LTE-Advanced
Radio Layer 2 and RRC aspects

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3GPP TSG-RAN WG2
Outline

E-UTRA overview
- LTE Advanced features
- E-UTRAN architecture
- User plane protocol stack
- Control plane protocol stack

User plane
- Reliable transport
- U-plane data flow
- Scheduling
- DRX
- Security

Control plane
- System information
- Connection control
- RRC state model
- IDLE mode mobility
- CONNECTED mode mobility
- Radio Link Failure handling
- Random Access
- Priority access

Performance
- U-plane latency
- C-plane latency
- HO interruption
LTE Advanced supports:

- Reliable, high rate, high capacity and low latency data transfer
  - suitable for a wide range of services
- Mobility
  - seamless and lossless (using packet forwarding)
  - optimized for low mobile speed from 0 to 15 km/h
  - higher mobile speed between 15 and 120 km/h also supported with high performance
  - mobility across the cellular network can be maintained at speeds from 120 km/h to 350 km/h (or even up to 500 km/h depending on the frequency band)
- Relays
  - to improve e.g. the coverage of high data rates, temporary network deployment, cell-edge throughput and/or to provide coverage in new areas
  - relay node wirelessly connected to donor cell of donor eNB
- Carrier and spectrum aggregation
  - to support wider transmission bandwidths up to 100MHz and spectrum aggregation
  - aggregation of both contiguous and non-contiguous component carriers is supported
- Coordinated Multi-Point transmission and reception
  - to improve the coverage of high data rates, the cell-edge throughput and/or to increase system throughput
LTE Advanced further supports:

- **Emergency Calls**
  - Provisioning of emergency call service to user equipment in both normal service mode (authenticated) and limited service mode (unauthenticated)

- **Positioning**
  - UE location determination through user plane and control plane based solutions; e.g., A-GNSS, OTDOA, cell level granularity location reporting

- **Public warning systems (PWS)**
  - Provisioning of timely and accurate alerts, warnings and critical information regarding disasters and other emergencies through Earthquake and Tsunami Warning System (ETWS) and Commercial Mobile Alert System (CMAS)

- **Home eNB (HeNB)**
  - Provisioning of LTE service through customer-premises equipment using operator’s licenced spectrum

- **Multimedia Broadcast/Multicast Service (MBMS)**
  - Multi-cell broadcast of multimedia services through efficient Single Frequency Network (SFN) mode of operation
E-UTRAN architecture

External IP networks (internet, corporate networks, operator services)

P-GW(s)

MME

S-GW(s)

EPC

E-UTRAN

IP Transport Network

S1-MME

S1-U

X2

Relay Node

eNodeB

Cells

External IP networks (internet, corporate networks, operator services)

Non-Access Stratum (NAS)

Access Stratum (AS)

MME

NAS

S-GW

Control Plane

User Plane

RRC

PDCP

RLC

MAC

PHY

User plane protocol stack

- **PDCP (Packet Data Convergence Protocol)**
  - Header compression using the RoHC protocol†;
  - In-sequence delivery and retransmission of PDCP SDUs for AM Radio Bearers at handover;
  - Duplicate detection;
  - Ciphering;
  - Integrity protection‡.

- **RLC (Radio Link Control)**
  - Transfer of upper layer PDUs supporting AM, UM and TM data transfer;
  - Error Correction through ARQ;
  - Segmentation according to the size of the TB;
  - Re-segmentation of PDUs that need to be retransmitted;
  - Concatenation of SDUs for the same radio bearer;
  - Protocol error detection and recovery;
  - In-sequence delivery

- **MAC (Media Access Control)**
  - Multiplexing/demultiplexing of RLC PDUs
  - Scheduling Information reporting;
  - Error correction through HARQ;
  - Logical Channel Prioritisation;
  - Padding;

†) for U-plane  ‡) for C-plane

Channel Mapping

Transport Channels:
- PCH: Paging Ch.
- BCH: Broadcast Ch.
- MCH: Multicast Ch.
- DL-SCH: Downlink Shared Ch.
- UL-SCH: Uplink Shared Ch.

Logical channels:
- PCCH: Paging Control Ch.
- BCCH: Broadcast Control Ch.
- CCCH: Common Control Ch.
- DCCH: Dedicated Control Ch.
- DTCH: Dedicated Traffic Ch.
- MCCH: Multicast Control Ch.
- MTCH: Multicast Traffic Ch.
Control plane protocol stack

- RLC and MAC sublayers perform the same functions as for the user plane.
- PDCP sublayer performs ciphering and integrity protection.

