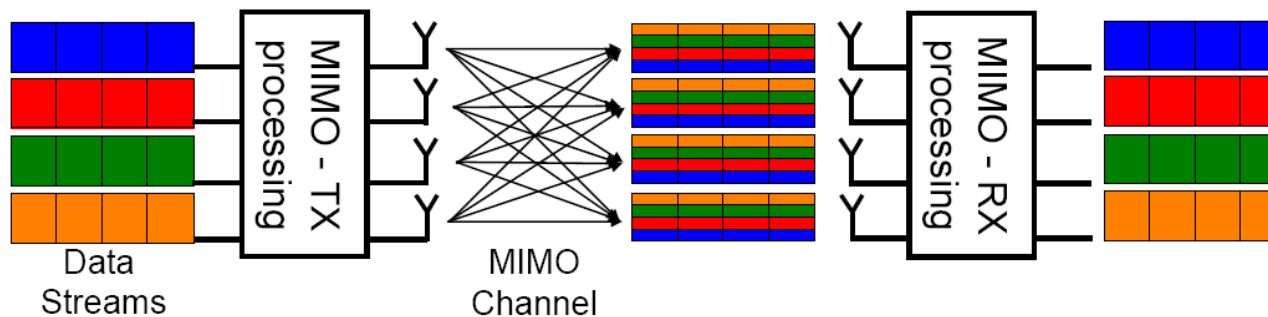
# E-UTRAN Layer 2

- Layer 2 is split into the following sublayers:
  - Medium Access Control (MAC)
  - Radio Link Control (RLC)
  - Packet Data Convergence Protocol (PDCP)
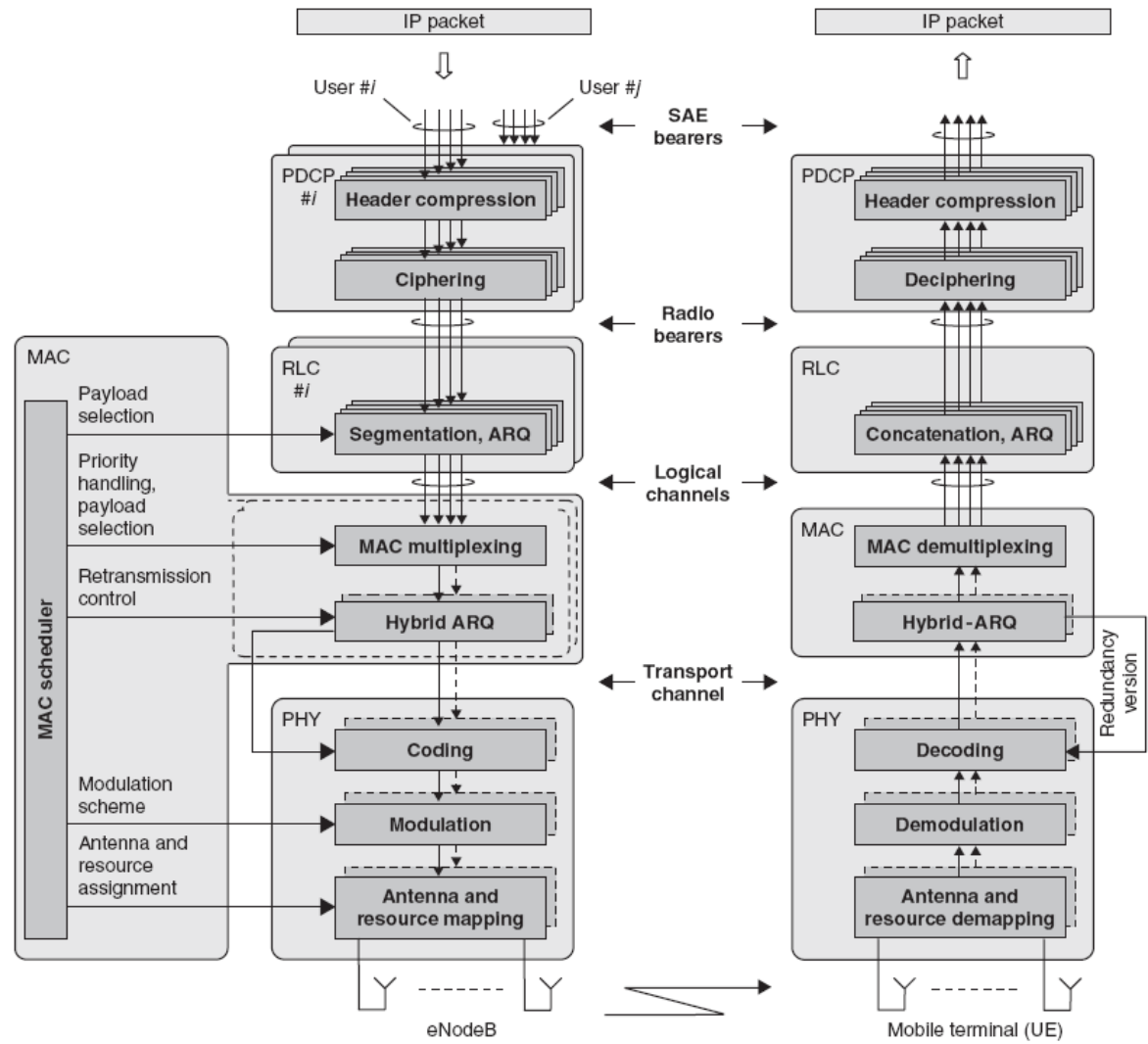
# RLC Sublayer
## Services and Functions

