Evolution of Wireless and Wireless

Wireline
- GPON 100 Mbps
- VDSL2 100 Mbps
- ADSL2+ 25-50 Mbps
- ADSL 16-20 Mbps
- ADSL 6-8 Mbps
- WCDMA 1.8 Mbps
- EDGE 0.384 Mbps
- EDGE 0.236 Mbps

Wireless
- HSDPA 3.6-7.2 Mbps
- HSPA 14 Mbps
- WCDMA 42 Mbps
- EDGE 2 Mbps
- EDGE 472 kbps

User data rate [Mbps]

2000 2005 2010

1.000
100
10
1
0.1
0.01
0.001

Commercial deployment


EDGE WCDMA HSDPA HSUPA HSPA+ LTE

Modul 13 - 4G LTE
Evolution 1G to 3,9 G

Peak Transfer Data Rate

| No packet data service | CSD : 9,6 Kbps | HSCSD : 38,4 Kbps | 56 – 114 Kbps | 384 Kbps | 2 Mbps | 14,4 Mbps | 50 Mbps (LTE) : 100 Mbps (LTE Advanced) |
Evolution step GSM / GPRS / UMTS / HSDPA

UMTS (WCDMA) INFRASTRUCTURE

GPRS INFRASTRUCTURE

GSM INFRASTRUCTURE

Modul 13 - 4G LTE
<table>
<thead>
<tr>
<th>Generation</th>
<th>Family/Standardization body</th>
<th>Technologies</th>
<th>Features</th>
<th>Mobil./Roam</th>
<th>Throughput</th>
<th>Capacity</th>
<th>Services</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>3GPP2</td>
<td>CdmaOne (IS-95 A and B)</td>
<td></td>
<td>![😊]</td>
<td>![😊]</td>
<td>![😊]</td>
<td>![😊]</td>
</tr>
<tr>
<td></td>
<td>Other</td>
<td>D-AMPS (IS-54 and IS-136), PDC, PHS</td>
<td></td>
<td>![😊]</td>
<td>![😊]</td>
<td>![😊]</td>
<td>![😊]</td>
</tr>
<tr>
<td>2.5G (1999 - 00)</td>
<td>GSM/3GPP</td>
<td>GPRS, HSCSD</td>
<td>PS data</td>
<td>![😊]</td>
<td>![😊]</td>
<td>![😊]</td>
<td>![😊]</td>
</tr>
<tr>
<td></td>
<td>3GPP2</td>
<td>CDMA2000 1xRTT (IS-2000)</td>
<td></td>
<td>![😊]</td>
<td>![😊]</td>
<td>![😊]</td>
<td>![😊]</td>
</tr>
<tr>
<td></td>
<td>3GPP2</td>
<td>CDMA2000 1xEV-DO (IS-856)</td>
<td></td>
<td>![😊]</td>
<td>![😊]</td>
<td>![😊]</td>
<td>![😊]</td>
</tr>
<tr>
<td>Generation</td>
<td>Family/Standard body</td>
<td>Technologies</td>
<td>Features</td>
<td>Mobil./Roam</td>
<td>Throughput</td>
<td>Capacity</td>
<td>Services</td>
</tr>
<tr>
<td>---------------</td>
<td>----------------------</td>
<td>------------------------</td>
<td>-----------------------------------------</td>
<td>-------------</td>
<td>------------</td>
<td>----------</td>
<td>----------</td>
</tr>
<tr>
<td>3.5G (2005–present)</td>
<td>3GPP</td>
<td>HSDPA, HSUPA</td>
<td>Higher data rates, less latency, more capacity</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>3GPP2</td>
<td>EV-DO Rev. A</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>3.75G (2007–present)</td>
<td>3GPP</td>
<td>HSPA+</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>3GPP2</td>
<td>CDMA2000 3x (EV-DO Rev. B)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>3.9G (2010)</td>
<td>3GPP</td>
<td>3GPP LTE</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Other</td>
<td>IEEE 802.16e-2005, Flash-OFDM, IEEE 802.20</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>4G (IMT-Advanced)</td>
<td>?</td>
<td>?</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Mobile Evolution


Services: Voice, SMS, MMS, Video Calls, Media Clips, Mobile TV, Mobile Triple Play/Gaming, Personalised Localised Services

Technology: GSM, GPRS, UMTS, HSDPA, HSUPA MBMS IP transp., HSPA+, LTE OFDM access, 4G

User Expectations: Voice and Text, Download, Real time delivery, Interactive Information Swapping, Anywhere Anytime Anyhow

Operators Strategy: Voice Centric, Coverage, Multimedia Centric, Capacity, Bundled Services @ home, office, Indoor Coverage, User Centric, FMS/FMC & NGN (All IP)

Modul 13 - 4G LTE
3 Kelemahan 3G

1. Bit rate maksimum masih 1/20 dari sistem 802.11n dan 802.16e/m.
2. Latency dari user plane traffic (UMTS: >30 ms) dan prosedur penugasan resource (UMTS: >100 ms) terlalu besar untuk menangani trafik dengan variansi tinggi secara efisien.
<table>
<thead>
<tr>
<th>Generation</th>
<th>Requirements</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>1G</td>
<td>No official requirements. Analog technology.</td>
<td>Deployed in the 1980s.</td>
</tr>
<tr>
<td>2G</td>
<td>No official requirements. Digital Technology.</td>
<td>First digital systems. Deployed in the 1990s. New services such as SMS and low-rate data. Primary technologies include CDMA2000 1xRTT and GSM.</td>
</tr>
<tr>
<td>3G</td>
<td>ITU’s IMT-2000 required 144 kbps mobile, 384 kbps pedestrian, 2 Mbps indoors</td>
<td>Primary technologies include CDMA2000 EV-DO and UMTS-HSPA. WiMAX now an official 3G technology.</td>
</tr>
<tr>
<td>4G</td>
<td>ITU’s IMT-Advanced requirements include ability to operate in up to 40 MHz radio channels and with very high spectral efficiency.</td>
<td>No technology meets requirements today. IEEE 802.16m and LTE Advanced being designed to meet requirements.</td>
</tr>
</tbody>
</table>
# Characteristics of 3GPP Technologies

