Long-Term Evolution (LTE) - Radio and PHY Aspects

- Background
- OFDM Basics
- Multiantenna Technologies
- Radio Interface
LTE Key Radio Features (Release 8)

- Multiple access scheme
  - DL: OFDMA with CP
  - 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 and 1x(2 or 4) uplink supported
  - Multi-layer transmission with up to four streams
  - Multi-user MIMO also supported

- Implicit support for interference coordination

- Support for both FDD and TDD
**LTE Frequency Bands**

- LTE will support all band classes currently specified for UMTS as well as additional bands

<table>
<thead>
<tr>
<th>E-UTRA Band</th>
<th>Uplink (UL) eNode B receive UE transmit</th>
<th>Downlink (DL) eNode B transmit UE receive</th>
<th>Duplex Mode</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1920 MHz - 1980 MHz</td>
<td>2110 MHz - 2170 MHz</td>
<td>FDD</td>
</tr>
<tr>
<td>2</td>
<td>1850 MHz - 1910 MHz</td>
<td>1930 MHz - 1990 MHz</td>
<td>FDD</td>
</tr>
<tr>
<td>3</td>
<td>1710 MHz - 1785 MHz</td>
<td>1805 MHz - 1880 MHz</td>
<td>FDD</td>
</tr>
<tr>
<td>4</td>
<td>1710 MHz - 1755 MHz</td>
<td>2110 MHz - 2155 MHz</td>
<td>FDD</td>
</tr>
<tr>
<td>5</td>
<td>824 MHz - 849 MHz</td>
<td>869 MHz - 894 MHz</td>
<td>FDD</td>
</tr>
<tr>
<td>6</td>
<td>830 MHz - 840 MHz</td>
<td>875 MHz - 885 MHz</td>
<td>FDD</td>
</tr>
<tr>
<td>7</td>
<td>2500 MHz - 2570 MHz</td>
<td>2620 MHz - 2690 MHz</td>
<td>FDD</td>
</tr>
<tr>
<td>8</td>
<td>880 MHz - 915 MHz</td>
<td>925 MHz - 960 MHz</td>
<td>FDD</td>
</tr>
<tr>
<td>9</td>
<td>1749.9 MHz - 1784.9 MHz</td>
<td>1844.9 MHz - 1879.9 MHz</td>
<td>FDD</td>
</tr>
<tr>
<td>10</td>
<td>1710 MHz - 1770 MHz</td>
<td>2110 MHz - 2170 MHz</td>
<td>FDD</td>
</tr>
<tr>
<td>11</td>
<td>1427.9 MHz - 1452.9 MHz</td>
<td>1475.9 MHz - 1500.9 MHz</td>
<td>FDD</td>
</tr>
<tr>
<td>12</td>
<td>698 MHz - 716 MHz</td>
<td>728 MHz - 746 MHz</td>
<td>FDD</td>
</tr>
<tr>
<td>13</td>
<td>777 MHz - 787 MHz</td>
<td>746 MHz - 756 MHz</td>
<td>FDD</td>
</tr>
<tr>
<td>14</td>
<td>788 MHz - 798 MHz</td>
<td>758 MHz - 768 MHz</td>
<td>FDD</td>
</tr>
<tr>
<td>...</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>33</td>
<td>1900 MHz - 1920 MHz</td>
<td>1900 MHz - 1920 MHz</td>
<td>TDD</td>
</tr>
<tr>
<td>34</td>
<td>2010 MHz - 2025 MHz</td>
<td>2010 MHz - 2025 MHz</td>
<td>TDD</td>
</tr>
<tr>
<td>35</td>
<td>1850 MHz - 1910 MHz</td>
<td>1850 MHz - 1910 MHz</td>
<td>TDD</td>
</tr>
<tr>
<td>36</td>
<td>1930 MHz - 1990 MHz</td>
<td>1930 MHz - 1990 MHz</td>
<td>TDD</td>
</tr>
<tr>
<td>37</td>
<td>1910 MHz - 1930 MHz</td>
<td>1910 MHz - 1930 MHz</td>
<td>TDD</td>
</tr>
<tr>
<td>38</td>
<td>2570 MHz - 2620 MHz</td>
<td>2570 MHz - 2620 MHz</td>
<td>TDD</td>
</tr>
<tr>
<td>39</td>
<td>1880 MHz - 1920 MHz</td>
<td>1880 MHz - 1920 MHz</td>
<td>TDD</td>
</tr>
<tr>
<td>40</td>
<td>2300 MHz - 2400 MHz</td>
<td>2300 MHz - 2400 MHz</td>
<td>TDD</td>
</tr>
</tbody>
</table>
OFDM Basics – Overlapping Orthogonal

- **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.

![conventional FDM diagram](image)

- OFDM: still FDM but carriers can actually be **orthogonal** (no cross-talk) while actually overlapping, if specially designed → saved bandwidth!

![OFDM diagram](image)
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 \( f_k = k \cdot f_0 \)
Modulating the symbols onto subcarriers can be done very efficiently in baseband using the FFT algorithm.
ISI (between OFDM symbols) eliminated almost completely by inserting a guard time.

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 → elimination of same cell interference.
Comparison with CDMA – Principle

- **OFDM**: particular modulation symbol is carried over a relatively **long symbol time and narrow bandwidth**
  - LTE: 66.67 µs symbol time and 15 kHz bandwidth
  - For higher data rates send more symbols by using more sub-carriers → increases bandwidth occupancy
- **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
Comparison with CDMA – Time Domain Perspective

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

  ![CDMA symbols diagram](chart)

  CDMA symbols

  Multipath reflections from one symbol significantly overlap subsequent symbols → ISI

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

  ![OFDM symbols diagram](chart)

  Little to no overlap in symbols from multipath
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**
Two competing factors in determining the right OFDM symbol time:
- CP length should be longer than worst case multipath delay spread, and the OFDM symbol time should be much larger than CP length to avoid significant overhead from the CP.
- On the other hand, the 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 ~5 μs and for speeds up to 350 km/h (~600 μs coherence time @ 2.6 GHz). As such, the following was decided:
- CP length = 4.7 μs
- OFDM symbol time = 66.67 μs (~1/10 the worst case coherence time)
Scalable OFDM for Different Operating Bandwidths

- With Scalable OFDM, the subcarrier spacing stays fixed at 15 kHz (hence symbol time is fixed to 66.67 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.
  - This is done by specifying different FFT sizes (i.e. 512 point FFT for 5 MHz, 2048 point FFT for 20 MHz).