- The main service and functions include:
  - Transfer of upper layer PDUs supporting Acknowledged Mode (AM) or Unacknowledged Mode (UM);
    - The UM mode is suitable for transport of Real Time (RT) services because such services are delay sensitive and cannot wait for retransmissions.
    - The AM mode, on the other hand, is appropriate for non-RT (NRT) services such as file downloads.
  - Transparent Mode (TM) data transfer;
    - The TM mode is used when the PDU sizes are known a priori such as for broadcasting system information.
  - Error Correction through ARQ
    - CRC check provided by the physical layer; no CRC needed at RLC level

# RLC Sublayer
## Services and Functions

- Segmentation according to the size of the TB:
  - only if an RLC SDU does not fit entirely into the TB
  - then the RLC SDU is segmented into variable sized RLC PDUs, which do not include any padding;
- Re-segmentation of PDUs that need to be retransmitted
  - if a retransmitted PDU does not fit entirely into the new TB used for retransmission then the RLC PDU is re-segmented
- Concatenation of SDUs for the same radio bearer;
- In-sequence delivery of upper layer PDUs except at HO;
- Duplicate Detection;
- Protocol error detection and recovery;
- SDU discard;

# MAC Sublayer
## Logical Channels

**Logical channels**
(characterized by the information that is transferred)

**Control channels**
(carry control plane info)

**Traffic channels**
(carry uer plane info)

**Broadcast Control Channel (BCCH)**
(DL channel for broadcasting system control info)

**Paging Control Channel (PCCH)**
(DL channel for transfering paging)

**Multicast Control Channel (MCCH)**
(DL p2m channel for transmitting MBMS control info

**Multicast Traffic Channel (MTCH)**
(DL p2m channel for transmission of MBMS data)

**Common Control Channel (CCCH)**
(UL channel for transmitting control info and used by UE without RRC connection)

**Dedicated Control Channel (DCCH)**
(p2p channel bidirectional channel for exchanging control information and used by Ues with RRC connection