<table>
<thead>
<tr>
<th>Technology Name</th>
<th>Type</th>
<th>Characteristics</th>
<th>Typical Downlink Speed</th>
<th>Typical Uplink Speed</th>
</tr>
</thead>
<tbody>
<tr>
<td>GSM</td>
<td>TDMA</td>
<td>Most widely deployed cellular technology in the world. Provides voice and data service via GPRS/EDGE.</td>
<td></td>
<td></td>
</tr>
<tr>
<td>EDGE</td>
<td>TDMA</td>
<td>Data service for GSM networks. An enhancement to original GSM data service called GPRS.</td>
<td>70 kbps to 135 kbps</td>
<td>70 kbps to 135 kbps</td>
</tr>
<tr>
<td>Evolved EDGE</td>
<td>TDMA</td>
<td>Advanced version of EDGE that can double and eventually quadruple throughput rates, halve latency and increase spectral efficiency.</td>
<td>175 kbps to 350 kbps expected (Single Carrier)</td>
<td>150 kbps to 300 kbps expected</td>
</tr>
<tr>
<td>UMTS</td>
<td>CDMA</td>
<td>3G technology providing voice and data capabilities. Current deployments implement HSPA for data service.</td>
<td>200 to 300 kbps</td>
<td>200 to 300 kbps</td>
</tr>
<tr>
<td>HSPA</td>
<td>CDMA</td>
<td>Data service for UMTS networks. An enhancement to original UMTS data service.</td>
<td>1 Mbps to 4 Mbps</td>
<td>500 kbps to 2 Mbps</td>
</tr>
<tr>
<td>HSPA+</td>
<td>CDMA</td>
<td>Evolution of HSPA in various stages to increase throughput and capacity and to lower latency.</td>
<td>1.5 Mbps to 7 Mbps</td>
<td>1 Mbps to 4 Mbps</td>
</tr>
<tr>
<td>LTE</td>
<td>OFDMA</td>
<td>New radio interface that can use wide radio channels and deliver extremely high throughput rates. All communications handled in IP domain.</td>
<td>4 Mbps to 24 Mbps (in 2 x 20 MHz)</td>
<td></td>
</tr>
<tr>
<td>LTE-Advanced</td>
<td>OFDMA</td>
<td>Advanced version of LTE designed to meet IMT-Advanced requirements.</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Background of LTE: Access Network Evolution

The Driver for LTE is Data…

Modul 13 - 4G LTE
Wireless Access Roadmap

Low Mobility

High Mobility

Vehicular

Pedestrian

Portable

Fixed

$0.30 - $20/Mbytes

$0.01-$0.07/Mbytes

White Data, Location Services, Augmented Reality, Music/Video, Voice over IP, Remote Control

2G

GPRS, cdmaOne, PDC

GSM, cdmaOne, PDC

DECT/Cordless Phones

56K Modems

Bluetooth

3G

W-CDMA/HSPA

R4 (2.3 Mbps), R5 (14.4 Mbps)

CDMA2000 1x

EV-DO (2.4 Mbps), EV-DV (3 Mbps)

HPSDA

WiMAX 802.16e, LTE

Early 4G Systems

802.16a FBWA

LTE 3.9G

802.16m WiMAX 2

4G

802.15a UWB PAN

802.11g

802.11b

760 Kbps

2-11 Mbps

1.5 – 20 Mbps

Broadband Fixed Wireless Access

T3 Lines

E1/T1 Lines

54 Mbps

144 kbps

Multimedia Data, Location Services, Augmented Reality, Music/Video, Voice over IP, Remote Control

802.11g

802.11a

802.16a FBWA

802.16m WiMAX 2

LTE Advanced

2G

3G

4G

2.5G

GPRS, EDGE, CDMA2000

Portability

Fixed

Modul 13 - 4G LTE
Mobile WiMAX

- Rel 1.0
  - 802.16e-2005

- Rel 1.5
  - 802.16e Rev 2

- Rel 2.0
  - 802.16m

3GPP

- HSPA
  - Rel-6

- HSPA+
  - Rel-7 & Rel-8

4G

- LTE & LTE Advanced

- IP e2e Network

3.5G

- Circuit Switched Network

3.9G

- Mobile WiMAX time to market advantage

4G

- CDMA-Based

- OFDMA-Based

IMT-Advanced

- 4G

Timeline:

- 2008
- 2009
- 2010
- 2011
- 2012

Modul 13 - 4G LTE
## Evolution of TDMA, CDMA and OFDMA Systems

<table>
<thead>
<tr>
<th>Year</th>
<th>Technology</th>
<th>DL</th>
<th>UL</th>
<th>Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td>2008</td>
<td>EDGE</td>
<td>474 kbps</td>
<td>474 kbps</td>
<td></td>
</tr>
<tr>
<td>2009</td>
<td>HSPA</td>
<td>14.4 Mbps</td>
<td>5.76 Mbps</td>
<td>In 5 MHz</td>
</tr>
<tr>
<td>2009</td>
<td>Rel 7 HSPA+</td>
<td>DL: 28 Mbps</td>
<td>UL: 11.5 Mbps</td>
<td>In 5 MHz</td>
</tr>
<tr>
<td>2010</td>
<td>Rel 8 HSPA+</td>
<td>DL: 42 Mbps</td>
<td>UL: 11.5 Mbps</td>
<td>In 5 MHz</td>
</tr>
<tr>
<td>2011</td>
<td>Rel 9 HSPA+</td>
<td>DL: 84 Mbps</td>
<td>UL: 23 Mbps</td>
<td>In 10 MHz</td>
</tr>
<tr>
<td>2012</td>
<td>LTE</td>
<td>326 Mbps</td>
<td>86 Mbps</td>
<td>In 20 MHz</td>
</tr>
<tr>
<td>2012</td>
<td>LTE (Rel 9)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2013</td>
<td>4G</td>
<td></td>
<td></td>
<td>LTE Advanced DL: &gt; 1 Gbps</td>
</tr>
</tbody>
</table>

### 3GPP2

<table>
<thead>
<tr>
<th>Year</th>
<th>Technology</th>
<th>DL</th>
<th>UL</th>
<th>Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td>2008</td>
<td>EV-DO Rev A</td>
<td>3.1 Mbps</td>
<td>1.8 Mbps</td>
<td>In 1.25 MHz</td>
</tr>
<tr>
<td>2010</td>
<td>EV-DO Rev B</td>
<td>14.7 Mbps</td>
<td>4.9 Mbps</td>
<td>In 5 MHz</td>
</tr>
</tbody>
</table>

