MIMO IN LTE AND LTE-ADVANCED

OUTLINE

- General Introduction
  - Pre-coding and beam-forming
  - Antenna design
- Introduction to LTE
  - Downlink and uplink physical layer
  - Reference signals and antenna ports
- MIMO transmission schemes in LTE
  - Code words, layers, and streams
    - Tx diversity
    - Downlink SU-MIMO
      - Closed loop, pre-coded spatial multiplexing
      - Open loop, large delay cyclic delay diversity
    - Downlink MU-MIMO
    - MIMO related feedback and downlink control signaling
      - CSI (RI, PMI, CQI)
    - Uplink MIMO
- MIMO in LTE Rel-9 and Rel-10 (LTE-Advanced)
  - Dual layer beam-forming
  - Uplink SU-MIMO
  - Extended downlink MIMO
  - CoMP
GENERAL INTRODUCTION

MULTI-ANTENNA TRANSMISSION TECHNIQUES

- **Diversity** for improved system performance
- **Beam-forming** for improved coverage (fewer cells to cover a given area)
- **SDMA** for improved capacity (more users per cell)
- **Multi-layer transmission** ("MIMO") for higher data rates in a given bandwidth

The multi-antenna technique to use depends on what to achieve.
GENERAL INTRODUCTION:
PRECODING AND BEAMFORMING

- Array-gain from transmit beam-forming improves SNR
  - Large coverage gain
  - Small gain at cell center
- Constructive summation of signals (in the air)
  - Align phases between several transmitted copies of the signal
- Spatial isolation between users
  - Multi-user scheduling (SDMA)

\[ \mathbf{x} = \mathbf{W} \mathbf{s} = \begin{bmatrix} w_1 \\ w_2 \\ \vdots \\ w_n \end{bmatrix} \begin{bmatrix} s_1 \\ s_2 \\ \vdots \\ s_n \end{bmatrix} \]

GENERAL INTRODUCTION:
MIMO IN CELLULAR SYSTEMS

- Throughput versus coverage tradeoff
  - Large path loss and high interference at cell edge \( \Rightarrow \) Beam-forming
  - Low path loss and low interference at cell center \( \Rightarrow \) Spatial multiplexing
General Introduction:
Antenna Design

- Base station antennas (angular spread is typically small)
  - 4-10 λ antenna separation is considered "large" while 0.5 λ is "small"
- Mobile station antennas (angular spread is typically large)
  - 0.5 λ antenna separation is considered "large"
- UE antenna design challenges
  - RF complexity and antenna placement
  - Correlation with other MIMO antennas
  - Coupling with other MIMO antennas, battery, display, etc.
  - Position and number of antennas for 802.11, Bluetooth, GPS, FM radio, etc.
  - Multiple-band support (e.g., 0.7, 2.1, 2.6 GHz)
  - Polarization
  - Requirements: Electromagnetic compatibility (EMC), Electro static discharge (ESD), Specific absorption rate (SAR), Hearing aid compatibility (HAR), harmonics, etc.
  - Hand and head effects
  - Mass production limitations
  - Form-factor

<table>
<thead>
<tr>
<th>Scenario</th>
<th>Difficulty</th>
<th>Antenna requirements</th>
<th>Practical effects</th>
</tr>
</thead>
<tbody>
<tr>
<td>Interference Mitigation</td>
<td>Low</td>
<td>Envelope correlation ≤ 0.7</td>
<td>Antenna BPD ≤ 10 dB</td>
</tr>
<tr>
<td>Spatial Multiplexing</td>
<td>Medium</td>
<td>Envelope correlation ≈ 0.3–0.5</td>
<td>Medium BPD required</td>
</tr>
<tr>
<td>Range Extension</td>
<td>High</td>
<td>Low</td>
<td>Diversity antenna as good as main antenna</td>
</tr>
</tbody>
</table>

Hand-held multi-stream MIMO is not feasible at large distance.
INTRODUCTION TO LTE: HSPA AND LTE = MOBILE BROADBAND