**Dedicated Traffic Channel (DTCH)**
(Bidirectional channel dedicated to single UE)
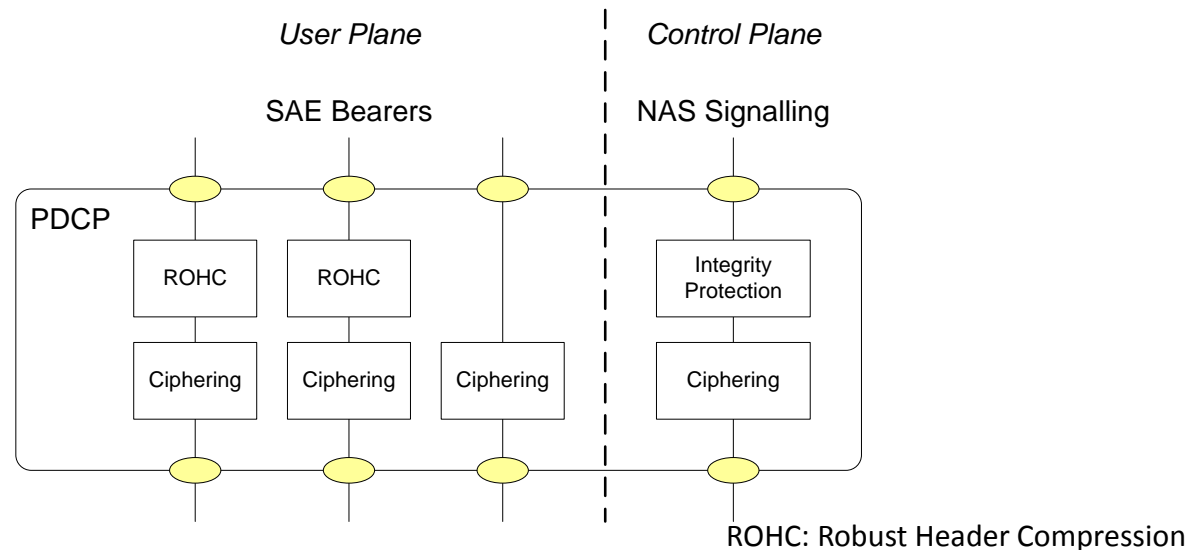
# MAC Sublayer
## Services and Functions

- The main services and functions include:
  - Mapping between logical channels and transport channels;
  - Multiplexing/demultiplexing of RLC PDUs belonging to one or different radio bearers into/from transport blocks (TB) delivered to/from the physical layer on transport channels;
  - Traffic volume measurement reporting;
  - Error correction through HARQ;
  - Priority handling between logical channels of one UE;
  - Priority handling between UEs by means of dynamic scheduling;
  - Transport format selection;
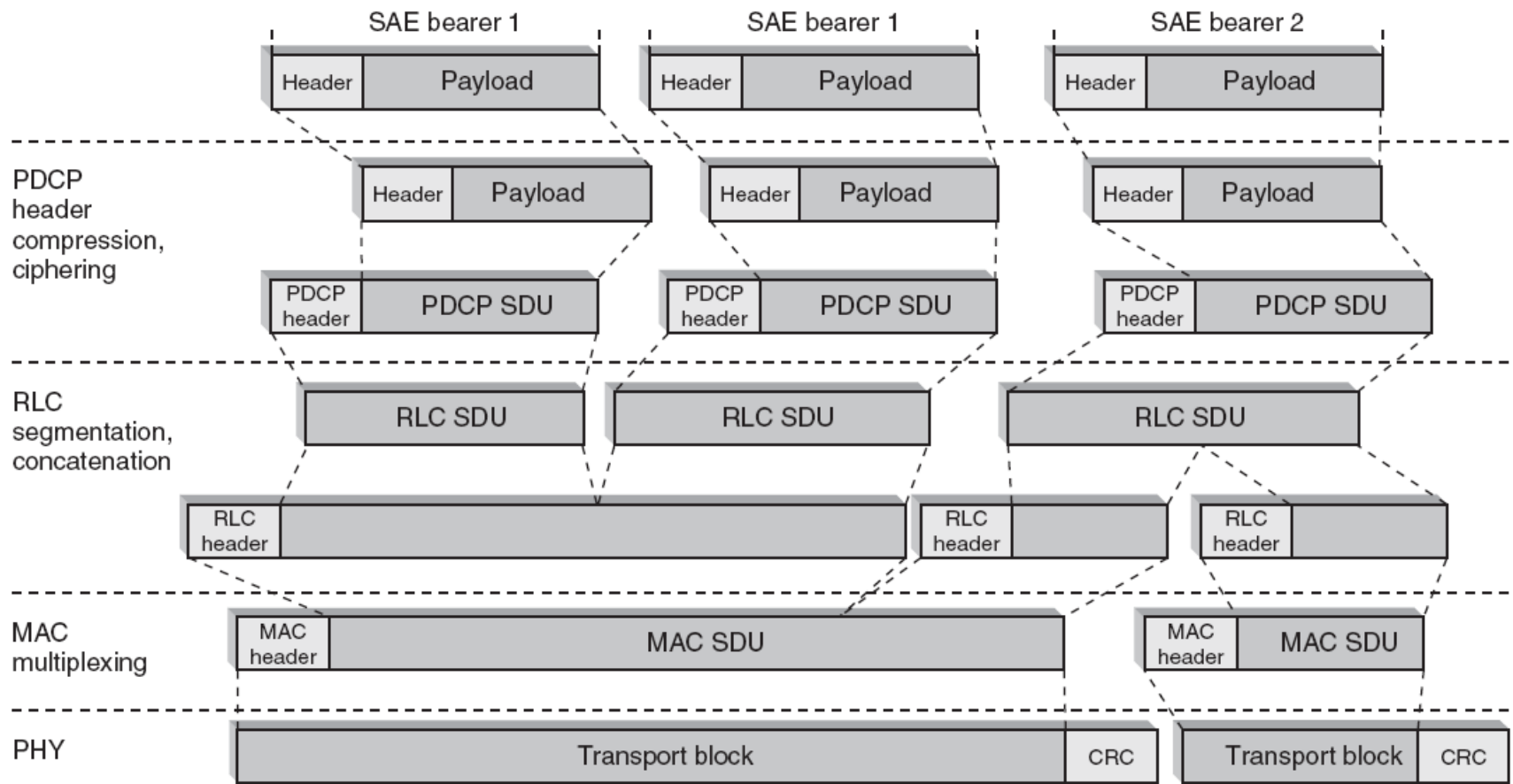  - Padding.