- 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

- Subframe length is 1 ms
  - consists of two 0.5 ms slots
- 7 OFDM symbols per 0.5 ms slot \(\rightarrow\) 14 OFDM symbols per 1ms subframe
  - In UL center SC-FDMA symbol used for the data demodulation reference signal (DM-RS)
LTE Downlink – Channel Structure and Terminology

Physical Resource Block (PRB)
- 7 OFDM Symbols x 12 Subcarriers
- Minimum unit of allocation: 2 PRBs

Reference Signal
- Staggered in the time-frequency plane

Resource Element
- Is a single subcarrier in an OFDM symbol

**First 1..3 OFDM symbols** reserved for L1/L2 control signaling (PCFICH, PDCCH, PHICH)

* 2..4 symbols for 1.4 MHz bandwidth only

Subframe (1 ms)
Slot (0.5 ms)

Slot (0.5 ms)

Subcarrier

PRB

Resource Element is a single subcarrier in an OFDM symbol

Reference Signal is staggered in the time-frequency plane

Physical Resource Block (PRB) = 7 OFDM Symbols x 12 Subcarriers
Minimum unit of allocation: 2 PRBs

* 2..4 symbols for 1.4 MHz bandwidth only
Spatial Multiplexing

- Rank of the MIMO channel determines the number of independent TX/RX channels offered by MIMO for spatial multiplexing
  - Rank $\leq \min(\#Tx, \#Rx)$
- To properly adjust the transmission parameters the UE provides feedback about the mobile radio channel situation
  - Channel quality (CQI), pre-coding matrix (PMI) and rank (RI)

$$H = U\Lambda V^H$$
Multiple Antenna Techniques Supported in LTE

- **SU-MIMO**
  - Multiple data streams sent to the same user (max. 2 codewords)
  - 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
  - Fall back scheme if channel conditions do not allow MIMO
  - Useful to improve reliability on common control channels
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 Duplexing Modes

- LTE supports both Frequency Division Duplex (FDD) and Time Division Duplex (TDD) to provide flexible operation in a variety of spectrum allocations around the world.

- Unlike UMTS TDD there is a high commonality between LTE TDD & LTE FDD
  - Slot length (0.5 ms) and subframe length (1 ms) is the same using the same numerology (OFDM symbol times, CP length, FFT sizes, sample rates, etc.)

- Half-Duplex FDD (HD-FDD) as additional method
  - Like FDD, but UE cannot transmit and receive at the same time
  - Useful e.g. in frequency bands with small duplexing space
The LTE downlink uses scalable OFDMA

- Fixed subcarrier spacing of 15 kHz for unicast
  - Symbol time fixed at $T = \frac{1}{15 \text{ kHz}} = 66.67 \mu\text{s}$
- Different UEs are assigned different sets of subcarriers so that they remain orthogonal to each other (except MU-MIMO)

**Diagram:**
- Bit stream
- Encoding + Interleaving + Modulation
- Serial to Parallel
- IFFT
- Parallel to Serial
- Add CP

**IFFT Sizes:**
- 20 MHz: 2048 pt IFFT
- 10 MHz: 1024 pt IFFT
- 5 MHz: 512 pt IFFT
Physical Channels to Support LTE Downlink

- **Synchronization Signals (SS)**
  - Allows mobile to get timing and frequency sync with the cell

- **Physical Broadcast Channel (PBCH)**
  - Carries basic system broadcast information

- **Physical Downlink Shared Channel (PDSCH)**
  - Carries DL traffic

- **Physical Downlink Control Channel (PDCCH)**
  - DL resource allocation
  - Time span of PDCCH

- **Physical Control Format Indicator Channel (PCFICH)**

- **Physical Uplink Control Channel (PUCCH)**
  - HARQ feedback for DL
  - CQI reporting
  - MIMO reporting

- **Physical Uplink Shared Channel (PUSCH)**
LTE Uplink Transmission Scheme (1/2)

- To facilitate efficient power amplifier design in the UE, 3GPP chose **single carrier frequency division multiple access (SC-FDMA)** in favor of OFDMA for uplink multiple access.
  - SC-FDMA results in better PAPR
    - Reduced PA back-off → 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 needed to be synchronous within a fraction of the CP length
    - 0.52 μs timing advance resolution
LTE Uplink Transmission Scheme (2/2)

- SC-FDMA implemented using an OFDMA front-end and a DFT pre-coder, this is referred to as either DFT-pre-coded OFDMA or DFT-spread OFDMA (DFT-SOFDMA)
  - Advantage is that numerology (subcarrier spacing, symbol times, FFT sizes, etc.) can be shared between uplink and downlink
  - Can still allocate variable bandwidth in units of 12 sub-carriers
  - Each modulation symbol sees a wider bandwidth
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 UEs

- **Sounding Reference Signal (SRS)**
  - Allows channel state information to be obtained by eNB

- **Physical Downlink Control Channel (PDCCH)**
  - UL scheduling grant

- **Physical HARQ Indicator Channel (PHICH)**
  - HARQ feedback for UL
The data rates supported by LTE depend on a number of parameters:
- bandwidth, modulation scheme, MIMO scheme

**Downlink peak rates**

- 1,4 MHz: 5 Mbps, 10 Mbps, 20 Mbps
- 5 MHz: 23 Mbps, 43 Mbps, 82 Mbps
- 20 MHz: 90 Mbps, 173 Mbps, 326 Mbps

