Long-Term Evolution (LTE) and System Architecture Evolution (SAE)
From GSM to LTE
3GPP Evolution – Background

• Discussion started in Dec 2004

• Combination of HSDPA and E-DCH (Enhanced Dedicated Channel)
  ✓ Provides very efficient packet data transmission capabilities
  ✓ UMTS should continue to be evolved to meet the ever increasing demand of new applications and user expectations

• From the application/user perspectives, UMTS evolution should target at
  ✓ Significantly higher data rates and throughput
  ✓ Lower network latency
  ✓ Support of always-on connectivity
From the operator perspectives, an evolved UMTS will make business sense if it

✓ Provide significantly improved power and bandwidth efficiencies
✓ Facilitate the convergence with other networks/technologies
✓ Reduce transport network cost
✓ Limit additional complexity

Evolved-UTRA is a packet only network - there is no support of circuit switched services (no MSC)

Long-term Evolution (LTE) for new radio access and System Architecture Evolution (SAE) for evolved network
LTE Requirements and Performance Targets

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

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

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

- **Improved Cell Edge Rates**
  - 2-3x HSPA Rel’6 in DL*
  - 2-3x HSPA Rel’6 in UL
  - Full broadband coverage

- **Low Latency**
  - < 5ms user plane (UE to RAN edge)
  - <100ms camped to active
  - < 50ms 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
  ✓ Support 1, 2, or 4 Tx antennas and MU-MIMO

• Simplified network architecture
  ✓ Reduction the no. of logical nodes ➔ flatter architecture
  ✓ Clean separation of user and control plane
3GPP / LTE R7/R8 Specifications Timeline

- After study phase: two lines in 3GPP
  - Evolution of HSPA to HSPA+ (enhanced W-CDMA incl. MIMO)
  - Revolution towards LTE/SAE (OFDM based)
- Stage 2 (Principles) completed in March 07
- Stage 3 (Specifications) completed in Dec 07
- Test specifications completed in Dec 08
LTE + SAE = EPS

• LTE would **not** be **backward compatible** with UMTS/HSPA

• In the RAN (Radio Access Network) working groups
  ✓ Evolved UMTS Terrestrial Radio Access Network (E-UTRAN) and **Long Term Evolution** (LTE) are used interchangeably

• In the SA (System Architecture) working groups
  ✓ **System Architecture Evolution** (SAE) was used to signify the **broad framework** for the **architecture**

• LTE/SAE is known as Evolved Packet System (EPS)
Network Simplification
From 3GPP to 3GPP LTE

- 3GPP architecture
  - 4 functional entities on the control plane and user plane
  - 3 standardized user plane & control plane interfaces

- 3GPP LTE architecture
  - 2 functional entities on the user plane: eNodeB and S-GW
  - SGSN control plane functions ➔ S-GW & MME
  - Less interfaces, some functions disappear

S-GW: Serving Gateway
MME: Mobility Management Entity
eNodeB: Evolved NodeB
• 4 layers into 2 layers
✓ Evolve GGSN
   ➔ integrated S-GW
✓ Move SGSN functionalities to S-GW
✓ RNC evolutions to **RRM** on a IP distributed network for enhancing mobility management
✓ Part of **RNC mobility function** being moved to **S-GW** & **eNodeB**

**S-GW** : Serving Gateway
**MME** : Mobility Management Entity
**eNodeB** : Evolved NodeB
**RRM** : Radio Resource Management
Evolved UTRAN Architecture

- Key elements of network architecture
  - No more RNC
  - RNC layers/functionalities moves in eNB
  - X2 interface for
    - Seamless mobility (i.e. data / context forwarding)
    - Interference management

EPC: Evolved Packet Core
EPS Architecture – Functional Description of the Nodes

**eNodeB** contains all radio access functions
- Admission Control
- Scheduling of UL & DL data
- Scheduling and transmission of paging and system broadcast
- IP header compression
- Outer ARQ (RLC)

**S-GW**: Serving-GW

**P-GW**: PDN-GW

**MME**: Mobility Management Entity

**NAS**: Non Access Stratum

**S-GW** and **P-GW** control plane functions
- Idle mode UE reachability
- Tracking area list management
- S-GW/P-GW selection
- Inter core network node signaling for mobility between 2G/3G and LTE
- NAS signaling
- Authentication
- Bearer management functions

