LTE (Long Term Evolution)

Assoc. Prof. Peter H J Chong, PhD (UBC)
School of EEE
Nanyang Technological University
Office: +65 6790 4437
E-mail: ehjchong@ntu.edu.sg
Outline

- Introduction
- SAE (System Architecture Evolution)
- LTE Air Interface
- Channel Types
1. Introduction
A - Cellular History

<table>
<thead>
<tr>
<th>Year</th>
<th>What Happen!</th>
</tr>
</thead>
<tbody>
<tr>
<td>1880</td>
<td>Hertz demonstrated a practical radio communication that a spark produced from a transmitter at a nearby receiver produced a voltage.</td>
</tr>
<tr>
<td>1897</td>
<td>Marconi demonstrated the wireless ship-to-shore telegraph link in English Channel.</td>
</tr>
<tr>
<td>1921</td>
<td>The first land mobile communication system was deployed for Detroit police vehicles in U.S.</td>
</tr>
<tr>
<td>1936</td>
<td>Edwin Armstrong demonstrated frequency modulation.</td>
</tr>
<tr>
<td>1960s - 1970s</td>
<td>The first cellular concept was first introduced and developed by AT&amp;T Bell Lab.</td>
</tr>
<tr>
<td>Year</td>
<td>What Happen!</td>
</tr>
<tr>
<td>-----------</td>
<td>------------------------------------------------------------------------------------------------------------------------------------------------</td>
</tr>
<tr>
<td>1983</td>
<td>First US cellular system called the Advanced Mobile Phone Service (AMPS) was first deployed in Chicago.</td>
</tr>
<tr>
<td>mid-1980s</td>
<td>European Total Access Communication System (ETACS) was introduced in Europe.</td>
</tr>
<tr>
<td>mid-1980s</td>
<td>Global System for Mobile Communication (GSM) was developed in Europe and was originally called Group spécial mobile.</td>
</tr>
<tr>
<td>1988</td>
<td>American TDMA (dual mode USDC/AMPS) system become a 2G digital cellular standard in US.</td>
</tr>
<tr>
<td>1989</td>
<td>QUALCOMM proposed another digital cellular system based on CDMA, namely IS-95 and now called cdmaOne.</td>
</tr>
<tr>
<td>Year</td>
<td>What Happen!</td>
</tr>
<tr>
<td>-------------------</td>
<td>-----------------------------------------------------------------------------</td>
</tr>
<tr>
<td>July 1991</td>
<td>GSM was first operated in Finland.</td>
</tr>
<tr>
<td>1994</td>
<td>TDMA system was introduced in Seattle, named Interim Standard 54 (IS-54) and later upgraded to IS-136.</td>
</tr>
<tr>
<td>1994</td>
<td>PDC (personal digital cellular) was operated in Japan.</td>
</tr>
<tr>
<td>1995</td>
<td>CDMA was introduced in Hong Kong.</td>
</tr>
<tr>
<td>Beginning of 1990s</td>
<td>Many regional standards bodies started the R&amp;D activities worldwide for 3G systems IMT-2000 and UMTS (Europe).</td>
</tr>
<tr>
<td>1997-1998</td>
<td>Two main 3G standards have been confirmed, WCDMA and cdma2000.</td>
</tr>
<tr>
<td>1999</td>
<td>ITU (International Telecommunication Union) decides 3G systems (e.g., WCDMA, cdma2000, TD-SCDMA)</td>
</tr>
<tr>
<td>Oct. 2001</td>
<td>WCDMA was operated in Japan.</td>
</tr>
</tbody>
</table>
First Generation Cellular Systems (1980s)

- American - Advanced Mobile Phone Service (AMPS)
- British - Total Access Cellular System (TACS)
- Scandinavian - Nordic Mobile Telephone (450/900) system (NMT)
- German - C - 450
- Japanese - Nippon Advanced Mobile Telephone System (NAMTS)
Second Generation Cellular Systems (1990s)

- American - *TDMA System* (USDC, IS-54, IS136)
- American - *CDMA System* (IS-95, cdmaOne)
- European - *Global System for Mobile Communications (GSM)*
  - **GPRS** (General Packet Radio Service) – 2.5G
  - **EDGE** (Enhanced Data Rates for GSM Evolution) – 2.75G
- Japanese - *Personal Digital Cellular (PDC)*

- Europe/Japan/Korea – Universal Mobile Telecommunications System (UMTS) or Wideband Code Division Multiple Access (WCDMA)
  - HSDPA (High Speed Downlink Packet Access) – 3.5G
  - HSUPA (High Speed Uplink Packet Access)
  - HSPA+/ (High Speed Packet Access) – 3.75G
- USA/Japan/Korea – CDMA2000
  - CDMA EVDO, CDMA EVDO Rev A, CDMA EVDO Rev B
- China – Time-division Synchronous Code Division Multiple Access (TD-SCDMA)