**Uplink peak rates**

- 1,4 MHz: 3 Mbps, 4 Mbps
- 5 MHz: 12 Mbps, 17 Mbps
- 20 MHz: 55 Mbps, 83 Mbps

**Bandwidth options:**
- 1 Stream
- 2 Streams
- 4 Streams
<table>
<thead>
<tr>
<th>Access Scheme</th>
<th>UL</th>
<th>DFTS-OFDM</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>DL</td>
<td>OFDMA</td>
</tr>
<tr>
<td>Bandwidth</td>
<td></td>
<td>1.4, 3, 5, 10, 15, 20 MHz</td>
</tr>
<tr>
<td>Minimum TTI</td>
<td></td>
<td>1 ms</td>
</tr>
<tr>
<td>Sub-carrier spacing</td>
<td>Short</td>
<td>4.7 µs</td>
</tr>
<tr>
<td></td>
<td>Long</td>
<td>16.7 µs</td>
</tr>
<tr>
<td>Modulation</td>
<td>QPSK, 16QAM, 64QAM</td>
<td></td>
</tr>
<tr>
<td>Spatial multiplexing</td>
<td>Single layer for UL per UE</td>
<td>Up to 4 layers for DL per UE</td>
</tr>
<tr>
<td></td>
<td>MU-MIMO supported for UL and DL</td>
<td></td>
</tr>
</tbody>
</table>
### 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>
<tr>
<td>Capability for physical functionalities</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>RF bandwidth</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>20 MHz</td>
</tr>
<tr>
<td>Modulation</td>
<td>DL</td>
<td>QPSK, 16QAM, 64QAM</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>UL</td>
<td>QPSK, 16QAM</td>
<td></td>
<td></td>
<td>QPSK, 16QAM, 64QAM</td>
</tr>
<tr>
<td>Multi-antenna</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2 Rx diversity</td>
<td>Assumed in performance requirements.</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2x2 MIMO</td>
<td>Not supported</td>
<td></td>
<td></td>
<td>Mandatory</td>
<td></td>
</tr>
<tr>
<td>4x4 MIMO</td>
<td>Not supported</td>
<td></td>
<td></td>
<td>Mandatory</td>
<td></td>
</tr>
</tbody>
</table>
Long-Term Evolution (LTE) – Radio Resource Management

- DL Scheduling
- MIMO Operation
- UL Scheduling
- Power and Interference Management
Scheduling and Resource Allocation

- Basic unit of allocation is called a Resource Block (RB)
  - 12 subcarriers in frequency (= 180 kHz)
  - 1 timeslot in time (= 0.5 ms, = 7 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>
Downlink Scheduling Mechanism

**eNodeB**
- Carries DL resource assignment on L1/L2 control channel (PDCCH)
- Reported on PUCCH or PUSCH: provides channel state info and info to select MIMO mode

**UE**
- DL Scheduling Grant
- CQI/PMI/RI, HARQ indication

**Notes:**
- DL resource assignment is carried on the L1/L2 control channel (PDCCH).
- Channel state information and MIMO mode selection is reported on PUCCH or PUSCH.
Downlink Scheduling & Resource Allocation

- Channel dependent scheduling is supported in both time and frequency domain → enables two dimensional flexibility
  - CQI feedback can provide both wideband and frequency selective feedback
  - PMI and RI feedback allow for MIMO mode selection
  - Scheduler chooses bandwidth allocation, modulation and coding set (MCS), MIMO mode, and power allocation
- HARQ operation is asynchronous and adaptive
- Assigned PRBs can be distributed for a given user in the downlink
Downlink HARQ Operation

- HARQ is a simple stop and wait ARQ
  - Up to 8 parallel HARQ processes (FDD)
  - UE feeds back ACK/NACK according to PDSCH data received in subframe \( n - 4 \)
- Adaptation of the coding rate
  - FEC coding with \( r = 1/3 \) Turbo code
  - Rate matching: puncturing and repeating bits of the encoded data
- LTE supports both types of retransmission
  - Incremental redundancy
  - Chase combining
- HARQ operation is asynchronous and adaptive
  - Different PRBs and MCS can be used for the retransmission
  - Scheduler decides on when to sent a retransmission
LTE Packet Scheduler

**QoS & Subscriber Profile**
- QoS Class Identifier (QCI)

**Feedback from UE**
- CQI, RI, PMI, ACK/NACK

**UE service metrics**
- Throughput, Buffer Status

**Radio Resources**
- Power, PRBs

**UE capabilities**
- max. MCS, MIMO

**Common Ch. Config.**
- BCH, PCH, ...

**Scheduler Output**
- Scheduled Users
- PRB Assignment per UE
- SISO-TxDiv/ MIMO Scheme
- MCS Selection
- Transmitted power per PRB
- PDCCH Control
- Common Ctrl Channels

Cellular Communication Systems 32 Andreas Mitschele-Thiel, Jens Mueckenheim Nov. 2018
DSCH Dynamic Scheduling Algorithm (example)

- DSCH scheduler runs every subframe (1ms)
- Basic scheduling flow (example)
  1. Perform tasks for all users actively allocated to the scheduler
     - Process received CQI, ACK/ NACK, PMI, RI
     - Select HARQ process and Logical Channel Queues
     - Estimate RF conditions: wideband, per subband
  2. Create user ranking list and process individual users iteratively
     - Select a user and allocate PRBs, MCS and Tx power
     - Update available resources (PRBs/ Tx power)
     - Repeat until there are no more resources or end of scheduling list
  3. Assemble MAC PDUs and assign IEs for PDCCH for the users to be scheduled
     - Update scheduling metric
- Other parts working on a different time-scale
  - Inputs such as buffer size, service metrics
  - Algorithms, e.g. quality control loop, MIMO mode selection
MCS Levels in the Downlink

- MCS index corresponds to a modulation format and transport block size index
  - Transport block size table gives the block size to be used based on the # of PRBs allocated
- Code rate depends
  - #PRBs allocated
  - #Tx antenna ports
  - #OFDM symbols reserved for L1/L2 control
  - Example: 50 PRBs, 1 antenna port and 3 OFDM symbols reserved

- Note: 3GPP allows the UE to skip decoding if the code rate on the initial transmission exceeds 0.93