### Fixed WIMAX

<table>
<thead>
<tr>
<th>Year</th>
<th>Technology</th>
<th>DL</th>
<th>UL</th>
<th>Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Fixed WIMAX</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

### Mobile WIMAX

<table>
<thead>
<tr>
<th>Year</th>
<th>Technology</th>
<th>DL</th>
<th>UL</th>
<th>Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Release 1.0</td>
<td>46 Mbps</td>
<td>4 Mbps</td>
<td>10 MHz 3:1 TDD</td>
</tr>
<tr>
<td>2014</td>
<td>Rel 1.5</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2015</td>
<td>4G</td>
<td></td>
<td></td>
<td>IEEE 802.16m</td>
</tr>
</tbody>
</table>

Notes: Throughput rates are peak theoretical network rates. Radio channel bandwidths indicated. Dates refer to expected initial commercial network deployment except 2008, which shows available technologies that year.
Radio Spektrum UMTS

fig. 3: Spectrum for UMTS -
- 1920 MHz - 1980 MHz: FDD Uplink
- 2110 MHz - 2170 MHz: FDD Downlink
- 1900 MHz - 1920 MHz: TDD
- 2010 MHz - 2025 MHz
- 1980 MHz - 2010 MHz: MSS (Mobile Satellite Service) Uplink
- 2170 MHz - 2200 MHz: MSS Downlink
Core Network Architecture UMTS

TE ... Terminal Equipment
MT ... Mobile Terminal
UTRAN ... Access Network
ERAN ... Edge Access Network
SGSN ... Serving GPRS Support Node
GGSN ... Gateway GPRS Support Node
HSS ... Home Subscriber Server
CSCF ... Call State Control Function

R-SGW ... Roaming Signalling Gateway Function
MGCF ... Media Gateway Control Function
MGW ... Media Gateway Function
T-SGW ... Transport Signalling Gateway Function

Modul 13 - 4G LTE
Gambar 2.4 Arsitektur Jaringan UMTS
# W-CDMA Parameters

<table>
<thead>
<tr>
<th>Parameters</th>
<th>3GPP (W-CDMA)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Carrier Spacing</td>
<td>5 MHz. (nominal) 4.2-5.4 MHz. On 200 kHz. raster</td>
</tr>
<tr>
<td>Downlink RF Channel Structure</td>
<td>Direct Spread</td>
</tr>
<tr>
<td>Chip Rate</td>
<td>3.84 Mcps</td>
</tr>
<tr>
<td>Roll-off factor for chip shaping</td>
<td>0.22</td>
</tr>
<tr>
<td>Frame Length</td>
<td>10 ms.</td>
</tr>
<tr>
<td>Number of slots/frame</td>
<td>15</td>
</tr>
<tr>
<td>Spreading modulation</td>
<td>Balanced QPSK (downlink)</td>
</tr>
<tr>
<td></td>
<td>Dual channel QPSK (uplink)</td>
</tr>
<tr>
<td></td>
<td>Complex spreading circuit</td>
</tr>
<tr>
<td>Data modulation</td>
<td>QPSK (downlink)</td>
</tr>
<tr>
<td></td>
<td>BPSK (uplink)</td>
</tr>
<tr>
<td>Coherent Detection</td>
<td>Pilot Symbols/channel</td>
</tr>
<tr>
<td>Channel multiplexing in uplink</td>
<td>Control and pilot channel time multiplexed. For the data and control</td>
</tr>
<tr>
<td></td>
<td>channels I and Q multiplexing</td>
</tr>
<tr>
<td>Multirate</td>
<td>Variable spreading and multicode</td>
</tr>
<tr>
<td>Spreading Factors</td>
<td>4-256</td>
</tr>
<tr>
<td>Power Control</td>
<td>Open and fast closed loop (1.5 kHz.)</td>
</tr>
<tr>
<td>Spreading (downlink)</td>
<td>Variable length orthogonal sequences for channel separation. Gold</td>
</tr>
<tr>
<td></td>
<td>sequences $2^{18}$ for user separation (different time shifts in I and Q</td>
</tr>
<tr>
<td></td>
<td>channel, truncated cycle 10 ms.)</td>
</tr>
<tr>
<td>Spreading (uplink)</td>
<td>Variable length orthogonal sequences for channel separation. Gold</td>
</tr>
<tr>
<td></td>
<td>sequences $2^{18}$ for user separation (different time shifts in I and Q</td>
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<tr>
<td></td>
<td>channel, truncated cycle 10 ms.)</td>
</tr>
<tr>
<td>Handover</td>
<td>Soft handover; Interfrequency Handover</td>
</tr>
</tbody>
</table>
W-CDMA Spreading

- W-CDMA uses long spreading codes
  - One set of codes are used for cell separation on downlink
  - One set of codes are used for user separation on uplink
- Downlink
  - Gold Codes of length $2^{18}$ are used
  - Truncated to same length as the 10 ms frames
  - Total number of scrambling codes is 512
  - Divided into 64 code groups with 8 codes in each group, to allow fast cell search (recently revised)
- Uplink
  - Short codes can be used to ease implementation of advanced multi-user receiver techniques
    - VL-Kasami Codes of length 256 chips
  - Otherwise long codes are used
    - Gold sequences of length $2^{41}$ chips, truncated to 10 ms

W-CDMA Channelization

- Orthogonal OVSF codes are used for channelization
- OVSF codes are used from a tree structure
  - This ensures that only orthogonal codes are used
W-CDMA Network
3 Steps to 3G: The GSM Network Transition

**GSM TODAY**

- PLMN PSTN
- ISDN
- Internet

Core Network
- Gateway MSC
- VLR
- HLR
- MSC Mobile Switching Center
- BTS Base Transceiver Stations
- BSC Base Station Controller

**2.5G: GSM + GPRS**

Core Network
- Gateway MSC
- VLR
- HLR
- MSC Mobile Switching Center
- BTS Base Transceiver Stations
- BSC Base Station Controller
- GPRS Support node
- PCU

**3G: UMTS, UTRA**

Core Network
- Gateway MSC
- VLR
- HLR
- MSC Mobile Switching Center
- BTS Base Transceiver Stations
- GPRS Support node

UTRAN
- RNC Radio Network Controller
- Node B

Modul 13 - 4G LTE
Model Radio Access W-CDMA

Pilihan utama

WCDMA Radio Access Modes

Code Multiplex

DS-CDMA IFDD

TD-CDMA TDD

(WCDMA TDD is based on TD-CDMA)