- Europe/Japan/Korea/USA
  - Long-Term Evolution (LTE) – 3.9 G
  - LTE-Advanced – 4G
- USA/Japan/Korea
  - Ultra-Mobile Broadband – 3.9G
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Global Evolution of Cellular Systems

- **IS-136**
- **GSM**
  - **HSCSD**
  - **GPRS** → **EDGE** → **WCDMA**
  - **HSDPA/HSUPA/HSPA**
  - **TD-SCDMA** → **LTE** → **LTE-Advanced**
- **PDC**
- **CDMA One** → **CDMA 2000 1x** → **CDMA 2000 1x-EV-DO, 1xEV-DV** → **CDMA 2000 Rev A, Rev B**
  - **UMB**

**Technology Generations**

- **2G**
  - 9.6-14.4 Kb/s
- **2.5G**
  - 56-144 Kb/s
- **3G**
  - 384 Kb/s-2 Mb/s
- **3.5G**
  - ~20 Mb/s
- **3.9G**
  - ~100 Mb/s
- **4G**
  - ~1 Gb/s
C - Major Cellular Standards

3GPP (3rd Generation Partnership Project)

- Dominant Standards created in 1996
- GSM and GPRS were developed before 3GPP creation
- 3GPP defined EDGE in 1997.

- During 2009, there is an open call for submission for IMT-Advanced.

<table>
<thead>
<tr>
<th>Version</th>
<th>Completion Date/ Deployment Date</th>
<th>Peak Data Rate</th>
<th>Major Contributions</th>
</tr>
</thead>
<tbody>
<tr>
<td>Release 99</td>
<td>End of 1999 2001 (Japan) 2002 (Europe)</td>
<td>0.4 Mbps (DL) 0.4 Mbps (UL)</td>
<td>WCDMA</td>
</tr>
<tr>
<td>Release 4</td>
<td>March 2001</td>
<td>0.4 Mbps (DL) 0.4 Mbps (UL)</td>
<td>Correction to R99 E.g., inclusion of TD-SCDMA</td>
</tr>
<tr>
<td>Release 5</td>
<td>March 2002 2005</td>
<td>14 Mbps (DL) 0.4 Mbps (UL)</td>
<td>HSDPA</td>
</tr>
<tr>
<td>Version</td>
<td>Completion Date/ Deployment Date</td>
<td>Peak Data Rate</td>
<td>Major Contributions</td>
</tr>
<tr>
<td>--------------</td>
<td>----------------------------------</td>
<td>----------------------------------</td>
<td>--------------------------------------</td>
</tr>
<tr>
<td>Release 6</td>
<td>March 2005 2007</td>
<td>14 Mbps (DL) 5.7 Mbps (UL)</td>
<td>HSUPA, MBMS Correction to R5</td>
</tr>
<tr>
<td>Release 7</td>
<td>June 2007 2009</td>
<td>28 Mbps (DL) 11 Mbps (UL)</td>
<td>HSPA+</td>
</tr>
<tr>
<td>Release 8</td>
<td>December 2008 2010+</td>
<td>LTE: 150 Mbps (DL) HSPA+: 42 Mbps (DL) LTE: 75 Mbps (UL)</td>
<td>LTE</td>
</tr>
<tr>
<td>Release 9</td>
<td>End of 2009</td>
<td>LTE-Advanced</td>
<td>Enhancement of LTE</td>
</tr>
<tr>
<td>Release 10</td>
<td>Early 2011 2013+</td>
<td>LTE-Advanced ~1 Gbps (low mobility) ~100 Mbps (high mobility)</td>
<td>Submitted to IMT-Advanced</td>
</tr>
</tbody>
</table>
3GPP2 (3rd Generation Partnership Project 2)

IEEE
- IEEE 802.16 2004 (Fixed WiMax)
- IEEE 802.16 e (Mobile WiMax)
- IEEE 802.16 m
# WCDMA Statistic

<table>
<thead>
<tr>
<th>Number of WCDMA Subscribers</th>
<th>Date</th>
</tr>
</thead>
<tbody>
<tr>
<td>17 million (Global)</td>
<td>End of 2004</td>
</tr>
<tr>
<td>50 million (Global)</td>
<td>February 2006</td>
</tr>
<tr>
<td>200 million+ (Global)</td>
<td>May 2008</td>
</tr>
<tr>
<td>2.3 million (Singapore)</td>
<td>October 2008</td>
</tr>
</tbody>
</table>

**Future Expectation**

<table>
<thead>
<tr>
<th>WCDMA (Global)</th>
<th>HSPA (Global)</th>
<th>Date</th>
</tr>
</thead>
<tbody>
<tr>
<td>265 million</td>
<td>50 million</td>
<td>By 2008</td>
</tr>
<tr>
<td>1000 million</td>
<td>800 million</td>
<td>By 2013</td>
</tr>
</tbody>
</table>
By the end of 2005, 100 open WCDMA networks were operated with a total of 150 operators with license for WCDMA operation.

