3G Long-Term Evolution (LTE) and System Architecture Evolution (SAE)

- Intro
- LTE/SAE Architecture
- Air Interface
- Bearers, States, Identifiers
- QoS

Separate sessions on
- LTE Radio
- LTE Applications & Services
- SON
3GPP Evolution – Background

• 3G Long-Term Evolution (LTE) is the advancement of UMTS with the following targets:
  - Significant increase of the data rates: mobile broadband
  - Simplification of the network architecture
  - Reduction of the signaling effort esp. for activation/ deactivation

• Work in 3GPP started in Dec 2004
  - LTE is not backward compatible to UMTS HSPA
  - LTE is a packet only network – there is no support of circuit switched services (no MSC)
  - LTE started on a clean state – everything was up for discussion including the system architecture and the split of functionality between RAN and CN

• Since 2010, LTE has been further enhanced
  - LTE-Advanced with increased performance targets
  - Application of new scenarios (MTC) and novel concepts (D2D)
**LTE Requirements and Performance Targets**

**High Peak Data Rates**
- 100 Mbps DL (20 MHz, 2x2 MIMO)
- 50 Mbps UL (20 MHz, 1x2)

**Improved Spectrum Efficiency**
- 3–4x HSPA Rel.6 in DL*
- 2–3x HSPA Rel.6 in UL
- 1 bps/Hz broadcast

**Support Scalable BW**
- 1.4, 3, 5, 10, 15, 20 MHz

**Improved Cell Edge Rates**
- 2–3x HSPA Rel.6 in DL*
- 2–3x HSPA Rel.6 in UL

**Low Latency**
- < 5 ms user plane (UE to RAN edge)
- < 100 ms camped to active
- < 50 ms dormant to active

**Packet Domain Only**
- High VoIP capacity
- Simplified network architecture

* Assumes 2x2 in DL for LTE, but 1x2 for HSPA Rel.6
Key Features of LTE to Meet Requirements

- Selection of OFDM for the air interface
  - Less receiver complexity
  - Robust to frequency selective fading and inter-symbol interference (ISI)
  - Access to both time and frequency domain allows additional flexibility in scheduling (including interference coordination)
  - Scalable OFDM makes it straightforward to extend to different transmission bandwidths

- Integration of MIMO techniques
  - Pilot structure to support 1, 2, or 4 Tx antennas in the DL and MU-MIMO in the UL

- Simplified network architecture
  - All IP architecture
  - Reduction in number of logical nodes → flatter architecture
  - Clean separation between user and control plane
# LTE/SAE Releases

<table>
<thead>
<tr>
<th>Release</th>
<th>Year/Quarter</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Release 8</td>
<td>2008 Q4</td>
<td>First <strong>LTE</strong> release. All-IP Network (SAE). New <strong>OFDMA</strong>, <strong>FDE</strong> and <strong>MIMO</strong> based radio interface.</td>
</tr>
<tr>
<td>Release 9</td>
<td>2009 Q4</td>
<td>SAES Enhancements, <strong>WiMAX</strong> and LTE/UMTS Interoperability. <strong>LTE HeNB</strong>.</td>
</tr>
<tr>
<td>Release 10</td>
<td>2011 Q1</td>
<td><strong>LTE Advanced</strong> fulfilling <strong>IMT Advanced 4G</strong> requirements. Backwards compatible with release 8 (LTE).</td>
</tr>
<tr>
<td>Release 11</td>
<td>2012 Q3</td>
<td>Advanced IP <strong>Interconnection</strong> of Services. <strong>Service layer</strong> interconnection between national operators/carriers as well as third party application providers. Heterogeneous networks (HetNet) improvements, Coordinated Multi-Point operation (CoMP). In-device Co-existence (IDC).</td>
</tr>
<tr>
<td>Release 12</td>
<td>2015 Q1</td>
<td>Enhanced Small Cells (higher order modulation, dual connectivity, cell discovery, self configuration), Carrier Aggregation (2 uplink carriers, 3 downlink carriers, FDD/TDD carrier aggregation), MIMO (3D channel modeling, elevation beamforming, massive MIMO), New and Enhanced Services (cost and range of MTC, D2D communication, eMBMS enhancements)</td>
</tr>
<tr>
<td>Release 14</td>
<td>2017 Q2</td>
<td>Energy Efficiency, Location Services (LCS), Mission Critical Data over LTE, Mission Critical Video over LTE, Flexible Mobile Service Steering (FMSS), Multimedia Broadcast Supplement for Public Warning System (MBSP), enhancement for TV service, massive Internet of Things, Cell Broadcast Service (CBS)</td>
</tr>
</tbody>
</table>
How to navigate in 3GPP documents?