RRC (Radio Resource Control) protocol performs:
- Broadcast of System Information related to NAS and AS;
- Establishment, maintenance and release of RRC connection;
- Establishment, configuration, maintenance and release of Signalling and Data Radio Bearers (SRBs and DRBs);
- Security functions including key management;
- Mobility functions including, e.g.:
  - Control of UE cell selection/reselection; Paging; UE measurement configuration and reporting; Handover;
- QoS management functions;
- UE measurement reporting and control of the reporting;
- Notification for ETWS, CMAS and MBMS;
- NAS direct message transfer between UE and NAS.

TS 36.331
User plane

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Reliable transport
Retransmission protocols

L1 applies 24 bit CRC protection to transport blocks (MAC PDUs)
- Erroneous transport blocks are discarded on L1

Hybrid ARQ protocol in MAC complemented by ARQ protocol in RLC for high reliability and radio efficiency
- HARQ feedback sent on L1/L2 control channel
  - Single, uncoded bit (low overhead)
  - Sent for each scheduled subframe (fast)
  - Retransmissions are soft-combined with previous attempt (efficient)
- ARQ status report sent as MAC data
  - protected by CRC and HARQ retransmissions
  - RLC Status is sent on demand (poll, timer, gap detection)

Both HARQ and ARQ protocols terminated in the eNB
- fast handling of residual HARQ errors

Ensures low latency and high reliability

†) RLC AM (Acknowledged Mode) only. No retransmissions in RLC UM (Unacknowledged mode).
Reliable transport
Lossless and in-sequence delivery

Lossless and in-sequence delivery of data provided by:
- RLC retransmission (ARQ) and re-ordering functions for normal operation (based on RLC SNs)
- PDCP forwarding, retransmission and reordering functions for handover cases (based on PDCP SNs)
  - For RLC AM data radio bearers only
  - PDCP SNs are maintained across handovers
  - Lower layers (RLC/MAC) are reset

Duplicate detection provided by PDCP
- Duplicates may disturb TCP performance
- Detects and removes duplicates based on PDCP Sequence Numbers (SNs)
User Plane data flow (downlink)
Scheduling

Scheduler residing in eNB with objective of:
• Fulfiling of "QoS Contracts";
• Maximising cell throughput;
• Providing Fairness,

based on measurements, scheduling information and QoS parameters.

Scheduling Information from UE, e.g.:
• Channel Quality Indication; Buffer Status Report; Power Headroom Report; Uplink Sounding.

QoS framework with per bearer granularity
• Bearers associated with several QoS parameters, e.g.:
  • QoS Class Identifier (QCI); Guaranteed Bit Rate (GBR); Allocation and Retention Priority (ARP); Logical Channel Priority; Prioritised Bit Rate (PBR); Aggregate Maximum Bitrate (AMBR).
• Supports wide range of services, e.g.:
  • Basic conversational service class, rich conversational service class and conversational low delay service class;
  • Also interactive high delay, interactive low delay, streaming live, streaming non-live and background.
Scheduling
Dynamic & Semi-Persistent & TTI Bundling

Scheduling decisions dynamically signaled on L1L2 control channel PDCCH
• 1ms Transmission Time Interval (TTI) for DL-SCH and UL-SCH
• PDCCH provides physical resource allocation, Modulation and Coding scheme, New-Data indicator, Transport Block size, Redundancy version, HARQ Process ID
• DL: adaptive HARQ
  • All (re-)transmissions are indicated on PDCCH
  • Synchronous HARQ feedback, asynchronous retransmissions
• UL: adaptive and non-adaptive HARQ
  • First transmission indicated on PDCCH
  • Retransmissions can be indicated on PDCCH or be derived from previous transmission parameters and HARQ feedback
  • Synchronous HARQ feedback, synchronous retransmissions

Semi-Persistent Scheduling (SPS)
• Reduced L1/L2 control signalling for traffic with periodic transmissions
  • UL/DL resources configured to occur at specific interval
  • Only first assignment/grant need to be signalled
  • Subsequent transmissions use the same resources as the first transmission
  • Can be deactivated with a special assignment/grant