By May 2008,

- 229 UMTS operators in service in 98 countries, and
- 200 HSPA (with HSDPA only or HSDPA and HSUPA) operators in service in 88 countries.
D - Requirement of LTE

- LTE must have higher capacity compared to Release 6.
  - Data rate
    - LTE: > 100 Mbps (DL) & > 50 Mbps (UL)
    - Release 6: 14.4 Mbps (DL) and 11 Mbps (UL)
  - UE latency (two way radio delay)
    - LTE: < 10 ms
    - Release 6: < 50 ms
  - Connection set-up latency (Idle state -> active state)
    - LTE: < 100 ms
  - Flexible system bandwidth
    - LTE: 1.4 – 20 MHz
    - Release 6: 5 MHz
- Packet-based network
- Simplified network architecture
- Seamless mobility within LTE and between different cellular networks
- Lower investment and operational cost to have flat rate charging model
- Lower power consumption for MS
**LTE/SAE**

- Release 8 is expected to provide much higher data rate compared to HSDPA or HSUPA. Up to four time in downlink and three times in uplink.
- Release 8 is also called LTE (Long Term Evolution) and SAE (System Architecture Evolution).
- In brief, the evolution of Release 8 includes LTE air interface and SAE network architecture.

**Target**
- Max data rate: 100 Mpbs (DL) and 50 Mpbs (UL) using 20 MHz spectrum
- Reduced UE latency below 5 ms
- Reduce network latency below 100 ms
- Support flexible system bandwidth
Key Developments

- The main focus is to introduce a flat network architecture, so-called, EPS (Evolved Packet System), for packet-only radio access network. A flat network architecture is especially good for IP-based services because of low network delay.

- Another major change in LTE is to use a completely new multiple access that OFDMA is used for downlink and SC-FDMA is used for uplink.

- Allow flexible frequency allocation with 1.4, 3. 5. 10. 15 and 20 MHz.

- Simpler and more efficient MIMO.
2. SAE (System Architecture Evolution)
The goals form next generation cellular network architecture are:

- optimizing packet services only;
- supporting higher data rates;
- improving activation and set-up time;
- reducing packet delivery delays;
- simplifying the system;
- Optimizing inter-working access with other 3GPP and non-3GPP access networks.
To achieve the goals, the evolution for next generation cellular networks is to

- only optimize for packet switched services; no more circuit switched services
- develop a flat architecture; less involved nodes for reducing latencies and improving performance.

A new network architecture, EPS (Evolved Packet System), is introduced in Release 8.
UMTS PLMN Architecture

- Uu
- Iub
- Iu CS
- Cu
- Iur
- Iu PS
- UTRAN
- RNS
- MSC/VLR
- GMSC
- HLR
- SGSN
- GGSN
- CS domain
- PS domain
- Ext. Net.
- PLMN, PSTN, ISDN
- Internet
- CN
- UE
- ME
- USIM
- UE
- UTRAN
- RNS
- RNS
- USIM
- ME
- UE
B - Overview of EPS Architecture

- Release 8 introduces a new EPS which is the combination of LTE/E-UTRAN (LTE/Evolved UTRAN) and SAE/EPC (System Architecture Evolution/Evolved Packet Core).

- The EPS architecture consists of two nodes in the user plane, E-UTRAN Node B (eNodeB) and SAE Gateway (SAE GW), and one separated node in control plane, Mobility Management Entity (MME).

- The SAE GW can be split into two GW: Serving GW (S-GW) and Packet Data Network GW (P-GW).
- EPS architecture is similar to HSPA with tunneling architecture.
- This allows independent growth for user traffic and control signaling.
- All of the previous RNC functionality in Release 5 and 6 has moved to eNodeB such as RLC, RRC, PDCP and RRM.
- So, it is expected a easy integration of HSPA network to EPS network. But it has not be well-defined yet.
EPS Flat Architecture

- **Control plane**
- **User plane**

**Release 7 HSPA**
- GGSN
- SGSN
- RNC
- Node B

**LTE**
- SAE GW
- MME
- eNode B

EPC

EPS

E-UTRAN

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UE, E-UTRAN and EPC represent the IP Connectivity Layer which is optimized for IP based connectivity. It is also called EPS.