› HSPA – High-Speed Packet Access ("Turbo-3G")
  - Gradually improved performance at a low additional cost
› LTE – Long-Term Evolution
  - Significantly higher performance in a wide range of spectrum allocations
    - Downlink: up to 300 Mbit/s
    - Uplink: up to 75 Mbit/s
    - Reduced latency: 10 ms RTT
  - Packet-switched services only
  - First step towards IMT-Advanced ("4G")
INTRODUCTION TO LTE:
DOWNLINK TRANSMISSION SCHEME - OFDM

- Subcarrier spacing $\Delta f = 15$ kHz
  $\Rightarrow T_u = 66.7 \mu s$
  - $\Delta f = 7.5$ kHz also specified, for MBSFN transmission only

- Two cyclic prefix lengths
  - Normal
  - Extended (for MBSFN and environments with large delay spread)

- Basic time unit $T_u = 1/(2048 \cdot 15000)$
  - All time quantities expressed as multiples of $T_u$

<table>
<thead>
<tr>
<th>Configuration, $\Delta f$</th>
<th>CP length</th>
<th>Symbols per slot</th>
</tr>
</thead>
<tbody>
<tr>
<td>Normal 15.14 kHz</td>
<td>4.7 $\mu s$</td>
<td>7</td>
</tr>
<tr>
<td>Extended 15.14 kHz</td>
<td>16.7 $\mu s$</td>
<td>6</td>
</tr>
<tr>
<td>7.5 kHz</td>
<td>33.3 $\mu s$</td>
<td>3</td>
</tr>
</tbody>
</table>

INTRODUCTION TO LTE:
DL-SCH PROCESSING

- CRC insertion (24 bit for DL-SCH)
- DL-SCH: Turbo w. QPP, extra CRC per code block
- BCH: tail-biting conv. code
- Rate matching, redundancy version generation per code block, circular buffer
- Transport-channel-specific scrambling using length-31 Gold sequences
- Modulation (QPSK, 16QAM, 64QAM)
- Mapping to transmission layers (for multi-layer transmission)
- Precoding (for multi-rank transmission)
- Resource block mapping (PDSCH)
INTRODUCTION TO LTE:
UPLINK TRANSMISSION SCHEME – DFTS-OFDM

- Single-carrier scheme – DFT-spread OFDM
  - Numerology aligned with downlink OFDM
  - Normal and extended CP, 15 kHz subcarrier spacing, ...

INTRODUCTION TO LTE:
UPLINK CONTROL ON PUCCH

- Specific frequency resources at the edges of the uplink spectrum
  - Scheduling request, ACK/NACK, CSI feedback
  - One PUCCH transmitted within one resource block
  - Frequency-hopping at slot border diversity

- Code-multiplexing of multiple UEs in one RB pair
  - Orthogonal within a cell
  - Non-orthogonal between cells
MIMO TRANSMISSION SCHEMES IN LTE

Downlink Transmission Modes

- Seven different semi-statically configured modes
  1. Single-antenna port (port 0)
  2. Transmit diversity (2 Tx or 4 Tx)
  3. Open-loop spatial multiplexing
  4. Closed-loop spatial multiplexing
  5. Multi-user MIMO
  6. Closed-loop rank=1 pre-coding
  7. Single-antenna port (port 5)

One dedicated pilot for e.g. additional beam-forming support

Multi-antennas a core feature of LTE!
MIMO TRANSMISSION SCHEMES IN LTE:

**DOWNLINK REFERENCE SIGNALS**

- Known symbols inserted into the downlink time-frequency grid
  - Channel estimation for downlink coherent detection
  - Channel quality estimation for CSI (CQI/PMI/RI) reporting
  - Mobility measurements
- Antenna port
  - Characterized by a reference signal "antenna" visible to UE
- Three types of antenna ports
  - Cell-specific reference signals
    - Antenna ports 0 – 3
      - Always present (in cells supporting unicast transmission)
  - UE-specific reference signals
    - Antenna port 5
      - Used for UE-specific beamforming
  - MBSFN reference signals
    - Antenna port 4
      - Used for MBSFN operation