Power

Time

Frequency

Uplink Spectrum

Downlink Spectrum

Duplex Spacing: 100MHz

625 µs

UL

DL

UMTS USER 1

UMTS USER 2

Modul 13 - 4G LTE
<table>
<thead>
<tr>
<th>Specification</th>
<th>Details</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Channel Bandwidth</strong></td>
<td>5 MHz</td>
</tr>
<tr>
<td><strong>Duplex Mode</strong></td>
<td>FDD and TDD</td>
</tr>
<tr>
<td><strong>Downlink RF Channel Structure</strong></td>
<td>Direct Spread (DS)</td>
</tr>
<tr>
<td><strong>Chip Rate</strong></td>
<td>3.84 Mcps</td>
</tr>
<tr>
<td><strong>Frame Length</strong></td>
<td>10 ms</td>
</tr>
<tr>
<td><strong>Spreading Modulation</strong></td>
<td>Balanced QPSK (downlink), Dual-channel QPSK (uplink)</td>
</tr>
<tr>
<td></td>
<td>Complex spreading circuit</td>
</tr>
<tr>
<td><strong>Data Modulation</strong></td>
<td>QPSK (downlink), BPSK (uplink)</td>
</tr>
<tr>
<td><strong>Channel Coding</strong></td>
<td>Convolutional and turbo codes</td>
</tr>
<tr>
<td><strong>Coherent detection</strong></td>
<td>- User dedicated time multiplexed pilot (downlink and uplink)</td>
</tr>
<tr>
<td></td>
<td>- Common pilot in downlink</td>
</tr>
<tr>
<td><strong>Channel Multiplexing in Downlink</strong></td>
<td>Data and control channel are multiplexed</td>
</tr>
<tr>
<td><strong>Channel Multiplexing in Uplink</strong></td>
<td>- Control and pilot channel time multiplexed</td>
</tr>
<tr>
<td></td>
<td>- I&amp;Q multiplexing for data and control channel</td>
</tr>
<tr>
<td><strong>Multirate</strong></td>
<td>Variable spreading and multicode</td>
</tr>
<tr>
<td><strong>Spreading Factors</strong></td>
<td>4-256 (uplink), 4-512 (downlink)</td>
</tr>
<tr>
<td><strong>Power Control</strong></td>
<td>Open and fast closed loop (1.6 kHz)</td>
</tr>
<tr>
<td><strong>Spreading (downlink)</strong></td>
<td>OVSF sequences for channel separation. Gold sequences $2^{18}-1$ for cell and user separation (truncated cycle 10 ms)</td>
</tr>
<tr>
<td><strong>Spreading (uplink)</strong></td>
<td>OVSF sequences. Gold sequence $2^{46}$ for user separation (different time shifts in I and Q channel, truncated cycle 10 ms)</td>
</tr>
<tr>
<td><strong>Handover</strong></td>
<td>Soft handover, Inter-frequency handover, etc.</td>
</tr>
</tbody>
</table>
Kanal Fisik - UMTS

Chip rate = 3.84 Mcps
RF bandwidth = 5 MHz
Physical layer data rates = 15, 30, 60, 120, 240, 480, 960 and 1920 kbps
Payload data rates = 12.2, 64, 144, 384, 768 and 2048 kbps
Frame length = 10 ms
Fast power control = bi-directional, 1500 Hz
Type Kanal pada UMTS

- Kanal Logika (Logical Channel) antara RLC dan MAC
  - Spesifik untuk tipe-tipe informasi
- Kanal Transport (Transport channel) antara MAC dan PHY
  - Spesifik untuk “Bagaimana informasi ditransfer?” (garansi kualitas)
- Kanal Fisik (Physical Channel)
  - Aktual transmisi pada physical layer
Modul 13 - 4G LTE
New **Broadband Packet Wireless Access Technology** will remarkably enhance system performance.

- **High-speed**
- **High-capacity**
- **Short delay**
- **Low bit cost**
- **IP-based?**

Mobil: Nationwide, Citywide, Premises, Indoor / FWA

Data rate (Mbit/s):
- 2G: IMT-2000
- 3G: Nomadic Wireless Access (W-LAN)
- 3.5G
- 4G: Millimeter-wave LAN
1Gbps Wireless Access

- MIMO (Multiple-Input Multiple-Output)

Spectrum efficiency target: 10bit/Hz. Demultiplexing method is the key.
4G Evolution Scenario

2G → 3G → 4G

- Mobile Internet
- Mobile multimedia
- Mobile Ubiquitous

Services
- i-mode
- E-mail
- Web Access
- FOMA
  - Visual mail
  - TV conference
  - Video phone
- Ubiquitous Collaboration
- Object-related application
  - Application based on real world info.

Systems
- PDC
- PDC-P
- ATM → IP
- 3G RAN → IP RAN
- 3G, 3.5G, 4G
  - WLAN, Non-cellular

Modul 13 - 4G LTE
4G Technologies

Mobile WiMAX
- Rel 1.0 802.16e-2005
- Rel 1.5 802.16e-2005
- Rel 2.0 802.16m

3GPP
- HSPA Rel-6
- HSPA+ Rel-7 & Rel-8

IP E2E Network

CKT Switched Network

LTE & LTE Advanced

IMT-Advanced

2008  2009  2010  2011  2012

CDMA - Based

OFDMA - Based

1G  Analog
2G  Digital
3G  Packets
4G  True Broadband
**From 3G to 4G**

**Coverage**
- 3G → large area
- 4G → wide area & small-area (WiFi-like)
  - wide- & narrow-area services from a single device, single network

**Spectrum-Efficiency**
- Researchers developed more spectrally efficient modulation schemes for encoding data onto carrier waves, such as 64 QAM
  - Incompatible with 3G & 3.5G

**ITU 4G Schedule**
- 2008-2009: selecting candidate technologies
- 2009-2010: developing detailed specification
- 2010-2012: official implementation
- 2015: wide deployment

**ITU 4G Requirement**
- Data rates > 100 Mb/s
- Transmission: OFDMA
- IP-based and packet-switched

4G
Definisi 4G

Generasi keempat dari standar nirkabel selular. Penerus standar 3G dan 2G.

- 1G : analog
- 2G : transmisi digital
- 3G : mendukung multimedia support, transmisi *spread spectrum* minimal 200 kbps
- 4G : jaringan seluruhnya berbasis *packet-switched*, *mobile ultra-broadband access*, *multi-carrier transmission*

4G secara standar merujuk ke *IMT Advanced* sebagaimana didefinisikan oleh ITU-R.