Other logical nodes in EPC are Policy Control and Charging Rules Function (PCRF) and Home Subscriber Server (HSS).

Inter-connection between eNodeB uses X2 interface.

Inter-connection between eNodeB and EPC uses S1 interface.

- S1-U to SAE GW
- S1-MME to MME
EPS System Architecture

- **EUTRAN**
  - eNodeB
  - X2
  - LTE-Uu

- **EPC**
  - S-GW
  - P-GW
  - S5/S8
  - S11
  - S6a
  - Gx
  - Rx
  - SGi
  - Ext. Net.

- **UE**
  - LTE-Uu

- **Internet**

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C - Open Interfaces

- **S1-U**: Interface between EUTRAN and Serving GW for user plane tunneling and inter eNode path switch during handover
- **S1-MME**: Interface between eNode B and MME for control plane protocol
- **S11**: Interface between MME and GW
- **S5**: Interface between Serving SAE GW and PDN SAE GW. Use for Serving GW relocation due to UE mobility or connecting to other PDN GW
- **X2**: Interface between eNode Bs for eNode B handover
- **SGi**: Interface between PDN SAE GW and external packet data network such as Internet.
EPS Architecture
UMTS PLMN Architecture

- **USIM**
- **ME**
- **UE**
- **Uu**
- **Iub**
- **Iu CS**
- **Iur**
- **Iu PS**
- **UTRAN**
- **RNS**

**CS domain**
- **MSC/VLR**
- **GMSC**
- **HLR**

**PS domain**
- **SGSN**
- **GGSN**

**Ext. Net.**
- **PLMN, PSTN, ISDN**
- **Internet**

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D - Node Functions

- **eNode B:**
  - Support LTE air interface
  - Support RRM such as power control, scheduling
  - Support RNC functions such as RRC, RLC, PDCP

- **MME:** Handled mobility, UE identities, idle mode, and security parameters
  - Signaling for inter-3GPP access network mobility
  - UE tracking and paging retransmission for idle mode.
  - Roaming
  - GW selection
  - Selection of MME during handover within LTE access network
  - Selection of SGSN for handover to 2G or 3G networks
  - Authentication
Serving SAE GW
- Each UE inside EPS has one Serving SAE GW
- Mobility Anchor for inter-eNode handover to relay traffic between eNode Bs
- Mobility Anchor for inter-3GPP handover to relay traffic between LTE and other 3GPP systems.
- Downlink packet buffering for EUTRAN idle mode
- Packet routing and forwarding to eNode Bs

PDN SAE GW
- Termination node of EPS
- Mobility anchor between 3GPP and non-3GPP access systems
- Packet filtering/packet inspection/packet screening
- UE IP address allocation
- Charging support
The radio access protocol of LTE aims for:
- Support for the PS domain
- Tight roundtrip delay: 5 ms for BW for 5 MHz or more and 10 ms for BW below 5 MHz

The control plane signaling is terminated at eNode B.

Since there is no soft handover in LTE, no data runs over X2 interface.

All radio-related functionalities have moved to eNode B such as RLC and RRC in addition to MAC as in HSDPA/HSUPA.

The previously radio-related protocol layers in UTRAN between Node B and RNC now are handled just between UE and eNode B.
Functions of Each Layer in eNode B

- **MAC** functions are similar to HSDPA/HSUPA: Scheduling. Priority handling. L1 retransmission. Multiplexing of logical channels to transport channel.
- **RLC**: Retransmission in case of L1 retransmission failed. Data segmentation.
- **PDCP**: Compression.
- **RRC**: Control terminal measurement report. Handle handover command.
  - LTE has less RRC states as in UTRAN:
  - **RRC_IDLE**: UE will monitor the paging messages and use cell reselection for mobility.
  - **RRC_CONNECTED**: UE can send and receive data and its location is known on the cell level.
3 LTE Air Interface
A - Introduction

- The larger spectrum allocation for UMTS based on Release 99, 5, 6, and 7 is 5 MHz.
- The Release 8 LTE targets to use larger bandwidth up to 20 MHz for higher data rate.
- Due to larger bandwidth, LTE decides to use OFDMA (Orthogonal Frequency Division Multiple Access) instead of WCDMA.
  - OFDMA signal remains orthogonal in a large bandwidth while WCDMA performance is degraded due to more multipath components.
- Thus, OFDMA is used for downlink.
However, OFDMA has a high-to-average power ratio because in OFDMA, some part of the spectrum may not be transmitted. Thus, a linear amplifiers is required.