### MCS Index Modulation Transport Block Size

<table>
<thead>
<tr>
<th>MCS Index</th>
<th>Modulation</th>
<th>TBS Index</th>
<th>TBS for 50 PRBs</th>
<th>Approx. Code Rate</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>QPSK</td>
<td>0</td>
<td>1384</td>
<td>0.11</td>
</tr>
<tr>
<td>1</td>
<td>QPSK</td>
<td>1</td>
<td>1800</td>
<td>0.14</td>
</tr>
<tr>
<td>2</td>
<td>QPSK</td>
<td>2</td>
<td>2216</td>
<td>0.18</td>
</tr>
<tr>
<td>3</td>
<td>QPSK</td>
<td>3</td>
<td>2856</td>
<td>0.23</td>
</tr>
<tr>
<td>4</td>
<td>QPSK</td>
<td>4</td>
<td>3624</td>
<td>0.29</td>
</tr>
<tr>
<td>5</td>
<td>QPSK</td>
<td>5</td>
<td>4392</td>
<td>0.35</td>
</tr>
<tr>
<td>6</td>
<td>QPSK</td>
<td>6</td>
<td>5160</td>
<td>0.41</td>
</tr>
<tr>
<td>7</td>
<td>QPSK</td>
<td>7</td>
<td>6200</td>
<td>0.49</td>
</tr>
<tr>
<td>8</td>
<td>QPSK</td>
<td>8</td>
<td>6968</td>
<td>0.55</td>
</tr>
<tr>
<td>9</td>
<td>QPSK</td>
<td>9</td>
<td>7992</td>
<td>0.64</td>
</tr>
<tr>
<td>10</td>
<td>16QAM</td>
<td>9</td>
<td>7992</td>
<td>0.32</td>
</tr>
<tr>
<td>11</td>
<td>16QAM</td>
<td>10</td>
<td>8760</td>
<td>0.35</td>
</tr>
<tr>
<td>12</td>
<td>16QAM</td>
<td>11</td>
<td>9912</td>
<td>0.39</td>
</tr>
<tr>
<td>13</td>
<td>16QAM</td>
<td>12</td>
<td>11448</td>
<td>0.46</td>
</tr>
<tr>
<td>14</td>
<td>16QAM</td>
<td>13</td>
<td>12960</td>
<td>0.52</td>
</tr>
<tr>
<td>15</td>
<td>16QAM</td>
<td>14</td>
<td>14112</td>
<td>0.56</td>
</tr>
<tr>
<td>16</td>
<td>16QAM</td>
<td>15</td>
<td>15264</td>
<td>0.61</td>
</tr>
<tr>
<td>17</td>
<td>64QAM</td>
<td>15</td>
<td>15264</td>
<td>0.40</td>
</tr>
<tr>
<td>18</td>
<td>64QAM</td>
<td>16</td>
<td>16416</td>
<td>0.43</td>
</tr>
<tr>
<td>19</td>
<td>64QAM</td>
<td>17</td>
<td>18336</td>
<td>0.49</td>
</tr>
<tr>
<td>20</td>
<td>64QAM</td>
<td>18</td>
<td>19848</td>
<td>0.53</td>
</tr>
<tr>
<td>21</td>
<td>64QAM</td>
<td>19</td>
<td>21384</td>
<td>0.57</td>
</tr>
<tr>
<td>22</td>
<td>64QAM</td>
<td>20</td>
<td>22920</td>
<td>0.61</td>
</tr>
<tr>
<td>23</td>
<td>64QAM</td>
<td>21</td>
<td>25456</td>
<td>0.67</td>
</tr>
<tr>
<td>24</td>
<td>64QAM</td>
<td>22</td>
<td>27376</td>
<td>0.72</td>
</tr>
<tr>
<td>25</td>
<td>64QAM</td>
<td>23</td>
<td>28336</td>
<td>0.75</td>
</tr>
<tr>
<td>26</td>
<td>64QAM</td>
<td>24</td>
<td>30576</td>
<td>0.81</td>
</tr>
<tr>
<td>27</td>
<td>64QAM</td>
<td>25</td>
<td>31704</td>
<td>0.84</td>
</tr>
<tr>
<td>28</td>
<td>64QAM</td>
<td>26</td>
<td>36696</td>
<td>0.97</td>
</tr>
</tbody>
</table>
## UE DSCH Reporting

<table>
<thead>
<tr>
<th></th>
<th>Periodic Reporting</th>
<th>Aperiodic Reporting</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Degree of details</strong></td>
<td>Less detailed</td>
<td>More detailed</td>
</tr>
<tr>
<td><strong>Phy Channel for report</strong></td>
<td>PUCCH/ PUSCH</td>
<td>PUSCH</td>
</tr>
<tr>
<td><strong>Trigger for report</strong></td>
<td>Periodical</td>
<td>Indicator in Scheduling Grant</td>
</tr>
<tr>
<td><strong>PMI feedback</strong> (for closed-loop SM)</td>
<td>Single PMI</td>
<td>Single PMI/ Multiple PMI</td>
</tr>
</tbody>
</table>
| **CQI feedback** (computed assuming calculated PMI) | 1. Wideband  
2. UE selected subband (coarse subband size) | 1. Wideband  
2. UE selected best M-subband (granular subband sizes)  
3. Higher layer configured subband (one report per subband) |
| **RI feedback**                  | Separate subframe from CQI/ PMI            | Together with CQI/ PMI                       |
CQI Definition

<table>
<thead>
<tr>
<th>CQI index</th>
<th>modulation</th>
<th>code rate x 1024</th>
<th>efficiency</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>out of range</td>
<td></td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>QPSK</td>
<td>78</td>
<td>0.1523</td>
</tr>
<tr>
<td>2</td>
<td>QPSK</td>
<td>120</td>
<td>0.2344</td>
</tr>
<tr>
<td>3</td>
<td>QPSK</td>
<td>193</td>
<td>0.3770</td>
</tr>
<tr>
<td>4</td>
<td>QPSK</td>
<td>308</td>
<td>0.6016</td>
</tr>
<tr>
<td>5</td>
<td>QPSK</td>
<td>449</td>
<td>0.8770</td>
</tr>
<tr>
<td>6</td>
<td>QPSK</td>
<td>602</td>
<td>1.1758</td>
</tr>
<tr>
<td>7</td>
<td>16QAM</td>
<td>378</td>
<td>1.4766</td>
</tr>
<tr>
<td>8</td>
<td>16QAM</td>
<td>490</td>
<td>1.9141</td>
</tr>
<tr>
<td>9</td>
<td>16QAM</td>
<td>616</td>
<td>2.4063</td>
</tr>
<tr>
<td>10</td>
<td>64QAM</td>
<td>466</td>
<td>2.7305</td>
</tr>
<tr>
<td>11</td>
<td>64QAM</td>
<td>567</td>
<td>3.3223</td>
</tr>
<tr>
<td>12</td>
<td>64QAM</td>
<td>666</td>
<td>3.9023</td>
</tr>
<tr>
<td>13</td>
<td>64QAM</td>
<td>772</td>
<td>4.5234</td>
</tr>
<tr>
<td>14</td>
<td>64QAM</td>
<td>873</td>
<td>5.1152</td>
</tr>
<tr>
<td>15</td>
<td>64QAM</td>
<td>948</td>
<td>5.5547</td>
</tr>
</tbody>
</table>