LTE :
- Long Term Evolution adalah teknologi pre-4G dari 3GPP sering dicap sebagai “4G”
- LTE release pertama tidak memenuhi persyaratan of the *IMT Advanced*
4G – Mobile Broadband Systems

- A variety of technology standards able to provide transmission rates beyond 3G (2 Mb/s)

Advantages
- Provides access to services and applications requiring these higher transmission rates
- Extends capacity in zones where 3G is close to saturation

Microwave and millimeter wave bands to be used mean smaller cell size (a few to 1000 meters); 5 GHz band will be first used with migration to higher carrier frequencies

Coverage not continuous, necessitating mobile units to roam between different bands and standards
Alasan Munculnya Kebutuhan LTE

- Kebutuhan akan laju data yang lebih tinggi dan efisiensi spectral yang lebih baik
  * Demand layanan broadband yang meningkat
  * Mahalnya spektrum

- Kebutuhan sistem Packet Switched yang teroptimisasi
  * Evolusi ke all IP Network

- Kebutuhan akan QoS yang tinggi
  * Penggunaan licensed frequency untuk jamininan QoS
  * Minimum latency

- Kebutuhan akan infrastructure yang lebih murah
  * Penyederhanaan architecture dan pengurangan network element
Theory of LTE

Modul 13 - 4G LTE
Introduction to LTE

- 3GPP Long Term Evolution - the next generation of wireless cellular technology beyond 3G
- Initiative taken by the 3rd Generation Partnership Project in 2004
- Introduced in Release 8 of 3GPP
- Mobile systems likely to be deployed by 2010
LTE background story
the early days

• Work on LTE was initiated as a 3GPP release 7 study item “Evolved UTRA and UTRAN” in December 2004:
  – “With enhancements such as HSDPA and Enhanced Uplink, the 3GPP radio-access technology will be highly competitive for several years. However, to ensure competitiveness in an even longer time frame, i.e. for the next 10 years and beyond, a long term evolution of the 3GPP radio-access technology needs to be considered.”

• Basic drivers for LTE have been:
  – Reduced latency
  – Higher user data rates
  – Improved system capacity and coverage
  – Cost-reduction.
Packet Switched data is becoming more and more dominant

VoIP is the most efficient method to transfer voice data

→ Need for PS optimised system

Amount of data is continuously growing

→ Need for higher data rates at lower cost

Users demand better quality to accept new services

→ High quality needs to be guaranteed

Alternative solution for non-3GPP technologies (WiMAX) needed

LTE will enhance the system to satisfy these requirements.
LTE Overview

- 3GPP R8 solution for the next 10 years.
- Peaks rates: DL 100Mbps with Orthogonal Frequency Division Multiple Access (OFDMA), UL 50Mbps with Single Carrier Frequency Division Multiple Access (SC-FDMA).
- Latency for Control-plane < 100ms, for User-plane < 5ms.
- Optimised for packet switched domain, supporting VoIP.
- Scaleable RF bandwidth between 1.25MHz to 20MHz.
- 200 users per cell in active state.
- Supports Mobile Broadband Multimedia Services.
- Uses MIMO multiple antenna technology.
- Optimised for 0-15km/h mobile speed and support for up-to 120-350 km/h.
- No soft handover, Intra-RAT handovers with UTRAN.
- Simpler E-UTRAN architecture: no RNC, no CS domain, no DCH.
LTE technical objectives

- **User throughput [MHz]:**
  - Downlink: 3 to 4 times Release 6 HSDPA
  - Uplink: 2 to 3 times Release 6 Enhanced Uplink

- **Downlink Capacity:** Peak data rate of 100 Mbps in 20 MHz maximum bandwidth

- **Uplink capacity:** Peak data rate of 50 Mbps in 20 MHz maximum bandwidth

- **Latency:** Transition time less than 5 ms in ideal conditions (user plane), 100 ms control plane (fast connection setup)
• Mobility: Optimised for low speed but supporting 120 km/h
  - Most data users are less mobile!

• Simplified architecture: Simpler E-UTRAN architecture: no RNC, no CS domain, no DCH

• Scalable bandwidth: 1.25MHz to 20MHz: Deployment possible in GSM bands.

• LTE
  - Higher data rate than legacy
  - Better coverage and performance
  - Flexible and scalable deployment
  - Designed from both, system and mobile terminal perspective

• SAE
  - Inter-operability between more RATs than LTE even non-3GPP
  - Simplified from predecesors (redundant features removed)
  - More secure than legacy
  - Faster than legacy
  - Better performance than legacy
LTE agreements

- 2 main issues have been investigated:
  - The physical layer
  - The access network internal architecture

- Physical layer
  - Downlink based on OFDMA
    - OFDMA offers improved spectral efficiency, capacity etc
  - Uplink based on SC-FDMA
    - SC-FDMA is technically similar to OFDMA but is better suited for uplink from hand-held devices
    - (battery power considerations)
  - For both FDD and TDD modes (User Equipment to support both)
    - With Similar framing + an option for TD SCDMA framing also

- Access Network consideration
  - For the access network it was agreed to get rid of the RNC which minimized the number of nodes

- Spectrum flexibility
  - Flexible bandwidth
  - Duplex flexibility

- Advanced antenna solutions
  - Diversity
  - Beam-forming
  - Multi-layer transmission (MIMO)

- New radio access
  - Downlink: OFDM
  - Uplink: SC-FDMA

Modul 13 - 4G LTE
LTE radio interface

- New radio interface modulation: **SC-FDMA UL** and **OFDMA DL**
  - Frequency division, TTI 1 ms
  - Scalable bandwidth 1.25-20MHz
  - TDD and FDD modes
    - **UL/DL** in either in same or in another frequency
    - OFDMA has multiple orthogonal subcarries that can be shared between users
      - quickly adjustable bandwidth per user
    - SC-FDMA is technically similar to OFDMA but is better suited for uplink from hand-held devices
      - Single carrier, time space multiplexing
      - Tx consumes less power

From Ericsson, H. Djuphammar
# FDD (left) and TDD (right) frequency bands defined in the 3GPP (May 2009)