Overview on 3GPP document series:
http://www.3gpp.org/specifications/specification-numbering

• 22 series: Service aspects
• 23 series: Technical realization
  – TS 23.203: Policy and Charging Control Architecture
  – TS 23.401: GPRS enhancements for E-UTRAN access
  – TS 23.501: Systems Architecture for the 5G System
• 24 series: Signaling protocols – user to network
  – TS 24.301 NAS protocol for EPS (MM, SM procedures)
• 29 series: Signaling protocols - intra-fixed-network
  – TS 29.171-173: Location Services
• 33 series: Security
• 36 series: LTE radio aspects
  – TS 36.300: E-UTRAN – Overall description; Stage 2
  – TS 36.331: Radio Resource Control (RRC); protocol specification
• 38: 5G radio aspects
LTE/SAE Network Architecture

- Evolved UTRAN (E-UTRAN)
  - Evolved Node B
- Evolved Packet System (EPS)
  - MME, S-GW, P-GW, HSS, PCRF
- EPS Protocol Architecture and Interfaces
Evolved UTRAN (E-UTRAN) Architecture

- Key elements of radio network architecture
  - No more RNC
  - RNC functionalities moved to evolved-NodeB (eNB)
  - Termination of radio access in eNB
  - X2 interface for seamless mobility (i.e. data/context forwarding) and load management among eNBs

- Note: Standard only defines logical structure/nodes!

EPC = Evolved Packet Core
eNodeB (eNB) provides all radio access functions

- Radio Resource Management (RRC, dynamic scheduling)
- Routing of User Plane data towards Serving Gateway
- Scheduling and transmission of paging and broadcast messages
- IP header compression and user plane ciphering
- Measurements and measurement reporting configuration
- Selection of a MME at UE attachment, when not given by UE
Evolved Packet System (EPS) Architecture

- EPS comprises EPC, E-UTRAN and UE
- E-UTRAN, i.e. eNB performs radio access functions
- EPC provides connectivity & performs mobility & user management functions
  - separation between C Plane and U Plane in EPC
Mobility Management Entity (MME)

- UE Reachability in ECM-Idle/RCC-Idle state
- Tracking area management
- NAS signaling/security, AS security control
- Authentication & authorization
- S-GW/P-GW selection
- MME selection for HO with MME change, SGSN selection for HO to 3G/2G
- Inter-EPC signaling for mobility between 3GPP access networks
- Bearer management functions including dedicated bearer establishment
Serving and PDN Gateways

**Serving Gateway (S-GW)**
- Serves EPC (U Plane) - E-UTRAN interface (S1-U interface)
- Local mobility anchor for inter-eNB as well as inter-3GPP handovers
- Packet routing and forwarding
- Idle mode (ECM_IDLE) DL packet buffering and triggering of network-based service request procedure
- Accounting on user and QCI granularity for inter-operator charging
- UL and DL charging per UE, PDN, and QCI
- Lawful Interception

**PDN Gateway (P-GW)**
- Serves SGi interface towards PDN
- UE IP address allocation
- Mobility anchor for internetworking with non-3GPP networks
- DL packet filtering and assignment to EPS bearers (QoS) based on TFTs
- QoS enforcement and flow based-charging according to rules from PCRF (Policy and Charging Enforcement Function – PCEF)
- Lawful Interception
Home Subscriber Server (HSS)

- User subscription repository for permanent user data (subscriber profiles including MSISDN, IMSI, keys, user capabilities, etc.)
- Dynamic user data esp. current location
- Combines functionality of HLR and AuC
PCRF – Policy Control and Charging Rules Function

**Key Functionalities:**

- fundamental entity to manage flow-specific traffic differentiation and QoS provisioning
- maps QoS requirements of individual services (SDF – beyond EPS) to an individual flow (EPS bearer – inside EPS)
- Subscriber-specific and service-specific selection of Access Point Name (APN) and APN-specific policy control, e.g. IMS for voice
- ensures proper charging for use of QoS enabled services (time-, volume- or event-based)
- instructs and authorizes the P-GW (PCEF – Policy and Charging Enforcement Function) about QoS authorization (QCI and throughput)

**PCRF**

- controls QoS and charging of EPS bearers
- provides policy and charging control (PCC) rules

See TS 23.203 for details
**LTE-Uu**: radio interface (UE - eNB)

**GPRS Tunneling Protocol for the user plane (GTP-U)**:
- tunnels user data between eNodeB and the S-GW as well as between the S-GW and the P-GW
Non-Access Stratum Signaling (NAS):
- supports mobility management functionality and user plane bearer activation, modification and deactivation
- ciphering and integrity protection of NAS signaling

S1 Application Protocol (S1-AP): Signaling Application Layer between eNB and MME

Streaming Control Transfer Protocol for the control plane (SCTP): guaranteed delivery of signaling messages between MME and eNodeB; defined in RFC 4960
Air Interface Protocol Architecture