- CQI indicates a MCS for the following conditions
  - Transport block sent with the indicated MCS
  - PRBs including the CQI reference resources
  - TBs sent with specific reference power
  - BLER ≤ 10%
- The CQI table is valid for all UE categories
Spatial Multiplexing

- UE indicates best combination of CQI/PMI/RI for max throughput (i.e. high-rank/low-MCS vs. low-rank/high MCS)
- Closed-loop SM is ideally suited for low speed scenarios when the CQI/PMI/RI feedback is accurate
- Open-loop SM provides robustness in high speed scenarios when the feedback is not accurate

<table>
<thead>
<tr>
<th></th>
<th>Closed-Loop SM</th>
<th>Open-Loop SM</th>
</tr>
</thead>
<tbody>
<tr>
<td>CQI</td>
<td>separate CQI for each codeword</td>
<td>one value applicable over all layers</td>
</tr>
<tr>
<td>PMI</td>
<td>PMI feedback from UE based on instantaneous channel state</td>
<td>no feedback from UE, fixed precoding at eNB with large delay CDD to improve robustness</td>
</tr>
<tr>
<td>RI</td>
<td>based on SINR and instantaneous channel matrix rank</td>
<td>typically based only on SINR</td>
</tr>
<tr>
<td></td>
<td>RI = 1 corresponds to closed loop TxDiv (CLTD) OR CL-MIMO 1 Layer</td>
<td>RI = 1 corresponds to open loop TxDiv (SFBC)</td>
</tr>
</tbody>
</table>

$$H = U \Lambda V^H$$
MIMO Definitions

- **Code Word**
  - Transport block format: CRC encoded data

- **Transmission layer**
  - Sub stream resulting from a mapping of modulated code word symbols
  - Number of layers ≤ number of antenna ports

- **Code book**
  - Quantized set of spatial combination vectors for precoding of symbols
    - layer for transmission on antenna ports

- **Rank of MIMO channel**
  - Number of independents TX/RX channels offered by MIMO for spatial multiplexing
  - Rank ≤ min(NTx, NRx)
Downlink Spatial Multiplexing Modes

- RRC allocates Transmission mode and number of antenna ports
- MAC scheduler decides on number of layers and pre-coding
  - Fallback in multi-antenna case: transmit diversity

<table>
<thead>
<tr>
<th>Transmission Mode</th>
<th>Scheme</th>
<th>Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mode 1</td>
<td>Single antenna</td>
<td></td>
</tr>
<tr>
<td>Mode 2</td>
<td>(Open Loop) Transmit Diversity</td>
<td>Alamouti-Scheme (Space Frequency Block Coding – SFBC)</td>
</tr>
<tr>
<td>Mode 3</td>
<td>Cyclic Delay Diversity (CDD)</td>
<td>Open Loop spatial multiplexing</td>
</tr>
<tr>
<td>Mode 4</td>
<td>Closed Loop Spatial Multiplexing</td>
<td>Single User MIMO</td>
</tr>
<tr>
<td>Mode 5</td>
<td>Multiuser MIMO</td>
<td></td>
</tr>
<tr>
<td>Mode 6</td>
<td>Closed Loop Spatial Multiplexing using single layer</td>
<td>Closed loop transmit diversity</td>
</tr>
<tr>
<td>Mode 7</td>
<td>Single Layer Transmission</td>
<td>Beamforming with UE specific RS</td>
</tr>
<tr>
<td>Mode 8</td>
<td>Dual Layer Transmission</td>
<td>Spatial Multiplexing with layer specific RS</td>
</tr>
</tbody>
</table>
MIMO Scheduling Operation

- Scheduler decides based on CQI/RI/PMI feedback
  - Each TTI: Precoding Matrix
  - Longer timeframe: Rank/ fallback to Tx diversity
- Adjustment of precoding matrix
  - Setting should follow the reported PMI
  - A set of precoding matrices is defined by 3GPP
    - 2 antenna ports: 4 vectors (1 layer)/ 3 matrices (2 layer)
    - 4 antenna ports: 16 vectors/ matrices
- Selection of the Rank/ transmission mode
  - Selection of the mode based e.g. on RI and CQI feedback
    - MIMO when high SNR (good CQI) and rank > 1
    - Tx diversity when low SNR (bad CQI) or rank = 1
    - Rank selected on RI feedback
    - Filtering of RI/ CQI to avoid toggling
  - Selected transmission mode may differ from reported rank
    - Rescaling of reported CQI required
Uplink Scheduling Mechanism

- **L2 message carried via a MAC control element (PUSCH):** indicates buffer status/power headroom
- **Carried on PUCCH for synchronized UEs; carried on PRACH when synchronization is lost**
- **Carried on downlink L1/ L2 control channel (PDCCH)**
- **Carried on PHICH**
- **Carried on PUSCH:** indicates buffer status/power headroom
- **UL Scheduling Requests**
- **Scheduling Report**
- **Sounding Reference Signal (SRS):**
- **UL Scheduling Grant**
- **HARQ indication**
- **Allows channel state information to be obtained by eNB**
Uplink Scheduling & Resource Allocation

- Channel dependent scheduling in both time and frequency enabled through the use of the sounding reference signal (SRS)
  - Scheduler selects bandwidth, modulation and coding set (MCS), use of MU-MIMO, and PC parameters
- HARQ operation is synchronous, and can be adaptive
- PRBs assigned for a particular UE to be contiguous in the uplink (SC-FDMA)
  - To reduce UE complexity, restriction placed on number of PRBs that can be assigned

![Diagram showing Uplink Scheduling & Resource Allocation]

- 14 SC-FDMA symbols (12 for data)
- 12 subcarriers
- Slot = 0.5ms
- UE A
- UE B
- UE C
- Frequency
- Time
- 12 subcarriers
Uplink HARQ Operation

- In principle UL HARQ functionality is the same than in the DL
  - Stop and wait protocol
- HARQ operation is synchronous
  - 8 HARQ processes (8 ms HARQ round-trip-time)
  - UE receives ACK/NACK on PHICH according to PUSCH data transmitted in subframe n – 4
- UL HARQ can be adaptive
  - UE will listen for a dynamic scheduling grant for an adaptive retransmission
    - SG combined with HARQ ACK/ NACK
    - Can contain new MCS/ PRBs for retransmission
  - If no scheduling grant is sent for a retransmission, the UE performs non-adaptive HARQ retransmission using pre-defined RV pattern on same PRBs
    - Saves PDCCH resources
USCH Dynamic Scheduling