# PDCP Sublayer
## Services and Functions

- The main service and functions for User plane
  - Header compression/decompression: ROHC
  - Transmission and Retransmission of user data
  - In-sequence delivery of upper layer PDU at HO for RLC AM
  - Duplicate detection of lower layer SDUs
  - Ciphering of user plane data and control plane data
  - Integrity protection of control plane data

*User Plane*                          *Control Plane*

SAE Bearers                           NAS Signalling

PDCP

| ROHC | ROHC |            | Integrity Protection |

| Ciphering | Ciphering | Ciphering |       | Ciphering |

ROHC: Robust Header Compression

# Data Flow

- for Downlink Data

# RRC Layer
## Services and Functions

- The main services and functions include:
    - Broadcast of System Information related to the NAS
    - Broadcast of System Information related to the AS
    - Paging
    - Establishment, maintenance and release of an RRC connection between the UE and the E-UTRAN
    - Security Function: key management
    - Establishment, maintenance and release of point to point Radio bearers
    - Mobility functions
    - Establishment, configuration, maintenance and release of Radio Bearers for MBMS services
    - QoS management functions

# RRC Layer
## Protocol States & State Transitions

- RRC_IDLE
  - PLMN selection
  - UE specific DRX configured by NAS
  - Broadcast of system information
  - Paging
  - Cell re-selection mobility
  - The UE shall have been allocated an id which uniquely identifies the UE in a tracking area
  - No RRC context stored in the eNB
  - UE keeps its IP address in order to rapidly move to LTE_ACTIVE when necessary