Since the linear amplifiers have low efficiency and require high power transmission, OFDMA is not used in uplink due to limited mobile transmission power.

In uplink, LTE uses a new technique, which is called SC-FDMA (Single Carrier-FDMA), to allow lower mobile transmit power with a more efficient power amplifier.
B – OFDMA in Downlink

- OFDMA uses narrow and mutually orthogonal sub-carriers with 15 kHz each.
- At the sampling instant of a single sub-carrier, the other sub-carrier remain zero. Thus, each sub-carrier is mutually orthogonal to others.
- The actual signal is transmitted at the transmitter and received at the receiver using the Inverse Fast Fourier Transform (IFFT) and FFT, respectively.
- To avoid inter-symbol interference, the transmitter uses a guard period or cyclic prefix (CP).

Guard interval

<table>
<thead>
<tr>
<th>CP</th>
<th>OFDMA Symbol</th>
<th>N last samples copied</th>
</tr>
</thead>
</table>

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Sampling of OFDMA Sub-carriers

Frequency

15 KHz

Sampling point

Zero for others
The important feature of OFDMA allows users to transmit their data at different sub-carriers over the entire OFDMA bandwidth subject to the channel conditions.

This is able to resolve the problem of frequency selective fading.

Thus, depending on the user’s channel condition, he can send his data at different sub-carriers to achieve different data rate.

However, in WCDMA, the entire transmission bandwidth regardless of information rate is used for transmission. The frequency selective problem may become serious if the transmission bandwidth is very large.
Concept of Sub-carrier Scheduling

Channel gain

User 1

User 2

frequency

1 sub-carrier

OFDMA

WCDMA

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Due to selective fading, user may have different channel gains at different frequencies.

The channel gains for User 1 and User 2 are different. The channel gains for User 1 are good for the beginning and last part of the spectrum. User 2 is good in the middle part.

If OFDMA is used, we can allocate different sub-carriers to different users in order to maximize the capacity.

However, if WCDMA is used, the entire spectrum is allocated to 1 user such as User 2. The performance may be degraded because most of the spectrum for User is bad.
D - OFDMA Downlink Parameters

- Each sub-frame of 1 ms has two slots.
- The frame is 10 ms with 10 sub-frames.
- One sub-frame may have 12 or 14 symbols. Each slot has 6 or 7 symbols depending on normal or extended CP.
- The extended CP is good for large cell with large channel delay.
- The number of symbols per slot depends on the CP.
- Each sub-carrier has 15 KHz of bandwidth.
- The number of sub-carrier depends on the total bandwidth.
- In each sub-frame, the first three symbols are used for signaling purposes such as uplink allocation and pilot symbol and the rest of the symbols carry user data.
## Physical Parameters for Downlink OFDMA

<table>
<thead>
<tr>
<th>Parameter</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><strong>Bandwidth (MHz)</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Frame</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Sub-frame (TTI)</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Slot/sub-frame</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Sub-carrier spacing</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Sampling frequency (MHz)</strong></td>
<td>1.92</td>
<td>3.84</td>
<td>7.68</td>
<td>15.36</td>
<td>23.04</td>
<td>30.72</td>
</tr>
<tr>
<td><strong>FFT</strong></td>
<td>128</td>
<td>256</td>
<td>512</td>
<td>1024</td>
<td>1536</td>
<td>2048</td>
</tr>
<tr>
<td><strong>Number of sub-carriers</strong></td>
<td>72+1</td>
<td>180+1</td>
<td>300+1</td>
<td>600+1</td>
<td>900+1</td>
<td>1200+1</td>
</tr>
<tr>
<td><strong>Symbols/sub-frame</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Cyclic prefix (us)</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

- Normal: 4.69x6, 5.21x1, Extended: 16.67
The resource unit allocated to users is in terms of resource block, not sub-carrier due to overhead.

Each resource block (RB) has 12 sub-carrier with a total of 180 kHz or 15 sub-carriers and a 0.5 ms time slot with 6/7 symbols per sub-frame.

The resource allocation is based on 1 ms sub-frame anyway.

Different resource block have different modulations. Not different sub-carrier to reduce the complexity.

A user can be assigned one or more resource blocks in the same or different sub-frame.
Downlink Sub-frame Structure

Sub-carrier

Frequency

12 sub-carriers

Resource Block

Sub-carriers for a symbol in a RB

Slot 1

Slot 2

1 ms
OFDMA Resource Allocation

Single RB

180 KHz

1 ms Allocation period

User 1

User 1

User 1

Total system BW
Reference Symbols

- Channel estimation of sub-carriers is done by placing reference or pilot symbol in both time and frequency domain with even distribution.
- Then, the receiver can estimate the channel effect to different sub-carriers by interpolating these time and frequency domain symbol ‘grid’.
- For multi-antennas within a cell, different antenna uses different positions for pilot symbols.
- For multi-antennas in different cells, different pilot symbol patterns and locations are used.
Reference Symbols

Sub-carriers (Frequency Domain)

Reference Signals

OFDM Symbols (Time Domain)
E – Downlink Data Rate

- Downlink OFDMA supports QPSK, 16 QAM and 64 QAM with/without 2x2 MIMO.