TTI Bundling
• Improved coverage at lower delay
  • UE performs multiple HARQ transmission attempts in consecutive TTIs before receiving HARQ feedback
  • Less HARQ signalling reduces risk of HARQ failure
UE battery efficiency
Discontinuous Reception - DRX

- Configurable Sleep Mode for UE’s receiver chain
- Periodic repetition of an “On Duration” followed by a possible period of inactivity

“Active time” defines periods of mandatory activity:
  - In configured On Duration (e.g. 2 ms per 20 ms);
  - While receiving assignments or grants for new data;
    (an Inactivity Timer is (re-)started and the UE is prepared to be scheduled continuously);
  - When expecting a retransmission of a Downlink HARQ transmission (one HARQ RTT after receiving
    an unsuccessful DL transmission);
  - When expecting HARQ feedback for an Uplink HARQ transmission;
  - After transmitting a Scheduling Request.

- Two-level DRX scheme
  - Long DRX for very power efficient operation during periods of low activity
  - Short DRX for low latency during periods of more activity
  - Autonomous transitions between states
Security
Ciphering and Integrity Protection

- AS security functions provided by PDCP controlled by RRC
  - Always activated early
  - Once started, always on
  - Based on SNOW3G and AES algorithms
  - Keys changed at handover; backward and forward security
  - Counter split in two parts for high radio efficiency:
    - Hyper Frame Number (HFN): maintained locally
    - Sequence Number (SN): signalled over the air

- Integrity protection
  - for C-plane radio bearers (Signalling Radio Bearers)
  - 32-bit Message Authentication Code (MAC-I)
  - MAC-I placed at end of PDU

- Ciphering (confidentiality protection)
  - for C-plane radio bearers (Signalling Radio Bearers)
  - for U-plane radio bearers (Data Radio Bearers)
  - PDCP Control PDUs (RoHC feedback and PDCP status reports) not ciphered
Control plane

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System Information

- System Information is provided by RRC, structured in MIB and SIBs
- **MIB** – transmitted in fixed location
  - Includes parameters essential to find SIB1 scheduled on DL-SCH (e.g., DL bandwidth and System Frame Number)
- **SIB1** – scheduled in the frequency domain (fixed timing) on DL-SCH
  - Contains information relevant when evaluating if a UE is allowed to access a cell and defines the scheduling of other system information
- Other SIBs are multiplexed in *SystemInformationMessages*
  - Scheduled in time and frequency domains as defined by SIB1
  - **SIB2**
    - contains resource configuration information that is common for all UEs; needed before accessing a cell
  - **SIB3, SIB4, ...**
    - other system information grouped according to functionality
Connection Management

Connection/session management is performed by:

- the RRC protocol between the UE and E-UTRAN
- the NAS protocol between the UE and CN

The NAS protocol performs e.g.:

- authentication, registration, bearer context activation/deactivation and location registration management

RRC messages are used e.g., to:

- establish connection, configure the radio bearers and their corresponding attributes, and to control mobility

The RRC protocol has two states:

- RRC_IDLE and RRC_CONNECTED
Mobility and RRC State Models

**IDLE:**
- UE known in EPC and has IP address;
- UE not known in E-UTRAN/eNB;
- UE location known on Tracking Area level;
- Unicast data transfer not possible;
- UE reached by paging in tracking areas controlled by EPC;
- UE-based cell-selection and tracking area update to EPC.

**CONNECTED:**
- UE known in EPC and E-UTRAN/eNB; "context" in eNB;
- UE location known on cell level;
- Unicast data transfer possible;
- DRX supported for power saving;
- Mobility is controlled by the network.
Idle Mode Mobility

UE known on Tracking Area (TA) level

TA list 1
- TA1
- TA2
- TA3

MME

Page in TA1, TA2, TA3

UE reached by paging in TAs
Idle Mode Mobility

1 area (3 in WCDMA)

- Tracking area, TA

<table>
<thead>
<tr>
<th>TA list 1</th>
<th>TA list 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>-TA1</td>
<td>-TA2</td>
</tr>
<tr>
<td>-TA2</td>
<td>-TA3</td>
</tr>
<tr>
<td>-TA3</td>
<td>-TA4</td>
</tr>
</tbody>
</table>

- MME
- TA Update request
- TA Update

Connected State Mobility

Source eNodeB configures UE measurements and reporting

Source eNB receives UE measurement report
Connected State Mobility

- HO request from source node
- Admission control
- HO Ack from target node

Diagram:
- MME
- S-GW
- eNode B
- HO Request
- HO Request ACK
Connected State Mobility