**Serving Gateway**
- Local mobility anchor for inter-eNB handovers
- Mobility anchor for inter-3GPP handovers
- Idle mode DL packet buffering
- Lawful interception
- Packet routing and forwarding

**PDN Gateway**
- UE IP address allocation
- Mobility anchor between 3GPP and non-3GPP access
- Connectivity to Packet Data Network
EPS Architecture –
Control Plane Layout over S1

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

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

- PDCP sub-layer performs:
  - Integrity protection & ciphering

NAS : Non Access Stratum
S-GW : Serving-GW
P-GW : PDN-GW

UE

eNode-B

MME

S1
EPS Architecture – User Plane Layout over S1

Physical sub-layer performs:
- DL: OFDMA, UL: SC-FDMA
- FEC
- UL power control
- Multi-stream transmission & reception (i.e. MIMO)

PDCP sub-layer performs:
- Header compression
- Ciphering

RLC sub-layer performs:
- Transferring upper layer PDUs
- In-sequence delivery of PDUs
- Error correction through ARQ
- Duplicate detection
- Flow control
- Segmentation/Concatenation of SDUs

MAC sub-layer performs:
- Scheduling
- Error correction through HARQ
- Priority handling across UEs & logical channels
- Multiplexing/de-multiplexing of RLC radio bearers into/from PhCHs on TrCHs
EPS Architecture – Interworking for 3GPP and non-3GPP Access

- Serving GW (S-GW) anchors mobility for
  - Intra-LTE handover between eNBs
  - Mobility between 3GPP access systems
  - HSPA/EDGE uses EPS core for access to PDNs

- PDN GW (P-GW)
  - The mobility anchor between 3GPP and non-3GPP access systems (SAE anchor function)
  - Handles IP address allocation

- S3 interface
  - Connects MME directly to SGSN for signaling to support mobility across LTE and UTRAN/GERAN

- S4 interface
  - Allows direction of user plane between LTE and GERAN/UTRAN (uses GTP)
LTE Key Radio Features (Release 8)

- Multiple access scheme
  - DL: OFDMA with CP (Cyclic Prefix)
  - UL: Single Carrier FDMA (SC-FDMA) with CP
- Adaptive modulation and coding
  - DL modulations: QPSK, 16QAM, and 64QAM
  - UL modulations: QPSK, 16QAM, and 64QAM (optional for UE)
  - Rel-6 Turbo code: Coding rate of 1/3, two 8-state constituent encoders, and a contention-free internal interleaver
- ARQ within RLC sublayer and Hybrid ARQ within MAC sublayer
- Advanced MIMO spatial multiplexing techniques
  - (2 or 4)x(2 or 4) downlink
  - 1x(2 or 4) uplink
  - Multi-layer transmission with up to four streams
  - Multi-user MIMO (MU-MIMO) also supported
- Implicit support for interference coordination
- Support for both FDD and TDD

Turbo codes: a class of high-performance forward error correction (FEC) codes to closely approach the channel capacity.
CP: Cyclic Prefix
LTE will support all band classes currently specified for UMTS as well as additional bands.
• OFDM: Orthogonal Frequency Division Multiplexing
• OFDMA: Orthogonal Frequency Division Multiple-Access
• FDM/ FDMA is nothing new: carriers are separated sufficiently in frequency so that there is minimal overlap to prevent cross-talk

• OFDM: still FDM but carriers can actually be orthogonal (no cross-talk) while actually overlapping, if specially designed ➔ saved bandwidth
OFDM Basics – Waveforms

- Frequency domain: overlapping sinc functions
  ✓ Referred to as subcarriers
  ✓ Typically quite narrow, e.g. 15 kHz
- Time domain: simple gated sinusoid functions
  ✓ For orthogonality: each symbol has an integer number of cycles over the symbol time
  ✓ Fundamental frequency $f_0 = 1/T$
  ✓ Other sinusoids with $f_k = k \times f_0$

$sinc(x) = \frac{\sin(x)}{x}$

$sinusoid$ : 正弦曲線
OFDM Basics – The Full OFDM Transceiver

Modulating the symbols onto subcarriers can be done very efficiently in baseband using FFT algorithm.

**Fourier Transform**: it expresses a mathematical function of time as a function of frequency, known as its frequency spectrum.