# RRC Layer
## Protocol States & State Transitions

- RRC_CONNECTED
  - UE has an E-UTRAN-RRC connection
  - UE has context in E-UTRAN
  - E-UTRAN knows which the cell belong to
  - Network can transmit and/or receive data from/to UE
  - Network controlled mobility
  - Neighbor cell measurements
  - At PDCP/RLC/MAC level:
    - Data transmission and/or reception to/from network
    - control signalling channel monitoring in UE
    - Channel quality report in UE
    - DRX period configuration in eNB
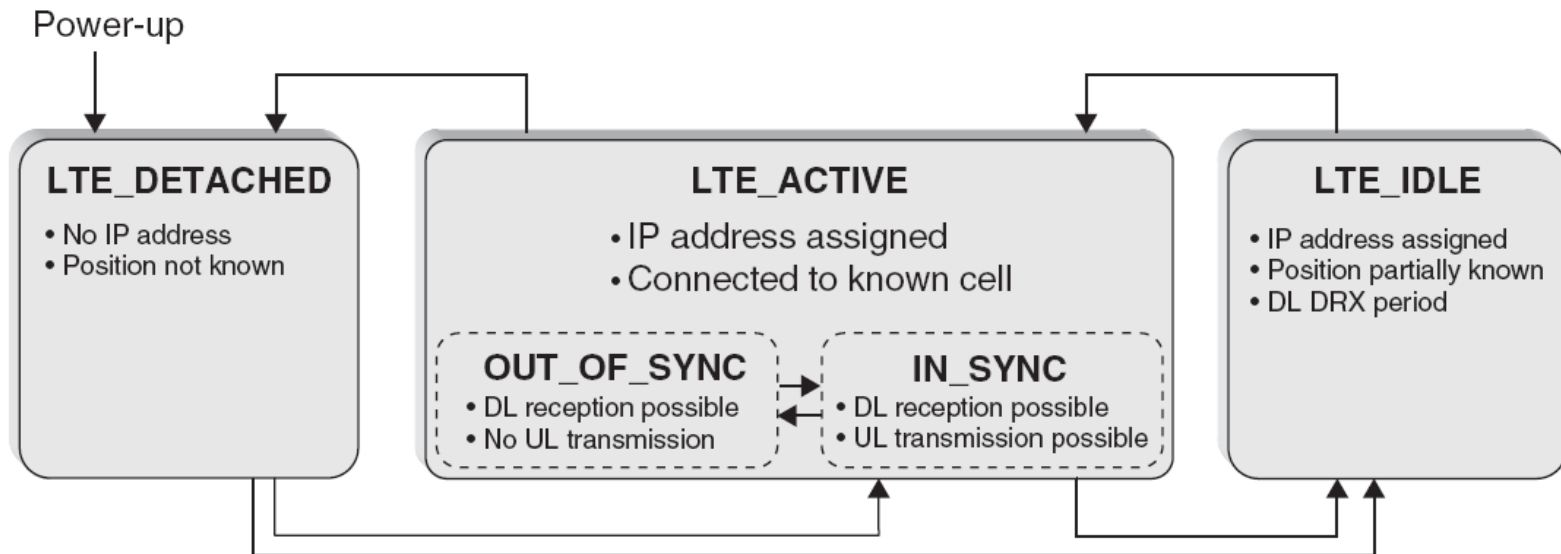
# NAS Control Protocol (1/2)
## Protocol States and State Transitions

- LTE_IDLE:
  - RRC_IDLE State
  - mobile terminal sleeps most of the time in order to reduce battery consumption.

- LTE_ACTIVE:
  - Mobile terminal is active with transmitting and receiving data
  - IP address and Cell Radio-Network Temporary Identifier (C-RNTI) assignments
  - RRC_CONNECTED state
  - IN_SYNC: uplink is synchronized
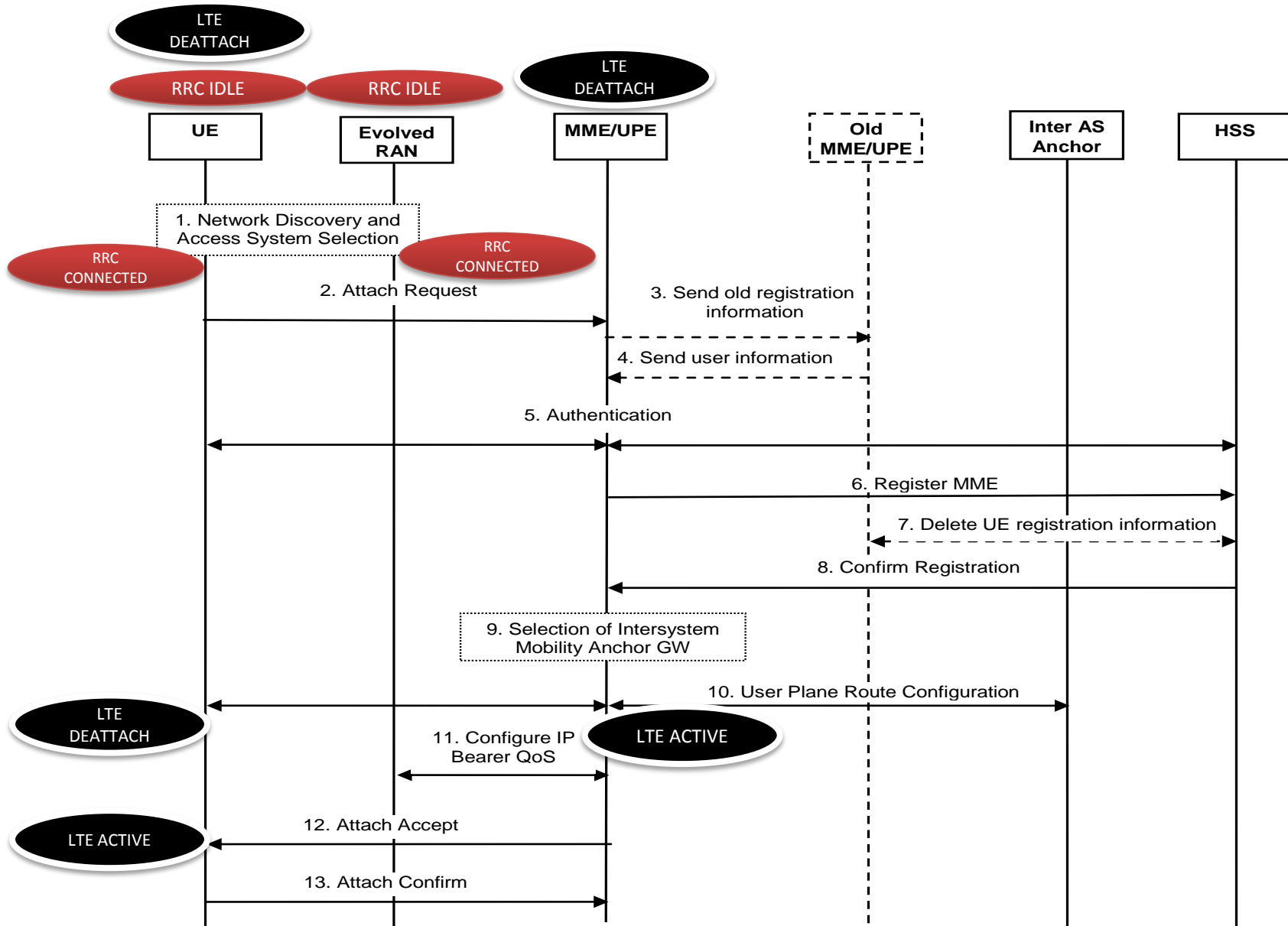  - OUT_OF_SYNC: uplink is not synchronized