- MME
- S-GW
- HO Command from source node

eNode B

HO Command

Connected State Mobility

Data forwarding initiated

MME → S-GW → Data Forwarding

eNode B ↔ MME

eNode B ↔ S-GW

eNode B ↔ Data Forwarding

Connected State Mobility

Handover confirm to target node

MME

S-GW

eNode B

eNode B

HO confirm
Connected State Mobility

Request EPC to switch data path
S-GW switches data path
HO completed
Radio Link Failure handling

1st phase:
- Layer 1 monitors downlink quality and indicates problems to RRC
  - RRC filters L1 indications and starts a timer
  - if no recovery within 1st phase, triggers 2nd phase
- Layer 2 monitors random access attempts and indicates problems to RRC
  - RRC triggers 2nd phase

2nd phase – Radio Link Failure (RLF):
- Possible recovery through an RRC Connection Reestablishment procedure
  - reestablishment may be performed in any cell to which the UE’s context is made available
- If no recovery within 2nd phase, UE goes autonomously to IDLE
Random Access procedure

Four-step procedure to...
• ...establish uplink synchronization
• ...obtain UL-SCH resources
• ...obtain identity (C-RNTI)

1. Preamble transmission on PRACH
   ▪ Timing estimation at eNodeB
2. Random access response
   ▪ Timing Advance command
   ▪ UL-SCH resource assignment for step 3
   ▪ Temporary C-RNTI
3. Contention resolution
   ▪ transmit terminal identity
   ▪ also other data
4. Contention resolution
   ▪ Echo terminal identity from step 3
   ▪ also other signaling/data

Also support for contention-free random access procedure ➔ only step 1 and 2 used
Priority access

Access classes used to differentiate admittance in accessing a cell

- UE associated to an access class for normal use
- UE may also belong to an access class in the special categories, e.g., PLMN staff, social security services, government officials

Access class barring

- Access load can be controlled by use of access barring
- For normal use, access barring rate and barring time could be broadcast in case of congestion
- For the special categories, 1-bit barring status could be broadcast for each access class
- Barring parameters could be configured independently for mobile originating data and mobile originating signaling attempts
- For emergency calls, a separate 1-bit barring status is indicated
Performance

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Performance
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User plane latency

User plane latency (FDD RIT)
- 4ms when HARQ retransmission is not needed

User plane latency (TDD RIT)
- Depends on UL/DL configuration and on whether UL or DL transmission
- 4.9ms possible for uplink and downlink jointly when HARQ retransmission is not needed
Control plane latency - IDLE $\rightarrow$ CONNECTED

**Diagram:**

- **UE**
  - 1. RACH Waiting
  - 2. Preamble
  - 3. Processing
  - 4. Grant
  - 5. Processing
  - 6. RRC + NAS Request
  - 7. RRC Processing
    - 11. NAS Processing
  - 8. RRC Setup
  - 9. Processing
  - 10. Connection Complete
  - 12. NAS Request
  - 13. Processing
  - 14. NAS Setup
  - 15. Processing
  - 16. NAS Setup
  - 17. Processing
  - 18. Setup Complete

- **eNB**
  - 3. Processing
  - 4. Grant
  - 5. Processing
  - 6. RRC + NAS Request
  - 7. RRC Processing
    - 11. NAS Processing
  - 8. RRC Setup
  - 9. Processing
  - 10. Connection Complete
  - 12. NAS Request
  - 13. Processing
  - 14. NAS Setup
  - 15. Processing
  - 16. NAS Setup
  - 17. Processing