**FFT (Fast Fourier Transform)**: a fast way to calculate the Discrete Fourier Transform (DFT).
**OFDM Basics – Cyclic Prefix**

- ISI (between OFDM symbols) eliminated almost completely by inserting a guard time

![OFDM Symbol Diagram]

- Within an OFDM symbol, the data symbols modulated onto the subcarriers are only orthogonal if there are an integer number of sinusoidal cycles within the receiver window

✓ Filling the guard time with a cyclic prefix (CP) ensures orthogonality of subcarriers even in the presence of multipath \(\rightarrow\) elimination of same cell interference

**ISI (Inter Symbol Interference):** a form of distortion of a signal in which one symbol interferes with subsequent symbols
Comparison with CDMA Principle

- CDMA
  ✓ Particular modulation symbol is carried over a relatively short symbol time and a wide bandwidth
  ✓ UMTS HSPA: 4.17 µs symbol time and 3.84 MHz bandwidth
  ✓ To get higher data rates use more spreading codes

- OFDM
  ✓ Particular modulation symbol is carried over a relatively long symbol time and narrow bandwidth
  ✓ LTE: 66.6 µs symbol time and 15 kHz bandwidth
  ✓ For higher data rates send more symbols by using more sub-carriers → increases bandwidth occupancy
Comparison with CDMA
Time Domain Perspective

- **Short symbol times** in CDMA lead to **ISI** in the presence of multipath

  If the path lengths of the longest and shortest rays are **different**, then symbols traveling on those rays will reach the receiver at **different times**. In particular, the **receiver** can start to receive one symbol on a **short direct ray**, while it is still receiving the previous symbol on a **longer reflected ray**. The two symbols therefore **overlap** at the receiver, causing **inter-symbol interference (ISI)**.

- **Long symbol times** in OFDM together with **CP** prevent ISI from multipath

  Little to no overlap in symbols from multipath
Comparison with CDMA
Frequency Domain Perspective

• In CDMA each symbol is spread over a large bandwidth, hence it will experience both good and bad parts of the channel response in frequency domain.

• In OFDM each symbol is carried by a subcarrier over a narrow part of the band.
  ➔ Can avoid send symbols where channel frequency response is poor based on frequency selective channel knowledge.
  ➔ Frequency selective scheduling gain in OFDM systems.
OFDM Basics – Choosing the Symbol Time for LTE

- Two competing factors in determining the right OFDM symbol time
  - CP length should be longer than worst case multipath delay spread
  - OFDM symbol time should be much larger than CP length to avoid significant overhead from the CP
  - OFDM symbol time should be much smaller than the shortest expected coherence time of the channel to avoid channel variability within the symbol time

- LTE is designed to operate in delay spreads up to ~5μs and for speeds up to 350 km/h (1.2ms coherence time @ 2.6GHz). As such, the following was decided:
  - CP length = 4.7 μs
  - OFDM symbol time = 66.6 μs (= 1/20 the worst case coherence time (1.2ms))

Coherence time: (1) the time over which a propagating wave may be considered coherent. (2) the time interval within which its phase is on average predictable.
Scalable OFDM for Different Operating Bandwidths

- With Scalable OFDM, the subcarrier spacing stays fixed at 15 kHz (hence symbol time is fixed to 66.6 μs) regardless of the operating bandwidth (1.4 MHz, 3 MHz, 5 MHz, 10 MHz, 15 MHz, 20 MHz)

- The total number of subcarriers is varied in order to operate in different bandwidths

- Influence of delay spread, Doppler due to user mobility, timing accuracy, etc. remain the same as the system bandwidth is changed → robust design
LTE Downlink Frame Format

- 1 radio frame length = 10 subframe length = 10 ms
- 1 subframe length = 2 slots = 1 ms
- 1 slot length = 7 OFDM symbols = 0.5 ms
- 1 subframe = 14 OFDM symbols
# LTE Downlink Frame Structure