- Basic principles and requirements are the same between USCH and DSCH scheduler
  - Scheduling period is 1 subframe
  - USCH scheduler assigns PRBs and MCS to be used for the USCH transmission
- Differences according to the UL specifics
  - Allocation of contiguous PRBs in order to maintain SC-FDMA transmission
  - Synchronous HARQ scheme
    - Internal follow of the PRBs occupation needed in case of retransmissions (esp. when FH employed)

![Diagram showing USCH Dynamic Scheduling](image-url)
MCS Levels in the Uplink

- MCS index corresponds to a modulation format and transport block size index
  - Transport block size table gives the block size to be used based on the #PRBs allocated
- Code rate depends
  - #PRBs allocated
  - SRS allocation
  - Example: 50 PRBs, no SRS allocated

<table>
<thead>
<tr>
<th>MCS Index</th>
<th>Modulation</th>
<th>TBS Index</th>
<th>TBS for 50 PRBs</th>
<th>Approx. Code Rate</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>QPSK</td>
<td>0</td>
<td>1384</td>
<td>0.10</td>
</tr>
<tr>
<td>1</td>
<td>QPSK</td>
<td>1</td>
<td>1800</td>
<td>0.13</td>
</tr>
<tr>
<td>2</td>
<td>QPSK</td>
<td>2</td>
<td>2216</td>
<td>0.16</td>
</tr>
<tr>
<td>3</td>
<td>QPSK</td>
<td>3</td>
<td>2856</td>
<td>0.20</td>
</tr>
<tr>
<td>4</td>
<td>QPSK</td>
<td>4</td>
<td>3624</td>
<td>0.25</td>
</tr>
<tr>
<td>5</td>
<td>QPSK</td>
<td>5</td>
<td>4392</td>
<td>0.31</td>
</tr>
<tr>
<td>6</td>
<td>QPSK</td>
<td>6</td>
<td>5160</td>
<td>0.36</td>
</tr>
<tr>
<td>7</td>
<td>QPSK</td>
<td>7</td>
<td>6200</td>
<td>0.43</td>
</tr>
<tr>
<td>8</td>
<td>QPSK</td>
<td>8</td>
<td>6968</td>
<td>0.49</td>
</tr>
<tr>
<td>9</td>
<td>QPSK</td>
<td>9</td>
<td>7992</td>
<td>0.56</td>
</tr>
<tr>
<td>10</td>
<td>QPSK</td>
<td>10</td>
<td>8760</td>
<td>0.61</td>
</tr>
<tr>
<td>11</td>
<td>16QAM</td>
<td>10</td>
<td>8760</td>
<td>0.31</td>
</tr>
<tr>
<td>12</td>
<td>16QAM</td>
<td>11</td>
<td>9912</td>
<td>0.35</td>
</tr>
<tr>
<td>13</td>
<td>16QAM</td>
<td>12</td>
<td>11448</td>
<td>0.40</td>
</tr>
<tr>
<td>14</td>
<td>16QAM</td>
<td>13</td>
<td>12960</td>
<td>0.45</td>
</tr>
<tr>
<td>15</td>
<td>16QAM</td>
<td>14</td>
<td>14112</td>
<td>0.49</td>
</tr>
<tr>
<td>16</td>
<td>16QAM</td>
<td>15</td>
<td>15264</td>
<td>0.53</td>
</tr>
<tr>
<td>17</td>
<td>16QAM</td>
<td>16</td>
<td>16416</td>
<td>0.57</td>
</tr>
<tr>
<td>18</td>
<td>16QAM</td>
<td>17</td>
<td>18336</td>
<td>0.64</td>
</tr>
<tr>
<td>19</td>
<td>16QAM</td>
<td>18</td>
<td>19848</td>
<td>0.69</td>
</tr>
<tr>
<td>20</td>
<td>16QAM</td>
<td>19</td>
<td>21384</td>
<td>0.74</td>
</tr>
<tr>
<td>21</td>
<td>64QAM</td>
<td>19</td>
<td>21384</td>
<td>0.50</td>
</tr>
<tr>
<td>22</td>
<td>64QAM</td>
<td>20</td>
<td>22920</td>
<td>0.53</td>
</tr>
<tr>
<td>23</td>
<td>64QAM</td>
<td>21</td>
<td>25456</td>
<td>0.59</td>
</tr>
<tr>
<td>24</td>
<td>64QAM</td>
<td>22</td>
<td>27376</td>
<td>0.63</td>
</tr>
<tr>
<td>25</td>
<td>64QAM</td>
<td>23</td>
<td>28336</td>
<td>0.66</td>
</tr>
<tr>
<td>26</td>
<td>64QAM</td>
<td>24</td>
<td>30576</td>
<td>0.71</td>
</tr>
<tr>
<td>27</td>
<td>64QAM</td>
<td>25</td>
<td>31704</td>
<td>0.73</td>
</tr>
<tr>
<td>28</td>
<td>64QAM</td>
<td>26</td>
<td>36696</td>
<td>0.85</td>
</tr>
</tbody>
</table>
Sounding Reference Signals

- SRS is used to sound uplink channel to support frequency selective scheduling
  - Channel sensitive scheduling in both time and frequency
- SRS parameters are UE specific and configured semi-statically
  - Last symbol in a subframe can be used for SRS
  - Periodicity: \{2, 5, 10, 20, 40, 80, 160, 320\} ms
  - UEs can be multiplexed by different transmission offsets
  - Bandwidth: typically transmitted over the entire PUSCH bandwidth (does not include PUCCH region)
- SRS is not sent when there is a scheduling request (SR) or CQI to be sent on PUCCH (to avoid multi-carrier transmission)
USCH Scheduling Information

- **Scheduling Request (SR)**
  - One bit flag on PUCCH
  - Request for UL-SCH resources for new transmission

- **MAC reporting on PUSCH**
  - Reported in separate MAC control elements
  - **Buffer Status Report**
    - Amount of UL data waiting for transmission
    - Reporting per logical channel group (LCG)
    - Short report: LCG-ID + buffer size
    - Long report: all buffer sizes in consecutive order (max. 4 LCG)

- **Power Headroom Report**
  - Difference between configured max. UE output power and the estimated Tx power for PUSCH transmission
  - Reporting range: \(-23 \ldots +40\) dB