- LTE Protocol Architecture
- LTE Channels
- Protocol Services and Functions
LTE Protocol Architecture - Overview

C Plane

U Plane

UE

NAS

RRC

PDCP

RLC

MAC

PHY

eNB

RRC

PDCP

RLC

MAC

PHY

MME

NAS

S-Gateway
LTE Protocol Architecture – U Plane Overview

Physical sub-layer performs:
- Modulation
- Coding (FEC)
- UL power control
- Multi-stream transmission & reception (MIMO)

PDCP sub-layer performs:
- Header compression
- Ciphering

RLC sub-layer performs:
- Transfer of upper layer PDUs
- Error correction through ARQ
- Reordering of RLC data PDUs
- Duplicate detection
- Flow control
- Segmentation/Concatenation of SDUs

MAC sub-layer performs:
- Mapping of logical channels to transport channels
- Scheduling
- Error correction through HARQ
- Priority handling across UEs & logical channels

S-Gateway

PDCP

RLC

MAC

PHY

UE

eNodeB

MME

UE
**LTE Protocol Architecture – C Plane Overview**

- **UE**
  - NAS
  - RRC
  - PDCP
  - RLC
  - PHY

- **eNB**
  - NAS
  - RRC
  - PDCP
  - RLC
  - MAC
  - PHY

- **NAS sub-layer performs:**
  - Authentication
  - Security control
  - Idle mode mobility handling/paging origination

- **RRC sub-layer performs:**
  - Broadcasting
  - Paging
  - RRC Connection Management
  - Radio bearer control
  - Mobility functions
  - UE measurement reporting & control

- **PDCP sub-layer performs:**
  - Integrity protection & ciphering
Downlink Scheduling & Resource Allocation

- Channel dependent scheduling is supported in both time and frequency domain → enables two dimensional flexibility
- Scheduler chooses bandwidth allocation, modulation and coding set (MCS), MIMO mode, and power allocation

Total number of RBs available depends on the operating bandwidth

<table>
<thead>
<tr>
<th>Bandwidth (MHz)</th>
<th>1.4</th>
<th>3.0</th>
<th>5.0</th>
<th>10.0</th>
<th>15.0</th>
<th>20.0</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of available resource blocks</td>
<td>6</td>
<td>15</td>
<td>25</td>
<td>50</td>
<td>75</td>
<td>100</td>
</tr>
</tbody>
</table>
Physical Layer Services - Transport Channels

- Shared Channel SCH (UL & DL)
  - Carries majority of data and control traffic
  - Adaptive modulation and coding (AMC) & Hybrid ARQ (HARQ)
  - Possibility to use beamforming
  - Controlled by eNodeB scheduler

- Broadcast Channel BCH (DL)
  - Broadcast of system information (MIB)
  - Fixed transport format, broadcast over entire cell

- Paging Channel PCH (DL)
  - Notification of UEs
  - Support of DRX, broadcast over entire cell
  - Mapped to PDSCH

- Random Access Channel RACH (UL):
  - Provides indication of UE request
  - Collision-based channel
Physical Layer Model: DL-SCH

Node B

Channel state information, etc.

HARQ

Acknowledgment (ACK/NACK)

HARQ info

N Transport blocks (dynamic size S1, ..., SN)

CRC

Redundancy for error detection

Coding + RM

Data modulation

Resource mapping

Antenna mapping

QPSK, 16QAM, 64QAM

Multi-antenna processing

Resource/power assignment

Modulation scheme

MAC scheduler

UE

Error indications

HARQ info

ACK/NACK

CRC

Data modulation

Resource demapping

Antenna demapping

Decoding + RM

Data demodulation

Antenna mapping

Error indications
Physical Layer Model: UL-SCH

Node B

- MAC scheduler
  - Resource assignment
    - Antenna mapping
  - Modulation scheme
  - Redundancy version
- HARQ
  - HARQ info
  - ACK/NACK
- CRC
- Decoding + RM
  - Deinterleaving
- Data demodulation
- Resource demapping
- Antenna demapping

UE

- Uplink transmission control
- HARQ
  - HARQ info
  - Redundancy version
- CRC
  - Interleaving
- Data modulation
  - Resource mapping
- Antenna mapping

Channel state information, etc.
Layer 2 - Structure (DL)

DL structure - eNodeB side
Layer 2 - Structure (UL)

UL structure - UE side
MAC Sublayer

- **Services – Logical Channels**
  - Dedicated Traffic Channel DTCH (UL & DL): user data
  - Dedicated Control Channel DCCH (UL & DL): control data (SRB1 & 2)
  - Common Control Channel CCCH: control data (SRB0)
  - Broadcast Control Channel BCCH: broadcast of cell information
  - Paging Control Channel PCCH: notification of UEs