<table>
<thead>
<tr>
<th>Spectrum allocation</th>
<th>1.4 MHz</th>
<th>3 MHz</th>
<th>5 MHz</th>
<th>10 MHz</th>
<th>15 MHz</th>
<th>20 MHz</th>
</tr>
</thead>
<tbody>
<tr>
<td>Slot duration</td>
<td></td>
<td></td>
<td></td>
<td>0.5 ms</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Sub-frame duration</td>
<td></td>
<td></td>
<td></td>
<td>1.0 ms ( = 2 slots)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Sub-carrier spacing</td>
<td></td>
<td></td>
<td></td>
<td>15 kHz (7.5 kHz for MBMS)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Sampling frequency</td>
<td>1.92 MHz (1/2 × 3.84)</td>
<td>3.84 MHz</td>
<td>7.68 MHz (2 × 3.84)</td>
<td>15.36 MHz (4 × 3.84)</td>
<td>23.04 MHz (6 × 3.84)</td>
<td>30.72 MHz (8 × 3.84)</td>
</tr>
<tr>
<td>FFT size</td>
<td>128</td>
<td>256</td>
<td>512</td>
<td>1024</td>
<td>1536</td>
<td>2048</td>
</tr>
<tr>
<td>Number of sub-carriers</td>
<td>75</td>
<td>150</td>
<td>300</td>
<td>600</td>
<td>900</td>
<td>1200</td>
</tr>
<tr>
<td>OFDM symbols per slot</td>
<td></td>
<td></td>
<td></td>
<td>7 (short CP), 6 (long CP)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>CP length</td>
<td>Short</td>
<td></td>
<td></td>
<td>4.69 μs x 6</td>
<td>5.21 μs x 1</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Long</td>
<td></td>
<td></td>
<td>16.67 μs</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

*Subframe length relevant to the latency requirement*

*Sampling rates are multiples of UMTS chip rate, to ease implementation of dual mode UMTS/LTE terminals*

*FFT size scales to support larger bandwidth → Scalable OFDM*
Multiple Antenna Techniques Supported in LTE

- SU-MIMO
  - Multiple data streams sent to the same user
  - Significant throughput gains for UEs in high SINR conditions

- MU-MIMO or beamforming
  - Different data streams sent to different users using the same time-frequency resources
  - Improves throughput even in low SINR conditions (cell-edge)
  - Works even for single antenna mobiles

- Transmit diversity (TxDiv)
  - Improves reliability on a single data stream
  - Useful to improve reliability on common control channels

Beamforming: a signal processing technique used in sensor arrays for directional signal transmission or reception.
MIMO Support is Different in Downlink and Uplink

• Downlink
  ✓ Supports SU-MIMO, MU-MIMO, TxDiv

• Uplink
  ✓ Initial release of LTE does only support MU-MIMO with a single transmit antenna at the UE ⇒ Desire to avoid multiple power amplifiers at UE
LTE Downlink

- The LTE downlink uses scalable OFDMA
  - Fixed subcarrier spacing of 15 kHz for unicast
    - Symbol time fixed at $T = 1/15 \text{ kHz} = 66.67 \mu s$
  - Different UEs are assigned different sets of subcarriers so that they remain orthogonal to each other (except MU-MIMO)
Physical Channels to Support LTE Downlink

- **Synchronization Channel (SCH)**
  - Carries basic system broadcast information
- **Physical Broadcast Channel (PBCH)**
  - Carries DL traffic
  - DL resource allocation
  - Time span of PDCCH
- **Physical Downlink Shared Channel (PDSCH)**
- **Physical Downlink Control Channel (PDCCH)**
  - Physical Control Format Indicator Channel (PCFICH)
- **Physical Uplink Control Channel (PUCCH)**
- **Physical Uplink Shared Channel (PUSCH)**

**eNode-B**

- Allows mobile to get timing and frequency sync with the cell
- HARQ feedback for DL
- CQI reporting
- MIMO reporting

**CQI**: Channel Quality Indicator
Mapping Between **DL** Logical, Transport and Physical Channels

- **PCCH**: paging control channel
- **BCCH**: broadcast control channel
- **CCCH**: common control channel
- **DCCH**: dedicated control channel
- **DTCH**: dedicated traffic channel
- **PCH**: paging channel
- **BCH**: broadcast channel
- **DL-SCH**: DL shared channel

paging, and part of broadcast information carried on **PDSCH**
LTE Uplink Transmission Scheme

- To facilitate efficient power amplifier design in UE, 3GPP chose single carrier frequency domain multiple access (SC-FDMA) for uplink multiple access

  ✓ SC-FDMA results in better PAPR (Peak to Average Power Ratio)
    - Reduced PA (Power Amplifier)
      → improved coverage