<table>
<thead>
<tr>
<th>Operating band</th>
<th>3GPP name</th>
<th>Total spectrum</th>
<th>Uplink [MHz]</th>
<th>Downlink [MHz]</th>
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<tbody>
<tr>
<td>Band 1</td>
<td>2100</td>
<td>2x60 MHz</td>
<td>1920-1980</td>
<td>2110-2170</td>
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<tr>
<td>Band 2</td>
<td>1900</td>
<td>2x60 MHz</td>
<td>1850-1910</td>
<td>1930-1990</td>
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<td>Band 3</td>
<td>1800</td>
<td>2x75 MHz</td>
<td>1710-1785</td>
<td>1805-1880</td>
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<tr>
<td>Band 4</td>
<td>1700/2100</td>
<td>2x45 MHz</td>
<td>1710-1755</td>
<td>2110-2155</td>
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<tr>
<td>Band 5</td>
<td>850</td>
<td>2x25 MHz</td>
<td>824-849</td>
<td>869-894</td>
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<tr>
<td>Band 6</td>
<td>800</td>
<td>2x10 MHz</td>
<td>830-840</td>
<td>875-885</td>
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<tr>
<td>Band 7</td>
<td>2600</td>
<td>2x70 MHz</td>
<td>2500-2570</td>
<td>2620-2690</td>
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<tr>
<td>Band 8</td>
<td>900</td>
<td>2x35 MHz</td>
<td>880-915</td>
<td>925-960</td>
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<tr>
<td>Band 9</td>
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<td>2x35 MHz</td>
<td>1750-1785</td>
<td>1845-1880</td>
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<tr>
<td>Band 10</td>
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<td>1710-1770</td>
<td>2110-2170</td>
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<td>Band 11</td>
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<td>1427.9-1452.9</td>
<td>1475.9-1500.9</td>
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<td>728-746</td>
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<tr>
<td>Band 13</td>
<td>US700</td>
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<td>777-787</td>
<td>746-756</td>
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<tr>
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<td>758-768</td>
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<td>Band 17</td>
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<td>734-746</td>
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<td>815-830</td>
<td>860-875</td>
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<td>Band 19</td>
<td>Japan800</td>
<td>2x30 MHz</td>
<td>830-845</td>
<td>875-890</td>
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</table>

<table>
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<tr>
<th>Operating band</th>
<th>3GPP name</th>
<th>Total spectrum</th>
<th>Uplink and downlink [MHz]</th>
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</thead>
<tbody>
<tr>
<td>Band 33</td>
<td>UMTS TDD1</td>
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<td>1900-1920</td>
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<td>Band 34</td>
<td>UMTS TDD2</td>
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<td>Band 35</td>
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<td>Band 36</td>
<td>US1900 DL</td>
<td>1x60 MHz</td>
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<td>Band 37</td>
<td>US1900</td>
<td>1x20 MHz</td>
<td>1910-1930</td>
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<td>Band 38</td>
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<td>1x50 MHz</td>
<td>2570-2620</td>
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<tr>
<td>Band 39</td>
<td>UMTS TDD</td>
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<td>1880-1920</td>
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<td>Band 40</td>
<td>2300</td>
<td>1x50 MHz</td>
<td>2300-2400</td>
</tr>
</tbody>
</table>

*Modul 13 - 4G LTE*
LTE Spectrum - New or Re-use: Main Trends

Today

- GSM 900 MHz
- UMTS 2100 MHz

2010

- GSM 900 MHz
- UMTS 2100 MHz
- LTE 2600 MHz

- Capacity driven
  - New spectrum application
  - Hot spots / femto cells

- Free 900 MHz needs for 1800 MHz contiguous coverage, but will provide favourable range

- Free 1800 MHz more adapted to hot spots capacity driven scenario

- Smooth LTE introduction in existing band, pre-empting a narrow BW in GSM, 5 MHz carrier in UMTS
LTE network...is an end-to-end IP network – migration already underway

Mobile communications and Web access → IP transformation → Enriched Web services including rich communications

Scalability * Cost efficiency * Service agility

LTE network diagram:

- **2G/3G (all radio)**: BTS, Node B
- **Access**: eNode B, OFDM, MIMO
- **Cell Site Access**: Cell Site, Transport
- **Ethernet/MPLS/Transport**: SGW
- **TDM and ATM aggregation**: BSC RNC
- **Backhaul**: Ethernet/MPLS/Transport
- **Evolved Packet Core**: MME, PCRF, PGW
- **Packet Switched Core (Data)**: GGSN, PDSN
- **Circuit Switched Core (Voice)**: MSC
- **IP/MPLS Backbone**: IMS

Modul 13 - 4G LTE
LTE network

...is an end-to-end IP network – migration already underway

2G/3G

- BTS
- Cell Site Access
- TDM and ATM aggregation
- BSC RNC
- MSC
- SGSN
- PDSN
- GGSN
- HA
- Circuit Switched Core (Voice)
- Packet Switched Core (Data)

- 2-16 Mbit/s per site TDM

LTE

- eNode B
- Cell Site Access
- Ethernet/MPLS/Transport
- SGW
- MME
- PCRF
- PGW
- IMS
- IP/MPLS Backbone

- 50-200 Mbit/s per site IP

Transmission networks need to be prepared for LTE capacities

Modul 13 - 4G LTE
All-IP mobile transformation: What happens?

TODAY

1. Radio intelligence moving to eNodeB
2. Backhaul transition to IP/Ethernet
3. RNC bearer mobility evolves to the SGW
4. RNC control distributed into the MME/eNB
5. Packet data control evolves into the MME
6. MSC voice and packet data switching evolve into the SGW
7. CS and PS evolve into a unified all-IP, IMS domain
8. Best effort to e2e QoS
9. IP anchor moves to PDN GW
10. Internet browsing to Web 2.0+

Backhaul (TDM/ATM)

CS Core

PS Core

Backhaul (IP/Ethernet)

Evolved Packet Core

Service and mobile aware all-IP network

SGW

MME

PCRF

HSS

PDN GW

Modul 13 - 4G LTE
• **E-UTRAN (Evolved Universal Terrestrial Radio Access Network)**

  - **eNB**
    - All radio interface-related functions
  
  - **MME**
    - Manages mobility, UE identity, and security parameters.
  
  - **S-GW**
    - Node that terminates the interface towards E-UTRAN.
  
  - **P-GW**
    - Node that terminates the interface towards PDN.