# NAS Control Protocol (2/2)
## Protocol States and State Transitions

- LTE_DETACHED:
  - No RRC entity

Power-up

**LTE_DETACHED**
- No IP address
- Position not known

**LTE_ACTIVE**
- IP address assigned
- Connected to known cell

**OUT_OF_SYNC**
- DL reception possible
- No UL transmission

**IN_SYNC**
- DL reception possible
- UL transmission possible

**LTE_IDLE**
- IP address assigned
- Position partially known
- DL DRX period

# Network Attachment Flow

# Mobility Management

- Intra E-UTRAN
  - Mobility Management in ECM-IDLE
  - Mobility Management in ECM-CONNECTED
- Example
  - Intra-MME/Serving Gateway HO Procedure
    - The HO procedure is performed without EPC involvement, i.e. preparation messages are directly exchanged between the eNBs.
    - The release of the resources at the source side during the HO completion phase is triggered by the eNB.

# Intra-MME/Serving Gateway HO Procedure
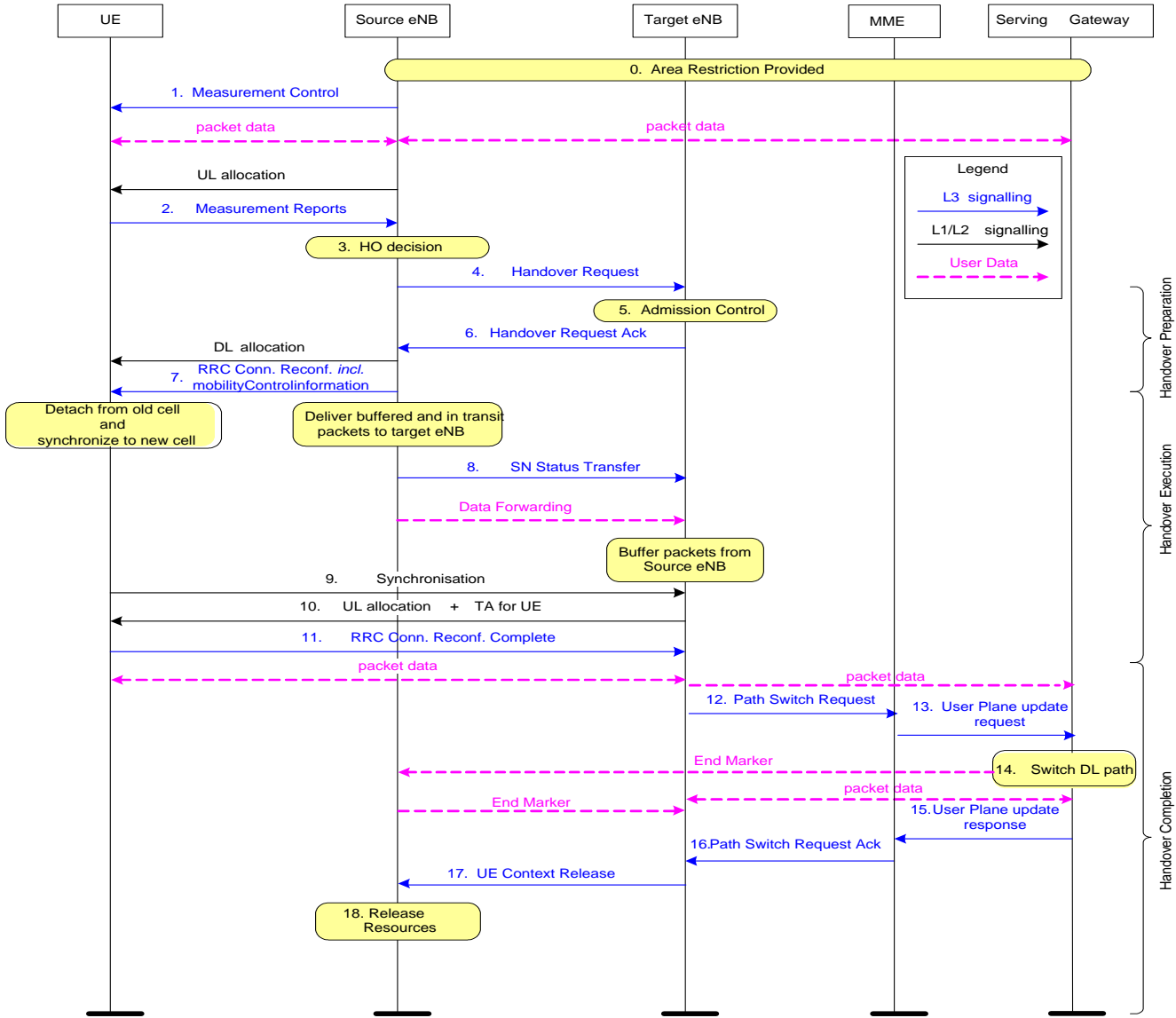
# Intra-MME/Serving Gateway HO Procedure

0. The UE context within the source eNB contains information regarding roaming restrictions which where provided either at connection establishment or at the last TA update.

1. The source eNB configures the UE measurement procedures according to the area restriction information. Measurements provided by the source eNB may assist the function controlling the UE's connection mobility.

2. UE is triggered to send MEASUREMENT REPORT by the rules set by i.e. system information, specification etc.

3. Source eNB makes decision based on MEASUREMENT REPORT and RRM information to hand off UE.

4. The source eNB issues a HANDOVER REQUEST message to the target eNB passing necessary information to prepare the HO at the target side (UE X2 signalling context reference at source eNB, UE S1 EPC signalling context reference, target cell ID, $K_{eNB*}$, RRC context including the C-RNTI of the UE in the source eNB, AS-configuration, E-RAB context and physical layer ID of the source cell + MAC for possible RLF recovery). UE X2 / UE S1 signalling references enable the target eNB to address the source eNB and the EPC. The E-RAB context includes necessary RNL and TNL addressing information, and QoS profiles of the E-RABs.

5. Admission Control may be performed by the target eNB dependent on the received E-RAB QoS information to increase the likelihood of a successful HO, if the resources can be granted by target eNB. The target eNB configures the required resources according to the received E-RAB QoS information and reserves a C-RNTI and optionally a RACH preamble. The AS-configuration to be used in the target cell can either be specified independently (i.e. an "establishment") or as a delta compared to the AS-configuration used in the source cell (i.e. a "reconfiguration").