- SC-FDMA is still an orthogonal multiple access scheme

  ✓ UEs are orthogonal in frequency

  ✓ Synchronous in the time domain through the use of timing advance (TA) signaling
    - Only need to be synchronous within a fraction of the CP length (CP length = 4.7 μs)
    - 0.52 μs timing advance resolution
Physical Channels to Support LTE Uplink

- **Physical Random Access Channel (PRACH)**: Random access for initial access and UL timing alignment.
- **Physical Uplink Shared Channel (PUSCH)**: Carries UL Traffic.
- **Physical Uplink Control Channel (PUCCH)**: UL scheduling request for time synchronized IEs.
- **Physical Downlink Control Channel (PDCCH)**: UL scheduling grant.
- **Physical HARQ Indicator Channel (PHICH)**: HARQ feedback for UL.
Mapping Between **UL** Logical, Transport and Physical Channels

**CCCH**: common control channel
**DCCH**: dedicated control channel
**DTCH**: dedicated traffic channel

**RACH**: random access channel
**UL-SCH**: UL shared channel

**PUSCH**: physical UL shared channel
**PUCCH**: physical UL control channel
**PRACH**: physical random access channel

**Uplink Logical channels**

**Uplink Transport channels**

**Uplink Physical Channels**
## Downlink Peak Rates

<table>
<thead>
<tr>
<th>bandwidth</th>
<th># of parallel streams supported</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>1</td>
</tr>
<tr>
<td>1.4 MHz</td>
<td>5.4 MBps</td>
</tr>
<tr>
<td>3 MHz</td>
<td>13.5 MBps</td>
</tr>
<tr>
<td>5 MHz</td>
<td>22.5 MBps</td>
</tr>
<tr>
<td>10 MHz</td>
<td>45 MBps</td>
</tr>
<tr>
<td>15 MHz</td>
<td>67.5 MBps</td>
</tr>
<tr>
<td>20 MHz</td>
<td>90 MBps</td>
</tr>
</tbody>
</table>

Assumptions: 64QAM, code rate = 1, 1OFDM symbol for L1/L2, Ignores subframes with P-BCH, SCH
### Uplink Peak Rates

<table>
<thead>
<tr>
<th>Bandwidth</th>
<th>Highest Modulation</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>16 QAM</td>
</tr>
<tr>
<td>1.4 MHz</td>
<td>2.9 MBps</td>
</tr>
<tr>
<td>3 MHz</td>
<td>6.9 MBps</td>
</tr>
<tr>
<td>5 MHz</td>
<td>11.5 MBps</td>
</tr>
<tr>
<td>10 MHz</td>
<td>27.6 MBps</td>
</tr>
<tr>
<td>15 MHz</td>
<td>41.5 MBps</td>
</tr>
<tr>
<td>20 MHz</td>
<td>55.3 MBps</td>
</tr>
</tbody>
</table>

Assumptions: code rate =1, 2PRBs reserved for PUCCH (1 for 1.4MHz), No SRS, ignores subframes with PRACH, Takes into account highest prime-factor restriction
## LTE-Release 8 User Equipment Categories

<table>
<thead>
<tr>
<th>Category</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
</tr>
</thead>
<tbody>
<tr>
<td>Peak rate Mbps</td>
<td>DL</td>
<td>10</td>
<td>50</td>
<td>100</td>
<td>150</td>
</tr>
<tr>
<td></td>
<td>UL</td>
<td>5</td>
<td>25</td>
<td>50</td>
<td>50</td>
</tr>
</tbody>
</table>

### Capability for physical functionalities

<table>
<thead>
<tr>
<th>RF bandwidth</th>
<th>20MHz</th>
</tr>
</thead>
<tbody>
<tr>
<td>Modulation</td>
<td></td>
</tr>
<tr>
<td>DL</td>
<td>QPSK, 16QAM, 64QAM</td>
</tr>
<tr>
<td>UL</td>
<td>QPSK, 16QAM</td>
</tr>
<tr>
<td></td>
<td>QPSK, 16QAM, 64QAM</td>
</tr>
</tbody>
</table>

### Multi-antenna

<table>
<thead>
<tr>
<th>2 Rx diversity</th>
<th>Assumed in performance requirements</th>
</tr>
</thead>
<tbody>
<tr>
<td>2x2 MIMO</td>
<td>Not supported</td>
</tr>
<tr>
<td>4x4 MIMO</td>
<td>Not supported</td>
</tr>
</tbody>
</table>