- **MME**
  - 12. NAS Request
  - 13. Processing

**LTE Advanced**

<table>
<thead>
<tr>
<th>Step</th>
<th>Description</th>
<th>Time [ms]</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Average delay due to RACH scheduling period (1ms RACH cycle)</td>
<td>0.5</td>
</tr>
<tr>
<td>2</td>
<td>RACH Preamble</td>
<td>1</td>
</tr>
<tr>
<td>3-4</td>
<td>Preamble detection and transmission of RA response (Time between the end RACH transmission and UE’s reception of scheduling grant and timing adjustment)</td>
<td>3</td>
</tr>
<tr>
<td>5</td>
<td>UE Processing Delay (decoding of scheduling grant, timing alignment and C-RNTI assignment + L1 encoding of RRC Connection Request)</td>
<td>5</td>
</tr>
<tr>
<td>6</td>
<td>Transmission of RRC and NAS Request</td>
<td>1</td>
</tr>
<tr>
<td>7</td>
<td>Processing delay in eNB (L2 and RRC)</td>
<td>4</td>
</tr>
<tr>
<td>8</td>
<td>Transmission of RRC Connection Set-up (and UL grant)</td>
<td>1</td>
</tr>
<tr>
<td>9</td>
<td>Processing delay in the UE (L2 and RRC)</td>
<td>12</td>
</tr>
<tr>
<td>10</td>
<td>Transmission of RRC Connection Set-up complete</td>
<td>1</td>
</tr>
<tr>
<td>11</td>
<td>Processing delay in eNB (Uu $\rightarrow$ S1-C)</td>
<td></td>
</tr>
<tr>
<td>12</td>
<td>S1-C Transfer delay</td>
<td></td>
</tr>
<tr>
<td>13</td>
<td>MME Processing Delay (including UE context retrieval of 10ms)</td>
<td></td>
</tr>
<tr>
<td>14</td>
<td>S1-C Transfer delay</td>
<td></td>
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<tr>
<td>15</td>
<td>Processing delay in eNB (S1-C $\rightarrow$ Uu)</td>
<td>4</td>
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<tr>
<td>16</td>
<td>Transmission of RRC Security Mode Command and Connection Reconfiguration (+TTI alignment)</td>
<td>1.5</td>
</tr>
<tr>
<td>17</td>
<td>Processing delay in UE (L2 and RRC)</td>
<td>16</td>
</tr>
<tr>
<td></td>
<td><strong>Total delay</strong></td>
<td><strong>50</strong></td>
</tr>
</tbody>
</table>

**NOTE:** LTE Rel-8 supports IDLE $\rightarrow$ CONNECTED latency of around 80ms and, hence, already meets the ITU requirement on C-plane latency for IDLE $\rightarrow$ CONNECTED transition.
Control plane latency – Dormant ➔ Active

Uplink initiated transition from dormant state (DRX substate) to active state (non-DRX substate) for synchronised UE; including first uplink data transmission.

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<tr>
<td>1</td>
<td>Average delay to next SR opportunity (1ms PUCCH cycle)</td>
<td>0.5</td>
</tr>
<tr>
<td>2</td>
<td>UE sends Scheduling Request</td>
<td>1</td>
</tr>
<tr>
<td>3</td>
<td>eNB decodes Scheduling Request and generates the Scheduling Grant (+ delay for nearest DL subframe)</td>
<td>3</td>
</tr>
<tr>
<td>4</td>
<td>Transmission of Scheduling Grant</td>
<td>1</td>
</tr>
<tr>
<td>5</td>
<td>UE Processing Delay (decoding of scheduling grant + L1 encoding of UL data)</td>
<td>3</td>
</tr>
<tr>
<td>6</td>
<td>Transmission of UL data</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td><strong>Total delay</strong></td>
<td><strong>9.5</strong></td>
</tr>
</tbody>
</table>
**Handover interruption**

**Intra-LTE inter-eNB handover**

- Target cell already identified and measured by the UE
  - Fast radio synchronisation to target aided by previous measurement

**Data forwarding initiated before radio synchronisation to target cell and backhaul faster than radio**

- Forwarded data available in target when UE is ready to receive
- Data forwarding does not affect overall delay
Handover interruption (cont’d)

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<td>Radio Synchronisation to the target cell</td>
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<td>7</td>
<td>Transmission of DL Datta</td>
<td>1</td>
</tr>
</tbody>
</table>

Total delay 10.5

Note: This delay does not depend on the frequency of the target in the typical case where the cell has already been measured by the UE.
References

- TR 36.912: Feasibility study for Further Advancements for E-UTRA (LTE-Advanced)
- TS 36.300: E-UTRA and E-UTRAN Overall description
- TS 36.304: E-UTRA User Equipment (UE) procedures in idle mode
- TS 36.321: E-UTRA Medium Access Control (MAC) protocol specification
- TS 36.322: E-UTRA Radio Link Control (RLC) protocol specification
- TS 36.323: E-UTRA Packet Data Convergence Protocol (PDCP) specification

Latest versions of these specifications can be acquired from:
http://www.3gpp.org/ftp/Specs/html-info/36-series.htm