- The lowest QPSK $\frac{1}{2}$ modulation provides 1 bps/Hz. With highest 64 QAM without coding and 2x2 MIMO, the spectrum efficiency can be 12 bps/Hz.

- Depending on modulation and coding, MIMO bandwidth, number of resource blocks, and long/short CP, the data rate can be from 0.9 Mbps to 172.8 Mbps.

- The bit rate is given by
  \[
  \text{Bit rate} = (\text{bps/Hz}) \times (\# \text{ of sub-carriers}) \times (\# \text{ of symbols per sub-frame} / 1\text{ms})
  \]
# Downlink Data Rate Table

<table>
<thead>
<tr>
<th>Modulation coding</th>
<th>MIMO</th>
<th>1.4 MHz (72)</th>
<th>3 MHz (180)</th>
<th>5 MHz (300)</th>
<th>10 MHz (600)</th>
<th>20 MHz (1200)</th>
</tr>
</thead>
<tbody>
<tr>
<td>QPSK $\frac{1}{2}$</td>
<td>-</td>
<td>0.9</td>
<td>2.2</td>
<td>3.6</td>
<td>7.2</td>
<td>14.4</td>
</tr>
<tr>
<td>16QAM $\frac{1}{2}$</td>
<td>-</td>
<td>1.7</td>
<td>4.3</td>
<td>7.2</td>
<td>14.4</td>
<td>28.8</td>
</tr>
<tr>
<td>16QAM $\frac{3}{4}$</td>
<td>-</td>
<td>2.6</td>
<td>6.5</td>
<td>10.8</td>
<td>21.6</td>
<td>43.2</td>
</tr>
<tr>
<td>64QAM $\frac{3}{4}$</td>
<td>-</td>
<td>3.9</td>
<td>9.7</td>
<td>16.2</td>
<td>32.4</td>
<td>64.8</td>
</tr>
<tr>
<td>64QAM 4/4</td>
<td>-</td>
<td>5.2</td>
<td>13.0</td>
<td>21.6</td>
<td>43.2</td>
<td>86.4</td>
</tr>
<tr>
<td>64QAM $\frac{3}{4}$</td>
<td>2x2</td>
<td>7.8</td>
<td>19.4</td>
<td>32.4</td>
<td>64.8</td>
<td>129.6</td>
</tr>
<tr>
<td>64QAM 4/4</td>
<td>2x2</td>
<td>10.4</td>
<td>25.9</td>
<td>43.2</td>
<td>86.4</td>
<td>172.8</td>
</tr>
</tbody>
</table>

Based on 6 symbols per slot
F – SC-FDMA in Uplink

- Due to short symbol duration, the receiver is more complicated due to multipath interference. The BS receiver needs to use equalizer.
- That is why SC-FDMA is not used in downlink because of the complex equalizer required at UE.
- Use QAM with cyclic prefix.
- The reason to use CP is to provide high performance such as eliminating the inter-symbol interference simplify the equalizer at BS.
- The maximum bandwidth is 20 MHz and the minimum is 180 kHz equal to one resource block.
- One frame is 10 ms with 20 slots with 0.5 ms each. This is similar to downlink frame.
- One symbol is transmitted at each TTI (transmission time interval) of 1 ms.
Reasons to Use SC-FDMA

- SC-FDMA provides a lower Peak to Average Ratio (PAR). Thus, a more efficient power amplifier can be used to lower terminal transmit power and increase the coverage.

- Because of the frequency-domain generation, the transmission bandwidth and frequency can be changed easily.

- BS scheduler assigns the time-frequency interval to a UE for data transmission. Thus, it can provide the intra-cell orthogonally.

- Slow power control can be used because of no near far problem due to orthogonal uplink transmission.
Multiple User Transmissions

Tx 1

Tx 2

BS receiver

frequency

frequency

frequency
G – Uplink Data Rate

- No MIMO is used in UE in uplink.
- So, the uplink data rate is up to 86 Mbps with 64 QAM.