Mandatory
Scheduling and Resource Allocation

- Basic unit of resource allocation is called a Resource Block (RB)
  - 12 subcarriers in frequency (= 180 kHz)
  - 1 subframe in time (= 1 ms, = 14 OFDM symbols)
  - Multiple resource blocks can be allocated to a user in a given subframe

- The 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>
• LTE uses a scheduled, shared channel on both uplink (UL-SCH) and downlink (DL-SCH)

• Normally, there is no concept of an autonomous transmission

✓ All transmissions in both uplink and downlink must be explicitly scheduled

• LTE allows "semi-persistent" (periodical) allocation of resources, e.g. for VoIP
Random-Access Procedure

- RACH only used for Random Access Preamble
- ✓ Response/Data are sent over SCH
- Non-contention based RA to improve access time, e.g. for Handover
LTE Handover

- LTE uses UE-assisted network controlled handover
  - UE reports measurements
  - Network decides when handover and to which cell
  - Relies on UE to detect neighbor cells ➔ no need to maintain and broadcast neighbor lists
    - Allows "plug-and-play" capability
    - Saves BCH resources
• **X2 interface** (eNB to eNB) used for **handover** preparation and **forwarding** of user data

✓ **Target eNB** prepares handover by sending **required information** to UE transparently through **source eNB** as part of the **Handover Request Acknowledge** message

- New configuration information needed from **system broadcast**

- Accelerates handover as UE does not need to read BCH on target cell

✓ **Buffered** and new data is **transferred** from **source** to target eNB until path switch → prevents data loss

✓ **UE** uses **contention-free** random access to accelerate handover
LTE Handover: Preparation Phase

- HO decision is made by source eNB based on UE measurement report.
- Target eNB prepares HO by sending relevant info to UE through source eNB as part of HO request ACK command, so that UE does not need to read target cell BCH.
LTE Handover: Execution Phase

- RACH is used here only so target eNB can estimate UE timing and provide timing advance for synchronization.
- RACH timing agreements ensure UE does not need to read target cell P-BCH to obtain SFN (System Frame Number).
LTE Handover: Completion Phase
LTE Handover: Illustration of Interruption Period

- **UEs stops Rx/Tx on the old cell**
- **UL**
  - **Handover Interruption (approx 35 ms)**
  - **Handover Preparation**
    - **Handover Latency (approx 55 ms)**
    - **Handover Complete**
      - **ACK**
        - **DL sync**
          - **RACH (no contention)**
          - **Timing Adv**
          - **UL Resource Req and Grant**
        - **HO Complete**
          - **HO Confirm**
            - **HO Request**
              - **Measurement Report**
                - **HO Command**
                  - **Source eNB**
                    - **Target eNB**
                      - **UE**
                        - **UE- plane active**
• Tracking Area Identifier (TAI) sent over **Broadcast Channel** (BCH)
• Tracking Areas can be **shared** by multiple MMEs
EPS Bearer Service Architecture

EPC : Evolved Packet Core
EPS : Evolved Packet System
EPS = E-UTRAN + EPC
RRC State Transitions in LTE

DRX: Discontinuous Reception
LTE RRC States

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

**DRX**: Discontinuous Reception
**DRX cycle**: MS藉此cycle調整各自喚醒的排程

- **RRC connection and 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**
**EPS Connection Management States**

**ECM IDLE**

- 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)

**ECM CONNECTED**

- Signaling connection established between UE and MME, consists of two components
  - RRC connection
  - S1-MME connection
- UE location is known to accuracy of Cell-ID
- Mobility via handover procedure
EPS Mobility Management States

- EMM context holds **no 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 within **tracking area**
- MME can **page** to UE
- UE always has **at least one PDN connection**
LTE – Summary

• LTE is a new air interface with no backward compatibility to WCDMA
  ✓ Combination of OFDM, MIMO and High Order Modulation (HOM)
• SAE/ EPS realizes a flatter IP-based network architecture with less complexity
  ✓ eNodeB, S-GW, P-GW
• Some procedures/protocols are being re-used from UMTS
  ✓ Protocol stack
  ✓ Concept of Logical/ Transport/ Physical Channels
• Complexity is significantly reduced
  ✓ Reduced UE state space
  ✓ Most transmission uses SCH
• LTE standard
  ✓ Rel. 8 is stable
  ✓ Rel. 9：technical enhancements/ E-MBMS
  ✓ Rel. 10：LTE-Advanced
**LTE-Advanced**

- The evolution of LTE
  - Corresponding to LTE Release 10 and beyond
- Motivation of LTE-Advanced
  - IMT-Advanced standardization process in ITU-R
  - Additional IMT spectrum band identified in WRC07
  - Further evolution of LTE Release 8 and 9 to meet
    - Requirements for IMT-Advanced of ITU-R
    - Future operator and end-user requirements
Evolution from IMT-2000 to IMT-Advanced

IMT-Advanced will encompass the capabilities of previous systems.