- Configured by RRC: timers to trigger the reports, LCG
Uplink Power Control

- Open-loop power control is the baseline uplink power control method in LTE (compensation for path loss and fading)
  - Constrain the dynamic range between signals received from different UEs
  - Fading is exploited by rate control

- Target SINR is now a function of the UE’s pathloss:

\[ \text{SI NR}_{(\text{dBm})} = \text{SI NR}_{\text{nom}(\text{dB})} - (1 - \alpha) \cdot \text{PL}_{(\text{dB})} \]

- \( \text{PL}_{\text{dB}} \): pathloss, estimated from DL reference signal
- **Fractional compensation factor** \( \alpha \leq 1 \)
  - only a fraction of the path loss is compensated
Management of Uplink Inter-cell Interference

- In a reuse-1 deployment it is critical to manage the uplink interference level.
- eNBs can send uplink overload indications to neighbor eNBs via the X2 interface.
- Power control parameters can be adapted based on overload indicators.
  - Allows control of the interference level to ensure coverage and system stability.

![Diagram showing the process of managing uplink interference](image)
Uplink Spatial Multiplexing

- LTE Rel.-8 and Rel.-9 support only single UE transmit antenna
  - Reduces complexity (power amplifiers)
  - Single user MIMO not supported
- With multiple receive antenna at the eNB spatial multiplexing between different UEs is still possible even with single transmit antenna
  - Beamforming when on different location
    - Reference Signals used to adjust antenna weights
  - Multi-user MIMO when different multipath
    - No pre-coding $\rightarrow$ separation is done purely in eNB
    - Different Reference Signals for each UE (shifts of the sequence) assigned by RRC
    - No separate MAC-signaling
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 HO

![Diagram of Random Access Procedure]

- **Contention based RA**
  1. Random Access Preamble
  2. Random Access Response
  3. Scheduled Transmission
  4. Contention Resolution

- **Non-Contention based RA**
  0. RA Preamble assignment
  1. Random Access Preamble
  2. Random Access Response
DRX Operation

- Mechanism to save battery resources for UE when in RRC connected mode
- DRX operation is fully controlled by the UE MAC
  - Switching to inactive mode in case some timer expires
  - UE will not listen on PDCCH neither sent on PUCCH/ PUSCH during inactive time
- Parameters are set by RRC
  - DRX Inactivity timer, DRX cycle, On Duration timer
  - DRX Retransmission timer
  - DRX Short cycle, DRX Short cycle timer
Semi-Persistent Resource Allocation

- Semi-persistent allocation is introduced to support a large number of users (e.g. VoIP) without running into control channel bottleneck.
  - RRC signaling configures *semi persistent scheduling interval* (periodicity of persistent allocation) and a *semi persistent scheduling C-RNTI*.
  - Scheduling grant on PDCCH used to activate a persistent allocation which applies to the first HARQ transmission.
    - Scheduling grant assigns MCS and subframe location for persistent allocation.
    - Resources implicitly released after inactivity.
  - Retransmissions *maybe dynamically scheduled selectively to optimize packing of VoIP users*.

![Diagram](attachment:image.png)
Long-Term Evolution (LTE) – LTE Advanced

- Motivation
- Performance Improvement Technologies
- Relaying/ HetNet
LTE-Advanced

- The evolution of LTE
  - Corresponding to LTE Release 10 and beyond
- Motivation of LTE-Advanced
  - IMT-Advanced standardisation process in ITU-R
  - Additional IMT spectrum band identified in WRC07
  - Further evolution of LTE Release 8 and 9 to meet:
    - Performance requirements for IMT-Advanced of ITU-R
    - Future operator and end-user requirements
- Other important requirements
  - LTE-Advanced to be backwards compatible with Release 8
  - Support for flexible deployment scenarios including downlink/uplink asymmetric bandwidth allocation for FDD and non-contiguous spectrum allocation
  - Increased deployment of indoor eNB and HNB in LTE-Advanced

Evolution from IMT-2000 to IMT-Advanced

**IMT-Advanced 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 and 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</strong> [bps/Hz]</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-layer transmission in downlink
  - Introduction of single-user MIMO up to 4-layer 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
Carrier Aggregation

- Further increase of the available bandwidth by flexible aggregation of the transmission channels (Carrier)
  - Increase of the available peak data rate
  - More flexible channel allocation

- For each channel (Component Carrier) there is a separate transmitter/ receiver chain
  - Combination of the data streams (aggregation) in the MAC-Layer
CA Radio Resource Management

- Activation and deactivation of SCC is done by MAC control elements
  - `sCellDeactivationTimer` for autonomous deactivation
- RRC procedures are performed on the PCC
  - Random Access
  - Handover
  - Adding/deleting SCC (incl. info about the SCC configuration)
- Mobility is based on existing RRC framework
  - Usage of existing measurement events for change of PCell
  - Adding option to compare with SCell in measurement events A3 and A5
  - To support change of SCell new measurement event A6: Neighbour becomes offset better than SCell
- UL Carrier aggregation has no impact on UE measurements
  - eNB may use SRS on other carrier
  - Simultaneous PUSCH and PUCCH supported (on different CC)
  - Separate UL TPC per CC, but total UE power limit remains!
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
MIMO Resource Scheduling

- In Downlink new transmission mode 9
  - Up two 8-layer transmission scheme
  - Non-codebook based precoding

- Definition of two transmission modes in Uplink

<table>
<thead>
<tr>
<th>Uplink Transmission Mode</th>
<th>Scheme</th>
<th>Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mode 1</td>
<td>Single antenna</td>
<td>Same as of Rel.-8</td>
</tr>
<tr>
<td>Mode 2</td>
<td>Closed Loop Spatial Multiplexing</td>
<td>Single User MIMO</td>
</tr>
</tbody>
</table>

- Mode 2: up to 4-layer transmission scheme
- Codebook based precoding
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/beamforming (CS/CB) between cell sites

- Similar for the uplink
  - Dynamic coordination in uplink scheduling
  - Joint reception at multiple sites
CoMP Radio Resource Management

- **DL CoMP handling**
  - Multiple transmission points are coordinated in their downlink data transmission.
  - The UE may be configured to measure and report the CSI from a set of CSI-RS resources.
  - The UE may also be configured with one or more interference measurements from another set of CSI-RS resources.