- **Functions**
  - Mapping between logical channels and transport channels
  - Multiplexing/ demultiplexing of MAC SDUs belonging to one or different logical channels into/from transport blocks (TB) delivered to/ from the physical layer on transport channels
  - Scheduling information 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
Mapping between DL Channels

**PCH:** paging channel

**BCH:** broadcast channel

**DL-SCH:** DL shared channel

**PDSCH:** physical DL shared channel

**PDCCH:** physical DL control channel

**PHICH:** physical HARQ indication channel

**PCFICH:** physical control format indication channel

**PBCH:** Physical broadcast channel

![Diagram of channel mapping](image)

**Downlink Logical channels**

**Downlink Transport channels**

**Downlink Physical Channels**
Mapping between UL Channels

**RACH**: random access channel

**UL-SCH**: UL shared channel

**PUSCH**: physical UL shared channel

**PUCCH**: physical UL control channel

**PRACH**: physical random access channel
RLC Sublayer

- **Services**
  - TM (transparent mode) data transfer: no modification
  - UM (unacknowledged mode) data transfer: error indication only
  - AM (acknowledged mode) data transfer: error correction

- **Functions**
  - Transfer of upper layer PDUs
  - Error correction through ARQ (only for AM data transfer)
  - Concatenation, segmentation and reassembly of RLC SDUs (only for UM and AM data transfer)
  - Re-segmentation of RLC data PDUs (only for AM data transfer)
  - Reordering of RLC data PDUs (only for UM and AM data transfer)
  - Duplicate detection (only for UM and AM data transfer)
  - RLC SDU discard (only for UM and AM data transfer)
  - RLC re-establishment
  - Protocol error correction (only for AM data transfer)
RLC Model for AM

RLC Acknowledged Mode Entity
PDCP Sublayer

- Functions on U Plane
  - Transfer of user data
  - Ciphering and deciphering
  - Robust header compression and decompression: ROHC
  - In-sequence delivery of upper layer PDUs at PDCP re-establishment procedure for RLC AM
  - Duplicate detection of lower layer SDUs at PDCP re-establishment procedure for RLC AM
  - Retransmission of PDCP SDUs after handover (RLC AM only)
  - Timer-based SDU discard in uplink

- Functions on C Plane
  - Transfer of control plane data
  - Ciphering and Integrity Protection
Data Flow through Layer 2

- PDCP SDU: IP packet (compressed/ uncompr.)
- PDCP header: 1 or 2 bytes

- RLC header:
  - Sequence number
  - Segmentation/concatenation information

- MAC control elements:
  - UL: MAC reports
  - DL: Timing advance
  - Control Information

All PDUs are byte-aligned
RRC Layer

• Services
  - Broadcast of common control information
  - Notification of UEs in RRC_IDLE, e.g. about an arriving call
  - Transfer of dedicated control information, i.e. information for one specific UE

• Functions
  - Broadcast of system information:
    - Including NAS common information
    - Information for UEs in RRC_IDLE state, e.g. cell (re-)selection parameters, neighbouring cell information
    - Information for UEs in RRC_CONNECTED state, e.g. common channel configuration information
RRC Layer (contd.)

• Functions (contd.)
  - RRC connection control:
    ▪ Paging
    ▪ Establishment, modification & release of RRC connection
    ▪ Initial security activation
    ▪ RRC connection mobility
    ▪ Establishment, modification & release of radio bearers carrying user data (DRBs)
    ▪ Radio configuration control
    ▪ QoS control
    ▪ Recovery from radio link failure
  - Inter-RAT mobility including e.g. security activation, transfer of RRC context information
  - Measurement configuration and reporting
  - Generic protocol error handling
RRC States

UMTS
- CELL_DCH
- CELL_PCH
- URA_PCH
- Connection establishment/release
- UTRA_Idle

LTE
- F-UTRA
  - RRC_CONNECTED
  - E-UTRA
    - RRC_IDLE

GSM/GPRS
- GSM_Connected
- GPRS Packet transfer mode
- CCO with optional NACC
- CCO, Reselection
- Connection establishment/release
- Reselection
- GSM_Idle/GPRS Packet_Idle
- CCO, Reselection

RRC States incl. Inter-RAT mobility (3GPP only)
• Tracking Area Identifier (TAI) sent over Broadcast Channel BCCH
• Tracking Areas can be shared by multiple MMEs
• An UE may be allocated to multiple tracking areas
• Different from UMTS, no hierarchy in the paging area!
Bearers, States and Identifiers

- EPS Bearers and Radio Bearers
- RRC, ECM & EMM States
- UE Identifiers
EPS Bearer Service Architecture (U Plane) – Overview

End-to-end Service

EPS Bearer

External Bearer

E-RAB

S5/S8 Bearer

Radio Bearer

S1 Bearer

Radio

S1

S5/S8

Gi

3GPP: TS 23.203 Policy and Charging Control Architecture
EPS Bearer: Default vs. Dedicated