6. Target eNB prepares HO with L1/L2 and sends the HANDOVER REQUEST ACKNOWLEDGE to the source eNB. The HANDOVER REQUEST ACKNOWLEDGE message includes a transparent container to be sent to the UE as an RRC message to perform the handover. The container includes a new C-RNTI, target eNB security algorithm identifiers for the selected security algorithms, may include a dedicated RACH preamble, and possibly some other parameters i.e. access parameters, SIBs, etc. The HANDOVER REQUEST ACKNOWLEDGE message may also include RNL/TNL information for the forwarding tunnels, if necessary.

# Intra-MME/Serving Gateway HO Procedure

7.  The target eNB generates the RRC message to perform the handover, i.e *RRCConnectionReconfiguration* message including the *mobilityControlInformation*, to be sent by the source eNB towards the UE. The source eNB performs the necessary integrity protection and ciphering of the message. The UE receives the *RRCConnectionReconfiguration* message with necessary parameters (i.e. new C-RNTI, target eNB security algorithm identifiers, and optionally dedicated RACH preamble, target eNB SIBs, etc.) and is commanded by the source eNB to perform the HO. The UE does not need to delay the handover execution for delivering the HARQ/ARQ responses to source eNB.

8.  The source eNB sends the SN STATUS TRANSFER message to the target eNB to convey the uplink PDCP SN receiver status and the downlink PDCP SN transmitter status of E-RABs for which PDCP status preservation applies (i.e. for RLC AM). The uplink PDCP SN receiver status includes at least the PDCP SN of the first missing UL SDU and may include a bit map of the receive status of the out of sequence UL SDUs that the UE needs to retransmit in the target cell, if there are any such SDUs. The downlink PDCP SN transmitter status indicates the next PDCP SN that the target eNB shall assign to new SDUs, not having a PDCP SN yet. The source eNB may omit sending this message if none of the E-RABs of the UE shall be treated with PDCP status preservation.

9.  After receiving the *RRCConnectionReconfiguration* message including the *mobilityControlInformation* , UE performs synchronisation to target eNB and accesses the target cell via RACH, following a contention-free procedure if a dedicated RACH preamble was indicated in the *mobilityControlInformation*, or following a contention-based procedure if no dedicated preamble was indicated. UE derives target eNB specific keys and configures the selected security algorithms to be used in the target cell.

10. The target eNB responds with UL allocation and timing advance.

# Intra-MME/Serving Gateway HO Procedure

11. When the UE has successfully accessed the target cell, the UE sends the *RRCConnectionReconfigurationComplete* message (C-RNTI) to confirm the handover, along with an uplink Buffer Status Report, whenever possible, to the target eNB to indicate that the handover procedure is completed for the UE. The target eNB verifies the C-RNTI sent in the *RRCConnectionReconfigurationComplete* message. The target eNB can now begin sending data to the UE.

12. The target eNB sends a PATH SWITCH message to MME to inform that the UE has changed cell.

13. The MME sends an UPDATE USER PLANE REQUEST message to the Serving Gateway.

14. The Serving Gateway switches the downlink data path to the target side. The Serving gateway sends one or more "end marker" packets on the old path to the source eNB and then can release any U-plane/TNL resources towards the source eNB.

15. Serving Gateway sends an UPDATE USER PLANE RESPONSE message to MME.

16. The MME confirms the PATH SWITCH message with the PATH SWITCH ACKNOWLEDGE message.

17. By sending UE CONTEXT RELEASE, the target eNB informs success of HO to source eNB and triggers the release of resources by the source eNB. The target eNB sends this message after the PATH SWITCH ACKNOWLEDGE message is received from the MME.

18. Upon reception of the UE CONTEXT RELEASE message, the source eNB can release radio and C-plane related resources associated to the UE context. Any ongoing data forwarding may continue.

# Reference

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[3] 3GPP. 3GPP SAE: Report on technical options and conclusions. 3GPP TR 23.882 v1.4.2, 2006-10

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[8] 3GPP. 3GPP SAE: CT WG4 aspects. 3GPP TR 29.803 v0.5.0, 2007-11

[9] 3GPP. 3GPP SAE: CT WG3 aspects. 3GPP TR 29.804 v0.3.0, 2007-11

[10]      3GPP. E-UTRA and E-UTRAN; Overall description; 3GPP TS 36.300 v8.3.0 2007-12

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