- **UL CoMP handling**
  - Multiple reception points are coordinated in their uplink data reception.
  - The UE may be configured with UE-specific parameters
    - DMRS configuration on PUSCH, PUCCH configuration
    - Independent of the physical cell identity of the UE’s serving cell.

- CoMP requires low latency and high bandwidth backhaul links with low UE mobility!
Relaying

Type 1 relay

- Relay node (RN) creates a separate cell distinct from the donor 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
RN Radio Aspects

- RN terminates the Uu-interface from the UE
  - Supports mostly eNB functionality
  - Support of user specific S1/ X2 functionality towards DeNB via new Um-interface
- When using the same carrier there is only half-duplex supported for the transmission from DeNB towards UE and vice versa
  - Avoid tx and rx at the same time
  - Reuse of MBMS frame format to provide backward-compatibility with Rel.-8 downlink channel estimation
Heterogeneous Networks (HetNet)

- Network expansion due to varying traffic demand & RF environment
  - Cell-splitting of traditional macro deployments is complex and iterative
  - Indoor coverage and need for site acquisition add to the challenge
- Future network deployments based on Heterogeneous Networks
  - Deployment of Macro eNBs for initial coverage only
  - Addition of Pico, HeNBs and Relays for capacity growth & better user experience
    - Improved in-building coverage and flexible site acquisition with low power base stations
    - Relays provide coverage extension with no incremental backhaul expense
HetNet Improvements

- Enhanced Inter-cell Interference Coordination (elICIC, Rel.-10)
  - Transmission gaps may be created to avoid interference: Almost Blank Subframes (ABS)
  - ABS information is sent over X2-Interface in \textit{LoadInformation} message
  - To suppress legacy signals, ABSs can be declared as MBSFN subframes

- Further enhanced non CA-based ICIC (feICIC, Rel.-11)
  - Provision of Cell specific Reference Symbol (CRS) assistance information from neighbour cells: \textit{neighCellsCRSInfo}
  - Aid UE to mitigate interference impact

- Other improvements
  - X2-Handover between HeNB and eNB
  - Dual connectivity: split bearer between eNB (cf. 5G solution)
LTE References

**Literature:**

**Standards**
- TS 36.xxx series: RAN Aspects
- TS 36.300 “E-UTRAN; Overall description; Stage 2”
- TR 25.814 “Physical layer aspect for evolved UTRA”
- TR 36.912 “Feasibility study for Further Advancements for E-UTRA (LTE-Advanced)”
## Abbreviations

<table>
<thead>
<tr>
<th>Abbreviation</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>ACK</td>
<td>Acknowledgement</td>
</tr>
<tr>
<td>BSR</td>
<td>Buffer Status Report</td>
</tr>
<tr>
<td>CC</td>
<td>Component Carrier</td>
</tr>
<tr>
<td>CP</td>
<td>Cyclic Prefix</td>
</tr>
<tr>
<td>CQI</td>
<td>Channel Quality Indicator</td>
</tr>
<tr>
<td>DFT</td>
<td>Discrete Fourier Transformation</td>
</tr>
<tr>
<td>DRB</td>
<td>Data Radio Bearer</td>
</tr>
<tr>
<td>DRX</td>
<td>Discontinuous Reception</td>
</tr>
<tr>
<td>eNodeB/ eNB</td>
<td>Evolved NodeB</td>
</tr>
<tr>
<td>E-UTRA</td>
<td>Evolved Universal Terrestrial Radio Access</td>
</tr>
<tr>
<td>FDD</td>
<td>Frequency-Division Duplex</td>
</tr>
<tr>
<td>FFT</td>
<td>Fast Fourier Transformation</td>
</tr>
<tr>
<td>FH</td>
<td>Frequency Hopping</td>
</tr>
<tr>
<td>HO</td>
<td>Handover</td>
</tr>
<tr>
<td>IE</td>
<td>Information Element</td>
</tr>
<tr>
<td>IFFT</td>
<td>Inverse FFT</td>
</tr>
<tr>
<td>LCG</td>
<td>Logical Channel Group</td>
</tr>
<tr>
<td>MAC</td>
<td>Medium Access Control</td>
</tr>
<tr>
<td>MCS</td>
<td>Modulation and Coding Scheme</td>
</tr>
<tr>
<td>MIMO</td>
<td>Multiple Input Multiple Output</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>PHR</td>
<td>Power Headroom Report</td>
</tr>
<tr>
<td>PHY</td>
<td>Physical Layer</td>
</tr>
<tr>
<td>PMI</td>
<td>Precoding Matrix Index</td>
</tr>
<tr>
<td>QoS</td>
<td>Quality of Service</td>
</tr>
<tr>
<td>RB</td>
<td>Resource Block</td>
</tr>
<tr>
<td>RLC</td>
<td>Radio Link Control</td>
</tr>
<tr>
<td>RI</td>
<td>Rank Indicator</td>
</tr>
<tr>
<td>RS</td>
<td>Reference Signal</td>
</tr>
<tr>
<td>RRC</td>
<td>Radio Resource Control</td>
</tr>
<tr>
<td>SCH</td>
<td>Shared Channel</td>
</tr>
<tr>
<td>SC-FDMA</td>
<td>Single Carrier FDMA</td>
</tr>
<tr>
<td>SG</td>
<td>Scheduling Grant</td>
</tr>
<tr>
<td>SM</td>
<td>Spatial Multiplexing</td>
</tr>
<tr>
<td>SR</td>
<td>Scheduling Request</td>
</tr>
<tr>
<td>SRS</td>
<td>Sounding Reference Signal</td>
</tr>
<tr>
<td>SS</td>
<td>Synchronization Signal</td>
</tr>
<tr>
<td>SU</td>
<td>Single Use</td>
</tr>
<tr>
<td>TA</td>
<td>Timing Advance (Tracking Area)</td>
</tr>
<tr>
<td>TB</td>
<td>Transport Block</td>
</tr>
<tr>
<td>TDD</td>
<td>Time-Division Duplex</td>
</tr>
<tr>
<td>TPC</td>
<td>Transmit Power Control</td>
</tr>
<tr>
<td>TTI</td>
<td>Transmission Time Interval</td>
</tr>
<tr>
<td>UCI</td>
<td>Uplink Control Information</td>
</tr>
<tr>
<td>UE</td>
<td>User Equipment</td>
</tr>
</tbody>
</table>