- **Default EPS Bearer (non-GBR)**
  - First connection, established during initial attach to a PDN
  - Remains established during lifetime of PDN connection
  - Possibly multiple default bearers to different PDNs (unique IP address)

- **Dedicated EPS Bearers (GBR or non-GBR)**
  - Additional EPS bearers established to the P-GW
  - Multiple bearer connections with dedicated QoS policies
Radio Bearer: SRB vs. DRB

- **Signaling Radio Bearers (SRB):** transfer RRC and NAS control messages between UE and eNodeB
  - SRB0: RRC messages over CCCH
  - SRB1: RRC and NAS (when no security) messages over DCCH
  - SRB2: NAS messages (when security established) over DCCH
- **Data Radio Bearer (DRB):** implements EPS bearer between UE and eNodeB
  - One-to-one mapping between DRB and the EPS bearer/E-RAB
LTE RRC States

- No RRC connection
- No context in eNodeB (but EPS bearers are retained)
- UE controls mobility through cell selection
- UE acquires system information from broadcast channel
- UE monitors paging channel to detect incoming calls
- UE-specific paging DRX cycle controlled by upper layers

- RRC connection
- Context in eNodeB
- Network controlled mobility
- Transfer of unicast and broadcast data to and from UE
- UE monitors control channels associated with the shared data channels
- UE provides channel quality and feedback information
- Connected mode DRX can be configured by eNodeB according to UE activity level

RRC_IDLE → Establish RRC connection → RRC_Connected

Release RRC connection
EPS Connection Management States (ECM)

- No signaling connection between UE and core network (no S1-U/S1-MME)
- No RRC connection (i.e. RRC_IDLE)
- UE performs cell selection and tracking area updates (TAU)

- Signaling connection established between UE and MME, consisting of two
  - RRC connection &
  - S1-MME connection
- UE location is known to accuracy of Cell-ID
- Mobility via handover procedure
EPS Mobility Management States (EMM)

- EMM context does not hold valid location or routing information for UE
- UE is not reachable by MME as UE location is not known
- UE successfully registers with MME with Attach procedure or Tracking Area Update (TAU)
- UE location known (at least) with accuracy of tracking area
- MME can page UE
- UE maintains at least one PDN connection (default EPS bearer)
Relation between EMM, ECM and RRC States

EMM-Deregistered

EMM-Registered

A

ECM-Idle

RRC-Idle

Power On

B

ECM-Idle

RRC-Idle

Power is turned off for a long time

C

ECM-Connected

RRC-Connected

Handover

D

ECM-Idle

RRC-Idle

UE Power Off

• UE Inactivity Detection
• TAU Accept

• Detach
• Attach Reject
• TAU Reject
• UE Power Off

• New Traffic
• TAU Request

Adapted from www.netmanias.com
### Case State User Experiences (Examples)

<table>
<thead>
<tr>
<th>Case</th>
<th>State</th>
<th>User Experiences (Examples)</th>
</tr>
</thead>
</table>
| **C** | EMM-Registered + ECM-Connected + RRC-Connected | • UE is attached to the network (an MME) and is using services (e.g. Internet, VoIP, Live TV)  
• Mobility handled by handover procedures |
| **D** | EMM-Registered + ECM-Idle + RRC-Idle | • UE is attached to the network (an MME), but **not using any service**  
• Mobility handled by cell reselection procedures |
State C:
- EMM-Registered
- ECM-Connected
- RRC-Connected
EPS Bearer and Signaling Connections in EMM-registered State

State D:
- EMM-Registered
- ECM-Idle
- RRC-Idle

EPS Bearer
- Data Radio Bearer
- S1 Bearer
- S5 Bearer

RRC Connection
- S11 GTP-C

Data Plane

Control Plane

UE
- ECM Connection/Signaling Conn.
- RRC Connection

eNB
- S1 signaling Connection
- S11 GTP-C

S-GW
- S5 GTP-C

P-GW
<table>
<thead>
<tr>
<th>Layer</th>
<th>State</th>
<th>Entity</th>
<th>Description</th>
</tr>
</thead>
</table>
| EMM    | EMM-De-registered    | UE, MME         | • UE is not attached to any LTE network  
• MME does not know the current location of the UE, but may have tracking area (TA) information last reported by the UE |
|        | EMM-Registered       | UE, MME         | • UE is attached to the LTE network  
• IP address assigned to UE  
• EPS bearer established  
• MME knows the location of the UE with an accuracy of a cell or, at least, a tracking area |
| ECM    | ECM-Idle             | UE, MME         | • No NAS signalling connection (ECM connection)  
• No physical resources assigned to UE, i.e. radio resources (SRB/DRB) and network resources (S1 bearer/S1 signalling connection) |
|        | ECM-Connected        | UE, MME         | • NAS signalling connection (ECM connection) established  
• UE has been assigned physical resources, i.e. radio resources (SRB/DRB) and network resources (S1 bearer/S1 signalling connection) |
| RRC    | RRC-Idle             | UE, eNB         | • No RRC connection |
|        | RRC-Connected        | UE, eNB         | • RRC connection is established |
UE Identifiers