New capabilities of IMT-Advanced

New Mobile Access

New Nomadic / Local Area Wireless Access

Peak useful data rate (Mbit/s)

Interconnection

Nomadic / Local Area Access Systems

Digital Broadcast Systems
System Performance Requirements

- Peak data rate
  - 1 Gbps data rate will be achieved by 4-by-4 MIMO
  - Transmission bandwidth wider than approximately 70 MHz
- Peak spectrum efficiency
  - DL: Rel. 8 LTE satisfies IMT-Advanced requirement
  - UL: need to double from Release 8 to satisfy IMT-Advanced requirement

<table>
<thead>
<tr>
<th></th>
<th>Rel. 8 LTE</th>
<th>LTE-Advanced</th>
<th>IMT-Advanced</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Peak data rate</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>DL</td>
<td>300 Mbps</td>
<td>1 Gbps</td>
<td>1 Gbps(*)</td>
</tr>
<tr>
<td>UL</td>
<td>75 Mbps</td>
<td>500 Mbps</td>
<td></td>
</tr>
<tr>
<td><strong>Peak spectrum efficiency [bps/Hz]</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>DL</td>
<td>15</td>
<td>30</td>
<td>15</td>
</tr>
<tr>
<td>UL</td>
<td>3.75</td>
<td>15</td>
<td>6.75</td>
</tr>
</tbody>
</table>

*“100 Mbps for high mobility and 1 Gbps for low mobility” is one of the key features as written in Circular Letter (CL)*
Technical Outline to Achieve LTE-Advanced Requirements

• Support wider bandwidth
  ✓ Carrier aggregation to achieve wider bandwidth
  ✓ Support of spectrum aggregation
  ➡ Peak data rate, spectrum flexibility

• Advanced MIMO techniques
  ✓ Extension to up to 8-stream transmission in downlink
  ✓ Introduction of single-user MIMO up to 4-stream transmission in uplink
  ➡ Peak data rate, capacity, cell-edge user throughput
• Coordinated multipoint transmission and reception (CoMP)
  ✓ CoMP transmission in downlink
  ✓ CoMP reception in uplink
  ➡ Cell-edge user throughput, coverage, deployment flexibility

• Relaying
  ✓ Type 1 relays create a separate cell and appear as Rel. 8 LTE eNB to Rel. 8 LTE UEs
  ➡ Coverage, cost effective deployment

• Further reduction of delay
  ✓ AS/NAS parallel processing for reduction of C-Plane delay
Carrier Aggregation

- Wider bandwidth transmission using **carrier aggregation**
  - Entire system bandwidth up to, e.g., 100 MHz, comprises **multiple basic frequency blocks** called **component carriers** (CCs)
  - Each CC is **backward compatible** with Rel. 8 LTE
  - Carrier aggregation supports both **contiguous** and **non-contiguous spectrums**, and **asymmetric bandwidth** for FDD
Advanced MIMO Techniques

- Extension up to 8-stream transmission for single-user (SU) MIMO in downlink
  ✓ Improve downlink peak spectrum efficiency
- Enhanced multi-user (MU) MIMO in downlink
  ✓ Specify additional reference signals (RS)
- Introduction of single-user (SU)-MIMO up to 4-stream transmission in uplink
  ✓ Satisfy IMT requirement for uplink peak spectrum efficiency
Coordinated Multipoint Transmission/Reception (CoMP)

- Enhanced service provisioning, especially for cell-edge users
- CoMP transmission schemes in downlink
  - Joint processing (JP) from multiple geographically separated points
  - Coordinated scheduling/Coordinated beamforming (CS/CB) between cell sites
- Similar for the uplink
  - Dynamic coordination in uplink scheduling
  - Joint reception at multiple sites