---

**UMTS 3G: UTRAN**

- **GGSN**
- **SGSN**
- **RNC**

**E-UTRAN**

- **eNB**
- **MME**
- **S-GW/P-GW**

---

**EPC (Evolved Packet Core)**

- **MME**
- **S-GW/P-GW**

---

*3GPP TS 36.300

**NB:** NodeB (base station)

**RNC:** Radio Network Controller

**SGSN:** Serving GPRS Support Node

**GGSN:** Gateway GPRS Support Node

---

*3GPP TS 36.300

**eNB:** E-UTRAN NodeB

**MME:** Mobility Management Entity

**S-GW:** Serving Gateway

**P-GW:** PDN (Packet Data Network) Gateway
Simplified LTE network elements and interfaces

3GPP TS 36.300 Figure 4: Overall Architecture

- **eNB** = E-UTRAN Node B
- All radio interface-related functions

- **MME** = Mobile Management entity
  - Manages mobility, UE identity, and security parameters.

- **S-GW** = Serving Gateway
  - Node that terminates the interface towards E-UTRAN.

- **P-GW** = PDN (Packet Data Network) Gateway
  - Node that terminates the interface towards PDN.

---

**Two types of interfaces:**

- **S1-flex:** Many-to-many relationship between “enhanced NodeBs” (eNB) and core network nodes (Access Gateways, aGW)
- **X2:** Direct interfacing between adjacent eNBs for handover and RRM

---

**Advantages:**

- Minimises single points of failure above eNBs
- All radio-related issues are handled in the RAN
- Allows RAN Sharing

---

*Evolved Packet Core (SAE)*

*Note:* aGW may be decomposed into Mobility Management Entity (MME) and User Plane Entity (UPE)
LTE Network Architecture

- Simple Architecture
- Flat IP-Based Architecture
- Reduction in latency and cost
- Split between EPC and E-UTRAN
- Compatibility with 3GPP and non-3GPP technologies
- eNB-radio interface-related functions
- MME-manages mobility, UE identity and security parameters
- S-GW-node that terminates the interface towards E-UTRAN

EPC = Evolved Packet Core
E-UTRAN = Evolved Universal Radio Access Network
MME = Mobile Management entity
S-GW = Serving Gateway
SAE = System Architecture Evolution
eNB = E-UTRAN Node B
Empat Level Jaringan LTE
Interface X2

- Interface X2 is a interface structure protocol which has been used for mobility occurs between 2 eNodeB near handover process.
- On data process handover which is transferred through this interface X2 is specific data from user.
- Function of Interface X2 are:
  - Intra-handover mobility management
  - Coordination of Resource status information, and traffic overload situation
  - Setting up and Resetting of Interface X2
  - The handling of error cases
E-UTRAN Node B (eNodeB)

- Mobility Management
- Bearer handling
- Security settings

- Radio Resource Management
- Mobility Management
- Bearer handling
- User Plane data delivery
- Securing and optimizing radio interface delivery

Pool of MMEs

- User Plane Tunnels for UL and DL data delivery

Pool of S-GWs

- Inter eNodeB handovers
- Forwarding of DL data during handovers

UEs

Other eNodeBs

Modul 13 - 4G LTE
Functions of eNodeB

- Terminates RRC, RLC and MAC protocols and takes care of Radio Resource Management functions
  - Controls radio bearers
  - Controls radio admissions
  - Controls mobility connections
  - Allocates radio resources dynamically (scheduling)
  - Receives measurement reports from UE
- Selects Mobility Management Entity (MME) at UE attachment
- Schedules and transmits paging messages coming from MME
- Schedules and transmits broadcast information coming from MME & O&M
- Decides measurement report configuration for mobility and scheduling
- Does IP header compression and encryption of user data
Functions of aGateWay

- Takes care of Mobility Management Entity (MME) functions
  - Manages and stores UE context
  - Generates temporary identities and allocates them to UEs
  - Checks authorization
  - Distributes paging messages to eNodeBs
  - Takes care of security protocol
  - Controls idle state mobility
  - Control SAE bearers
  - Ciphers & integrity protects NAS signaling
Mobility Management Entity (MME)

- Handovers between MMEs
- Idle state mobility between MMEs

- Authentication and Security parameters
- Location Management
- User profile

- Control of User Plane Tunnels
- Inter eNodeB handovers
- State Transitions
- Bearer Management
- Paging

- Mobility Management
- UE Requested Bearer Management

Other MMEs

S-GWs

HSS

UEs

eNodeBs
Serving Gateway (S-GW)

GTP S5/S8:
- Control of GTP Tunnels
- GTP Tunnels for UL and DL data delivery

PMIP S5/S8:
- IP service flows

MMEs
- Control of GTP tunnels & IP service flows
- S-GW Mobility control

P-GWs

PCRFs
(PMIP S5/S8)

PMIP S5/S8:
- IP service flow <-> GTP tunnel mapping information

S-GWs
- Indirect forwarding of DL data during handovers (in S1-U format), when direct inter-eNodeB connection is not available

eNodeBs

MME
- User Plane Tunnels for UL and DL data delivery
Packet Data Network Gateway (P-GW)

- IP Flows of user data
- Control of User Plane Tunnels
- User Plane Tunnels for UL and DL data delivery
- Policy and Charging Control requests
- PCC rules
Modul 13 - 4G LTE

Aristektur LTE

HSS
- Maintain and provide subscription data
- User Identification handling
- Access Authorisation
- Provide Keys for Authentication and Encryption
- User Registration management
- Maintain knowledge of used PDN GW

MME
- Authentication
- NAS signalling
- GW selection
- Roaming (S6a to home HSS)
- Bearer management
- Idle mode tracking
- Paging
- Inter-MME and IRAT mobility
- NAS Ciphering and Integrity protection

PDN GW
- S5/S8

PCRF
- Provides Service Data Flow gating
- Set QoS for each Service Data Flow
- Define Charging for each Service Data Flow
- Enables Bearer QoS Control
- Correlation between Application and Bearer charging
- Notification of bearer events to application function
- Bearer bindings towards Serv-GW for PMIP-based S5

SAE GW

PDN GW part:
- External IP point of interconnect
- IP address allocation
- Packet routing & forwarding
- Lawful intercept
- Policy enforcement
- In home or visited network

$GW part:
- In visited network in case of roaming
- Intra-LTE mobility anchor
- Packet routing & forwarding
- Lawful intercept
- LTE idle mode DL buffering
- Charging per UE, PDN and QCI
- Bearer bindings for PMIP S5/S8
Fitur LTE/SAE