- **IMSI**: International Mobile Subscriber Identity
  - Assigned by service provider, stored on SIM-card
- **TMSI**: Temporary Mobile Subscriber Identity
  - Assigned temporarily by the control nodes
- **IMEI**: International Mobile Equipment Identity
  - Unique identity for each mobile assigned by manufacturer
- **MSISDN**: Mobile Subscriber ISDN number
  - Telephone number assigned by service provider

### IMSI (15 digits)

- **MCC**: Mobile Country Code
- **MNC**: Mobile Network Code
- **MSIN**: Mobile Subscriber Identification Number
- **MSISDN**: Mobile Subscriber ISDN number

Example: 262 01 1234567

Example: D1 network

= Germany

Example: +49 171 xxxxxxx

Example: D1 network

= Germany

<table>
<thead>
<tr>
<th>CC</th>
<th>NDC</th>
<th>SN</th>
</tr>
</thead>
<tbody>
<tr>
<td>Country Code</td>
<td>Network Destination Code</td>
<td>Subscriber Number</td>
</tr>
</tbody>
</table>

- **MSISDN**: Mobile Subscriber ISDN number
UE Identifiers

- **GUTI**: Global Unique Temporary Identity
  - UE identity without revealing the mobile or the user
  - GUTI has two parts
    - Globally Unique MME Identifier (GUMMEI) identifies the MME, assigned by service provider
    - M-TMSI identifies UE within the MME, assigned by MME

- The UE can attach to the network using either IMSI or GUTI
UE Identifiers

- **RNTI**: Radio Network Temporary Identifier
  - Used by eNB to temporary address the UEs (MAC)

- There exist a variety of different RNTIs
  - **Cell RNTI (C-RNTI)**: unique identification used for identifying RRC connection and scheduling
  - **Paging RNTI (P-RNTI)**
  - **Random Access RNTI (RA-RNTI)**
  - **System Information RNTI (SI-RNTI)**
  - **Transmit Power Control RNTI (TPC-RNTI)**
  - **MBMS RNTI (M-RNTI, Rel.-9)**
UE IDs maintained in Network Elements

GUTI (Globally Unique Temporary UE Identity) replaces TMSI to uniquely identify the UE and the used MME

<table>
<thead>
<tr>
<th>Case</th>
<th>State</th>
<th>UE</th>
<th>eNB</th>
<th>S-GW</th>
<th>P-GW</th>
<th>MME</th>
<th>HSS</th>
<th>PCRF</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>EMM-Deregistered + ECM-Idle + RRC-Idle</td>
<td>IMSI</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>IMSI</td>
<td>-</td>
</tr>
<tr>
<td>B</td>
<td>EMM-Deregistered + ECM-Idle + RRC-Idle</td>
<td>IMSI, GUTI</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>IMSI, GUTI</td>
<td>IMSI</td>
<td>-</td>
</tr>
<tr>
<td>C</td>
<td>EMM-Registered + ECM-Connected + RRC-Connected</td>
<td>IMSI, GUTI, UE IP addr, C_RNTI</td>
<td>C-RNTI, eNB/MME UE S1AP ID, Old/New eNB UE X2AP ID</td>
<td>IMSI</td>
<td>IMSI, UE IP addr</td>
<td>IMSI, GUTI, UE IP addr, eNB/MME UE S1AP ID</td>
<td>IMSI</td>
<td>IMSI, UE IP addr</td>
</tr>
<tr>
<td>D</td>
<td>EMM-Registered + ECM-Idle + RRC-Idle</td>
<td>IMSI, GUTI, UE IP addr</td>
<td>-</td>
<td>IMSI</td>
<td>IMSI</td>
<td>IMSI, GUTI, UE IP addr</td>
<td>IMSI</td>
<td>IMSI, UE IP addr</td>
</tr>
</tbody>
</table>
Quality of Service

- QoS Architecture
- QoS Parameters
- QoS Bearers
QoS Architecture (U Plane) - Overview

3GPP: TS 23.203 Policy and Charging Control Architecture
Review on Implementation of QoS

- QoS involves functions in
  - C plane (connection management) and
  - U plane (forwarding and policing)

- QoS requires **end-to-end** considerations of all involved network entities as QoS can only be as good as its weakest element