<table>
<thead>
<tr>
<th>Modulation coding</th>
<th>1.4 MHz</th>
<th>3 MHz</th>
<th>5 MHz</th>
<th>10 MHz</th>
<th>20 MHz</th>
</tr>
</thead>
<tbody>
<tr>
<td>QPSK ½</td>
<td>0.9</td>
<td>2.2</td>
<td>3.6</td>
<td>7.2</td>
<td>14.4</td>
</tr>
<tr>
<td>16QAM ½</td>
<td>1.7</td>
<td>4.3</td>
<td>7.2</td>
<td>14.4</td>
<td>28.8</td>
</tr>
<tr>
<td>16QAM ¾</td>
<td>2.6</td>
<td>6.5</td>
<td>10.8</td>
<td>21.6</td>
<td>43.2</td>
</tr>
<tr>
<td>16QAM 4/4</td>
<td>3.5</td>
<td>8.6</td>
<td>14.4</td>
<td>28.8</td>
<td>57.6</td>
</tr>
<tr>
<td>64 QAM ¾</td>
<td>3.9</td>
<td>9.7</td>
<td>16.2</td>
<td>32.4</td>
<td>64.8</td>
</tr>
<tr>
<td>64 QAM 4/4</td>
<td>5.2</td>
<td>13.0</td>
<td>21.6</td>
<td>43.2</td>
<td>86.4</td>
</tr>
</tbody>
</table>
H - Terminal Types

- Release 8 defines five terminal categories for different rate.
- Category 1 is lowest capability with 10 Mbps downlink and 5 Mbps uplink. It does not support MIMO.
- Category 5 is highest capability with 300 Mbps downlink and 75 Mbps uplink. It supports 4x4 MIMO.
- The data rates depend on the max transport block size within TTI of 1 ms.
- All support bandwidth from 1.4 MHz to 20 MHz.
- All support 64 QAM downlink modulation.
- All support 16 QAM uplink modulation; except Category 5 supports 64 uplink modulation.
## Terminal Categories

<table>
<thead>
<tr>
<th></th>
<th>Category 1</th>
<th>Category 2</th>
<th>Category 3</th>
<th>Category 4</th>
<th>Category 5</th>
</tr>
</thead>
<tbody>
<tr>
<td>Peak rate downlink</td>
<td>10 Mbps</td>
<td>50 Mbps</td>
<td>100 Mbps</td>
<td>150 Mbps</td>
<td>300 Mbps</td>
</tr>
<tr>
<td>(approximately)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Peak rate uplink</td>
<td>5 Mbps</td>
<td>25 Mbps</td>
<td>50 Mbps</td>
<td>50 Mbps</td>
<td>75 Mbps</td>
</tr>
<tr>
<td>(approximately)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Max bits received</td>
<td>10296</td>
<td>51024</td>
<td>102048</td>
<td>149776</td>
<td>299552</td>
</tr>
<tr>
<td>within TTI</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Max bits transmitted</td>
<td>5160</td>
<td>25456</td>
<td>51024</td>
<td>51024</td>
<td>75376</td>
</tr>
<tr>
<td>within TTI</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>RF bandwidth</td>
<td>20 MHz</td>
<td>20 MHz</td>
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<td>Modulation downlink</td>
<td>64QAM</td>
<td>64QAM</td>
<td>64QAM</td>
<td>64QAM</td>
<td>64QAM</td>
</tr>
<tr>
<td>Modulation uplink</td>
<td>16QAM</td>
<td>16QAM</td>
<td>16QAM</td>
<td>16QAM</td>
<td>64QAM</td>
</tr>
<tr>
<td>Receiver diversity</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>eNodeB diversity</td>
<td>1–4 tx</td>
<td>1–4 tx</td>
<td>1–4 tx</td>
<td>1–4 tx</td>
<td>1–4 tx</td>
</tr>
<tr>
<td>MIMO downlink</td>
<td>Optional</td>
<td>2 × 2</td>
<td>2 × 2</td>
<td>2 × 2</td>
<td>4 × 4</td>
</tr>
</tbody>
</table>

4 Channel Types
A – Downlink Channels

- Since all channel allocations are short-term allocation due to PS services, no DCH is defined in LTE. The channel types in LTE is much simpler compared to WCDMA.

- Four transport channels have been defined in LTE: BCH (Broadcast Channel), PCH (Paging Channel), DL-SCH (Downlink Shared Channel), and MCH (Multicast Channel).

- They are mapped to three physical channels: PDSCH (Physical Downlink Shared Channel), PDCCH (Physical Downlink Control Channel), and CCPCH (Common Control Physical Channel), PBCH (Physical Broadcast Channel).