EPS (Evolved Packet System) / SAE (System Architecture Evolution) / LTE (Long Term Evolution)

EUTRAN (Evolved UTRAN)

- OFDMA/SC-FDMA
- MIMO (beam-forming/spatial multiplexing)
- HARQ
- Scalable bandwidth (1.4, 3, 5, 10, .. 20 MHz)

Evolved Node B / No RNC
- IP Transport Layer
- UL/DL resource scheduling
- QoS Aware
- Self Configuration

EPC (Evolved Packet Core)

- PS Domain only, No CS Domain
- IP Transport Layer
- QoS Aware
- 3GPP (GTP) or IETF (MIPv6)
- Prepared for Non-3GPP Access

IP Network

Modul 13 - 4G LTE
Fitur LTE/SAE

- **Evolved NodeB**
  - Tidak diperlukan RNC lagi
  - Evolved Node B mengambil alih semua fungsi manajemen radio
  - Hal ini memungkinkan manajemen sumberdaya radio menjadi cepat dan arsitektur jaringan menjadi lebih sederhana

- **IP transport layer**
  - EUTRAN menggunakan IP sebagai transport layer

- **UL/DL resource scheduling**
  - Sumber daya pada UMTS masih berupa sumberdaya yang di-shared atau dedicated
  - Evolved Node B menangani semua sumberdaya dengan melalui suatu scheduler dan melakukan penugasan secara dinamis ke pengguna dan kanal
  - Hal ini memungkinkan LTE memiliki fleksibilitas yang lebih baik
Teknologi Kunci LTE

- **LTE radio access**
  - Downlink: OFDM
  - Uplink: SC-FDMA

- **Advanced antenna solutions**
  - Diversity
  - Beam-forming
  - Multi-layer transmission (MIMO)

- **Spectrum flexibility**
  - Flexible bandwidth
  - New and existing bands
  - Duplex flexibility: FDD and TDD
LTE Radio Access Network – Physical Elements

E-UTRAN Architecture

- Evolved NodeB (eNB) now has most of the Node B and RNC functionality in a single entity.
- MME & GateWay (xGW) has most of the SGSN and GGSN functionality.

User Plane Protocol
Control Plane Protocol

RRM: Radio Resource Management
RB: Radio Bearer
RRC: Radio Resource Control
PDCP: Packet Data Convergence Protocol
NAS: Non-Access Stratum
EPS: Evolved Packet System

Modul 13 - 4G LTE
Flat architecture of LTE and Service Architecture Evolution

Heterogeneous N/Ws for IMT-Advanced service

UMTS/ TD-SCDMA HSPA
~ 300kbps to 14 Mbps
- Interactive 3D graphics
- High-resolution video streaming
- Mobile Web 2.0

LTE/ Wi-MAX
~ 10 to 100 Mbps
- HD video streaming
- Multi-view real time video streaming

GPRS/ EDGE
~ 200kbps
- SMS, Internet Browsing

IMT-Advanced
~ 100 Mbps to 1Gbps
- Virtual reality
- Context & Preference-Aware
- Advanced video display

Modul 13 - 4G LTE
• Evolusi lanjutan dalam standar jaringan selular yang ditentukan oleh 3GPP (*Third Generation Partnership Project*).
• Teknologi lanjutan dari generasi 1xEV-DO.
• Berbeda dengan Wimax yang awalnya dikembangkan untuk komunikasi data.

**Roadmap evolusi teknologi selular di dunia yaitu :**

(1) GSM(2G) → GPRS(2.5G) → EDGE → WCDMA(3G) → HSDPA (3.5G) → LTE (4G).

(2) CDMA (2G) → CDMA 2000 → EV-DO (3G) → UMB (4G).

(3) Wi-Fi → Fixed WiMAX → Mobile WiMAX → WiMAX II (4G).

*Modul 13 - 4G LTE*
**LTE, UMB, WIMAX II**

| Modul 13 - 4G LTE |

<table>
<thead>
<tr>
<th>Channel bandwidth</th>
<th>3GPP LTE</th>
<th>3GPP2 UMB</th>
<th>Mobile WiMAX</th>
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<tr>
<td></td>
<td>1.4, 3, 5, 10, 15, and 20 MHz</td>
<td>1.25, 2.5, 5, 10, and 20 MHz</td>
<td>5, 7, 8.75, and 10 MHz</td>
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</table>

<table>
<thead>
<tr>
<th>DL multiple access</th>
<th>OFDMA</th>
<th>OFDMA</th>
<th>OFDMA</th>
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<thead>
<tr>
<th>UL multiple access</th>
<th>SC-FDMA</th>
<th>OFDMA and CDMA</th>
<th>OFDMA</th>
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<table>
<thead>
<tr>
<th>Duplexing</th>
<th>FDD and TDD</th>
<th>FDD and TDD</th>
<th>TDD</th>
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<table>
<thead>
<tr>
<th>Subcarrier mapping</th>
<th>Localized</th>
<th>Localized and distributed</th>
<th>Localized and distributed</th>
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<table>
<thead>
<tr>
<th>Subcarrier hopping</th>
<th>Yes</th>
<th>Yes</th>
<th>Yes</th>
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<table>
<thead>
<tr>
<th>Data modulation</th>
<th>QPSK, 16QAM, and 64QAM</th>
<th>QPSK, 64QAM, 16QAM, and 64QAM</th>
<th>QPSK, 16QAM, and 64QAM</th>
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<table>
<thead>
<tr>
<th>Subcarrier spacing</th>
<th>15 kHz</th>
<th>9.6 kHz</th>
<th>10.94 kHz</th>
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<table>
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<tr>
<th>FFT size (5 MHz)</th>
<th>512</th>
<th>512</th>
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<tr>
<th>Channel coding</th>
<th>Convolutional coding and turbo coding</th>
<th>Convolutional coding, turbo coding, and LDPC coding</th>
<th>Convolutional coding and convolutional turbo coding, Block turbo coding and LDPC coding optional</th>
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<table>
<thead>
<tr>
<th>MIMO</th>
<th>Multi-layer precoded spatial multiplexing space-time/frequency block coding, switched transmit diversity, and cyclic delay diversity</th>
<th>Multi-layer precoded spatial multiplexing, space-time transmit diversity, spatial division multiple access, and beamforming</th>
<th>Beamforming, Space-time coding, and spatial multiplexing</th>
</tr>
</thead>
</table>