- QoS is a **cross-layer** issue involves basically all layers
  - Application layer: identification of service and classification, source coding, service adaptation
  - Transport layer: Retransmission policy – latency and reliability
  - Network, data link and PHY layer: provisioning of needed resources (transport and processing), forwarding and scheduling over physical resources (including, modulation, channel coding, scheduling, diversity and redundancy strategy)
Review of QoS Requirements and Influencing Factors

- Throughput
  \[ \Rightarrow \text{depends on amount of resources allocated} \]

- Error rate/reliability
  \[ \Rightarrow \text{depends on robustness of transmission (modulation and coding, TX power/SINR, transmission diversity, etc.)} \]

- Latency
  \[ \Rightarrow \text{depends on scheduling strategy, processing delay, error rate/retransmission rate, system load, error correction strategy} \]

=> See AMCN course for details on QoS over wireless
### QoS Class Identifiers (QCI s)

<table>
<thead>
<tr>
<th>QCI</th>
<th>Resource Type</th>
<th>Priority</th>
<th>Packet Delay Budget</th>
<th>Packet Error Loss Rate</th>
<th>Example Services</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>GBR</td>
<td>2</td>
<td>100 ms</td>
<td>$10^{-2}$</td>
<td>Conversational Voice</td>
</tr>
<tr>
<td>2</td>
<td>GBR</td>
<td>4</td>
<td>150 ms</td>
<td>$10^{-3}$</td>
<td>Conversational Video (Live Streaming)</td>
</tr>
<tr>
<td>3</td>
<td></td>
<td>3</td>
<td>50 ms</td>
<td>$10^{-3}$</td>
<td>Real Time Gaming</td>
</tr>
<tr>
<td>4</td>
<td></td>
<td>5</td>
<td>300 ms</td>
<td>$10^{-6}$</td>
<td>Non-Conversational Video (Buffered Streaming)</td>
</tr>
<tr>
<td>5</td>
<td></td>
<td>1</td>
<td>100 ms</td>
<td>$10^{-6}$</td>
<td>IMS Signalling</td>
</tr>
<tr>
<td>6</td>
<td></td>
<td>6</td>
<td>300 ms</td>
<td>$10^{-6}$</td>
<td>Video (Buffered Streaming) TCP-based (e.g., www, e-mail, chat, ftp, p2p file sharing, progressive video, etc.)</td>
</tr>
<tr>
<td>7</td>
<td>Non-GBR</td>
<td>7</td>
<td>100 ms</td>
<td>$10^{-3}$</td>
<td>Voice, Video (Live Streaming) Interactive Gaming</td>
</tr>
<tr>
<td>8</td>
<td></td>
<td>8</td>
<td>300 ms</td>
<td>$10^{-6}$</td>
<td>Video (Buffered Streaming) TCP-based (e.g., www, e-mail, chat, ftp, p2p file sharing, progressive video, etc.)</td>
</tr>
<tr>
<td>9</td>
<td></td>
<td>9</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
EPS bearer – QoS definition

- QCI's represent type of traffic, i.e. handling wrt latency, error correction and data rate (throughput itself not included)
- Throughput, i.e. Guaranteed Bit Rate (GBR) and Maximum Bit Rate (MBR)
- TFT (Traffic Flow Template), i.e. the rules to identify external flows (Service Data Flows – SDFs) and to map them to a specific EPS bearer comprising IP source and destination, port numbers, protocol ID, etc.
- ARP (Admission and Retention Policy) for overload handling
Mapping of External Flows on EPS bearers

Mapping of external Service Data Flows (SDFs) on EPS bearers is implemented at the edges of the network, i.e. UE and P-GW

Legend:
- GBR: Guaranteed Bit Rate
- MBR: Maximum Bit Rate
- AMBR: Aggregated MBR
- APN-AMBR: APN-specific MBR

Source: www.netmanias.com
Service Data Flow (SDF):
- defines QCI, ARP, MBR and possibly GBR

EPS bearer
- defines QCI, ARP, possibly GBR, MBR or UE-AMBR and APN-AMBR
- may combine several SDFs to a single EPS bearer

EPS session:
- comprises one or more SDFs (i.e. services) mapped to one or more EPS bearers (default or dedicated bearer) connecting to the same PDN
QoS Policing and Scheduling for DL