- Since all of the PS services are sharing the resources for short time, all of the transport channels are mapped to PDSCH.
Mapping of Transport DL Channels to Physical Channels

Transport Channels

- BCH
- PCH
- DL-SCH
- MCH

Physical Channels

- CCPCH
- PBCH
- PDSCH
- PDCCH
1 – Downlink Shared Channel (PDSCH)

- PDSCH supports QPSK, 16 QAM and 64 QAM and uses bandwidth up to 20 MHz.
- With MIMO, the data rate can be up to 170 Mbps depending on modulation and coding and control overhead.
- Support HARQ with soft combining.
- Support AMC.
- Similar to R99, it uses turbo coding with a new turbo interleaver.
2 – Downlink Control Channel (PDCCH)

- PDCCH is transmitted with PDSCH simultaneously.
- Within each downlink sub-frame of PDSCH, the downlink transmission contains the control information including downlink scheduling grant, uplink scheduling grant, and DL ACK/NACK for the UL data transmission.
  - Downlink scheduling grant contains the information for UE to demodulate the messages on DL-SCH such as resource block, duration, transport format, modulation, HARQ process number, redundancy version and new data indicator etc.
  - Uplink scheduling grant contains the similar information for UE to send its data to BS.
  - The DL ACK/NACK contains 1 bit control information.
The downlink control symbols are located in the first $n$ ($\leq 3$) symbols.

The first symbol is the Control Channel Format Indicator with max of 2 bits to indicate the number of OFDM symbols used for downlink signaling for every sub-frame.

The control channel uses QPSK 1/3.

No mixing of control and data in one OFDM symbol.

A UE monitors a number of the control channels in LTE downlink.
3 – Other Physical Channels

A number of physical channels are defined for signaling purposes:

- PBCH
- P/S-SCH (Primary/Secondary Synchronization Channel)

PBCH

- A pre-defined transport format
- Broadcast over the entire coverage area
- Transmit system information on P-BCH (Primary-BCH) and D-BCH (Dynamic-BCH)
- P-BCH contains the necessary information to demodulate D-BCH and defined as single fixed size transport, QPSK, sent on CCPCH and no HARQ.
- D-BCH contains remaining system information
Synchronization and Cell Search

- Downlink Synchronization Channel is for terminals to:
  - Synchronize with the DL frame
  - Obtain the correct cell (Cell Search)
  - Find the number of antennas in BCH
  - Assist for handover

- Two types of synchronization channel: P-SCH and S-SCH
- They are sent on sub-frame 0 and 5 over a 10 ms radio frame with 10 sub-frames.
- They occupy 2 symbols in a sub-frame.
- P-SCH: Identify the SCH symbol timing, the cell ID within a cell group ID
- S-SCH: Detect the cell ID group, BCH antenna configuration and CP length

Dr. Peter H J Chong
B – Uplink Channels

- Similarly, due to short-term allocation due to PS services, no DCH is defined in LTE.
- Two transport channels have been defined in LTE: UL-SCH (Uplink Shared Channel), and RACH (Random Access Channel)
- They are mapped to three physical channels: PUSCH (Physical Uplink Shared Channel), PUCCH (Physical Uplink Control Channel), and PRACH (Physical Random Access Channel).
- One frame of 10 ms has 10 sub-frames with 20 slots of 0.5 ms each. The slot is numbered from 0 to 19.
- The TTI is 1 ms regardless of bandwidth.
Mapping of Uplink Transport Channels to Physical Channels

Transport Channels

- RACH
- PRACH

Physical Channels

- PUCCH
- PUSCH

UL-SCH
1 – Shared Channel

- Uplink physical channels is PUSCH.
- Support the same set of modulation as in PDSCH except 64 QAM.
- No MIMO.
- Up to 20 MHz bandwidth with a multiple of 180 kHz resource block.
- Provide up to 50 Mbps.
2 – Reference Signal

- Two types of reference signals
  - Demodulate reference signal to provide a signal reference for demodulator at BS receiver
  - Transmitted with uplink data/control signaling
  - Sounding reference signal as pilot signal
  - Not transmitted with uplink data transmission.

- Both signals are mapped to SC-FDMA symbol.
3 - PUCCH

- PUCCH is not transmitted with PUSCH simultaneously.
- The PUCCH is scrambled with the UE-specific scrambling code.
- Mapped to uplink control channel resource in terms of a code, two resource blocks, and time.
- PUCCH contains:
  - CQI: provide the current channel conditions to BS scheduler
  - ACK/NACK: HARQ feedback to downlink data transmission includes a single bit ACK/NACK per HARQ process
  - Scheduling request
Uplink power control is employed by the UE. It has open-loop and closed-loop power to control the transmit power. The intra-cell power control is adjusted by the closed-loop power control based on the reference transmit power set by open-loop power control.