Coherent combining or dynamic cell selection
Joint transmission/dynamic cell selection
Coordinated scheduling/beamforming
Receiver signal processing at central eNB (e.g., MRC, MMSEC)

MRC: Maximal Ratio Combining
MMSEC: Minimum Mean Square Combining
Relaying

- Type 1 relay
  - Relay node (RN) creates a separate cell
  - UE receives/transmits control signals for scheduling and HARQ from/to RN
  - RN appears as a Rel. 8 LTE eNB to Rel. 8 LTE UEs
    - Deploy cells in the areas where wired backhaul is not available or very expensive
<table>
<thead>
<tr>
<th>Abbreviation</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>CP</td>
<td>Cyclic Prefix</td>
</tr>
<tr>
<td>DFT</td>
<td>Discrete Fourier Transformation</td>
</tr>
<tr>
<td>DRX</td>
<td>Discontinuous Reception</td>
</tr>
<tr>
<td>ECM</td>
<td>EPS Connection Management</td>
</tr>
<tr>
<td>EMM</td>
<td>EPS Mobility Management</td>
</tr>
<tr>
<td>eNodeB/eNB</td>
<td>Evolved NodeB</td>
</tr>
<tr>
<td>EPC</td>
<td>Evolved Packet Core</td>
</tr>
<tr>
<td>EPS</td>
<td>Evolved Packet System</td>
</tr>
<tr>
<td>E-UTRAN</td>
<td></td>
</tr>
<tr>
<td>FDD</td>
<td>Frequency-Division Duplex</td>
</tr>
<tr>
<td>FDM</td>
<td>Frequency-Division Multiplexing</td>
</tr>
<tr>
<td>FFT</td>
<td>Fast Fourier Transformation</td>
</tr>
<tr>
<td>HD-FDD</td>
<td>Half-Duplex FDD</td>
</tr>
<tr>
<td>HO</td>
<td>Handover</td>
</tr>
<tr>
<td>HOM</td>
<td>Higher Order Modulation</td>
</tr>
<tr>
<td>HSS</td>
<td>Home Subscriber Server</td>
</tr>
<tr>
<td>IFFT</td>
<td>Inverse FFT</td>
</tr>
<tr>
<td>ISI</td>
<td>Inter-Symbol Interference</td>
</tr>
<tr>
<td>LTE</td>
<td>Long Term Evolution</td>
</tr>
<tr>
<td>MIMO</td>
<td>Multiple-Input Multiple-Output</td>
</tr>
<tr>
<td>MME</td>
<td>Mobility Management Entity</td>
</tr>
<tr>
<td>MU</td>
<td>Multi-User</td>
</tr>
<tr>
<td>OFDM</td>
<td>Orthogonal Frequency-Division Multiplexing</td>
</tr>
<tr>
<td>OFDMA</td>
<td>Orthogonal Frequency-Division Multiple-Access</td>
</tr>
<tr>
<td>PCRF</td>
<td>Policy &amp; Charging Function</td>
</tr>
<tr>
<td>PDN</td>
<td>Packet Data Network</td>
</tr>
<tr>
<td>P-GW</td>
<td>PDN Gateway</td>
</tr>
<tr>
<td>RA</td>
<td>Random Access</td>
</tr>
<tr>
<td>RB</td>
<td>Resource Block</td>
</tr>
<tr>
<td>RRC</td>
<td>Radio Resource Control</td>
</tr>
<tr>
<td>SAE</td>
<td>System Architecture Evolution</td>
</tr>
<tr>
<td>SCH</td>
<td>Shared Channel</td>
</tr>
<tr>
<td>S-GW</td>
<td>Serving Gateway</td>
</tr>
<tr>
<td>SC-FDMA</td>
<td>Single Carrier FDMA</td>
</tr>
<tr>
<td>SU</td>
<td>Single User</td>
</tr>
<tr>
<td>TDD</td>
<td>Time-Division Duplex</td>
</tr>
<tr>
<td>TA</td>
<td>Timing Advance/ Tracking Area</td>
</tr>
<tr>
<td>TAI</td>
<td>Tracking Area Indicator</td>
</tr>
<tr>
<td>TAU</td>
<td>Tracking Area Update</td>
</tr>
<tr>
<td>UE</td>
<td>User Equipment</td>
</tr>
</tbody>
</table>