**DL Scheduling**

- **Application**
  - Bearer ID = 10
  - Bearer ID = 8
  - Bearer ID = 5

- **Non-GBR Bearer**

- **UE-AMBR (DL) Scheduling**

- **Dedicated Bearer (GBR), Bearer ID=10**

- **Dedicated Bearer (Non-GBR), Bearer ID=8**

- **Default Bearer (Non-GBR), Bearer ID=5**

**SDF-EPS mapping via TFTs**

**Policing**

- **MBC (DL) Policing**
  - EBI = 1
  - EBI = 8
  - EBI = 5

**SDF-EPS**

**Templates (DL)**

**P-GW**

- **IP flow 1**
  - **Packet Filter 1**
    - SDF Template1 (TFT1)
      - Filter Rule: (*, UE IP, RTP, *, UDP)
      - SDF: 1
      - Bearer ID: 10
  - **Packet Filter 2**
    - SDF Template2 (TFT1)
      - Filter Rule: (*, UE IP, Video, *, UDP)
      - SDF: 2
      - Bearer ID: 10
  - **Packet Filter 3**
    - SDF Template3 (TFT2)
      - Filter Rule: (*, UE IP, SIP, *, UDP)
      - SDF: 3
      - Bearer ID: 8
  - **Packet Filter 4**
    - SDF Template4 (TFT3)
      - Filter Rule: (*, UE IP, Game, *, *)
      - SDF: 4
      - Bearer ID: 8
  - **Packet Filter 5**
    - SDF Template5 (TFT3)
      - Filter Rule: (*, *, *, *)
      - SDF: 5
      - Bearer ID: 5

**Source:** www.netmanias.com
QoS Policing and Scheduling for UL

SDF-EPS mapping via TFTs

Policing on provided UL grants

Provision of UL grants

1. Application
2. TFT (UL)
3. MBR (UL) Policing
4. MBR (UL) Scheduling
5. UE-AMBR (UL) Scheduling
6. APN_AMBR (UL) Policing
7. APN-AMBR (UL) Policing
8. SDF (Templates) in P-GW
9. MBR (UL) Policing

UL TFTs in UE

<table>
<thead>
<tr>
<th>Filter Rule</th>
<th>Bearer ID</th>
</tr>
</thead>
<tbody>
<tr>
<td>Packet Filter 1</td>
<td>Bearer 10</td>
</tr>
<tr>
<td>Packet Filter 2</td>
<td>Bearer 10</td>
</tr>
<tr>
<td>Packet Filter 3</td>
<td>Bearer 8</td>
</tr>
<tr>
<td>Packet Filter 4</td>
<td>Bearer 8</td>
</tr>
<tr>
<td>Packet Filter 5</td>
<td>Bearer 5</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Filter Rule</th>
<th>SDF Template</th>
<th>Bearer ID</th>
</tr>
</thead>
<tbody>
<tr>
<td>Packet Filter 1</td>
<td>SDF Template1 (TFT1)</td>
<td>Bearer 10</td>
</tr>
<tr>
<td>Packet Filter 2</td>
<td>SDF Template2 (TFT1)</td>
<td>Bearer 10</td>
</tr>
<tr>
<td>Packet Filter 3</td>
<td>SDF Template3 (TFT2)</td>
<td>Bearer 8</td>
</tr>
<tr>
<td>Packet Filter 4</td>
<td>SDF Template4 (TFT3)</td>
<td>Bearer 8</td>
</tr>
<tr>
<td>Packet Filter 5</td>
<td>(UE IP, *, *, *, *)</td>
<td>Bearer 5</td>
</tr>
</tbody>
</table>

Packet Filter: (Src IP, Dst IP, Src Port, Dst Port, Protocol ID)

Packet Filter: (Src IP, Dst IP, Src Port, Dst Port, Protocol ID)
Summary of Important Terms and Ingredients for QoS

- QCI (QoS Class Identifier) – defines QoS requirements with exception of throughput
- ARP (Admission and Retention Policy) – defines priority of EPS bearer for admission and contention cases
- TFT (Traffic Flow Template) – defines mapping of external SDFs on EPS bearer (formerly PDP context)
- SDF (Service Data Flow) – service-specific (external) IP flow
- EPS bearers (IP addresses, port numbers, protocol ID) – unit for QoS management within EPS
- IP CAN (end-to-end bearer), i.e. an IP flow

- GBR: Guaranteed Bit Rate
- MBR: Maximum Bit Rate
- AMBR: Aggregated MBR
- APN-AMBR: APN-specific MBR
References

• Literature
  - Sesia, Toufik, Baker: LTE - The UMTS Long Term Evolution: From Theory to Practice, Wiley 2011
  - The LTE Network Architecture - strategic white paper – Alcatel-Lucent, 2009
  - LTE EMM and ECM States: www.netmanias.com

• 3GPP standards (www.3gpp.org/specifications):
  - TS 23.002: Network Architecture (HSS; MME, GWs, PCRF, IMS, CSCF)
  - TS 23.401 GPRS Enhancements for E-UTRAN access (Ch 4.7 for QoS, 5.4 for SM/QoS procedures)
  - 36.300: E-UTRAN – Overall description; Stage 2
  - 36.321: Medium Access Control (MAC) protocol specification
  - 36.331: Radio Resource Control (RRC); protocol specification
  - 36.213: Physical layer procedures