MIMO TRANSMISSION SCHEMES IN LTE:

**CELL-SPECIFIC REFERENCE SIGNALS**

- Time-domain position: In OFDM symbol #0 and #4 of each slot
  - Symbol #0 and #3 in case of extended CP
- Frequency-domain position: Every 6th subcarrier
  - 3 subcarriers staggering between symbols
- 504 different Reference Signal Sequences
  - Pseudo-random sequences
MIMO TRANSMISSION SCHEMES IN LTE:
CELL-SPECIFIC REFERENCE SIGNALS

- Frequency-multiplexing between antenna port 0 and 1
  - 3 subcarriers offset
- RS resource element "empty" on other antenna port
  - No inter-antenna RS interference
- Reduced density for antenna port 2 and 3

MIMO TRANSMISSION SCHEMES IN LTE:
UE SPECIFIC RS (ANTENNA PORT 5)

- UE-specific reference signals are supported for single-antenna-port transmission of PDSCH
- The UE is informed by higher layers whether the UE-specific reference signal is present
- UE-specific reference signals are transmitted only on the resource blocks upon which the corresponding PDSCH is mapped.
- PDSCH and antenna port 5 uses the same pre-coding
MIMO TRANSMISSION SCHEMES IN LTE:
MBSFN OPERATION (ANTENNA PORT 4)

- Multicast-Broadcast Single Frequency Network
  - Synchronized transmission from multiple cells
  - Seen as multipath propagation by terminal
    - Combining gain "for free" thanks to OFDM
- MBSFN operation not supported in Rel-8
  - Physical layer (almost) complete
  - Functionality missing on higher layers

MIMO TRANSMISSION SCHEMES IN LTE:
MULTI-ANTENNA TRANSMISSION

- Transmit Diversity ("open-loop")
  - Transmission of same information from multiple antenna ports ⇒ Diversity
  - One code word
  - Number of layers = Number of antenna ports
- Spatial Multiplexing ("open-loop" or "closed loop")
  - Multiple parallel data streams ⇒ Higher data rates
  - One or two code words
  - Number of layers ≤ Number of antenna ports
MIMO TRANSMISSION SCHEMES IN LTE:
TRANSMIT DIVERSITY (OPEN LOOP)

› Common channels (PDCCH, PCFICH, PHICH, PBCH)
  – Link adaptation not possible
› Feedback not possible
  – High Doppler
  – Cell edge
› Large Tx Antenna Distance is desirable
› Two antenna ports:
  – Space-Frequency Block Coding
› Four antenna ports:
  – SFBC + Frequency Shift Transmit Diversity (FSTD)

MIMO TRANSMISSION SCHEMES IN LTE:
LTE DOWNLINK TRANSMIT DIVERSITY

› Two antenna ports:
  – Space-Frequency Block Coding SFBC
  – Like WCDMA STTD (Alamouti) but in frequency domain

Subcarrier

- Antenna 0
- Antenna 1

\[
\begin{bmatrix}
S_0 \\
S_1
\end{bmatrix}
\]
MIMO TRANSMISSION SCHEMES IN LTE:
LTE DOWNLINK TRANSMIT DIVERSITY

- Four antenna ports:
  - SFBC + Frequency Shift Transmit Diversity (FSTD)
  - Like Time Switched Transmit Diversity but in frequency domain

MIMO TRANSMISSION SCHEMES IN LTE:
SPECIAL TX-DIVERSITY FOR PHICH

- Four ACK/NACK bits are transmitted over 4 sub-carriers with up to 3 repetitions

- Using both Type 1 and Type 2 simultaneously ensures uniform power distribution over the eNB antennas
MIMO TRANSMISSION SCHEMES IN LTE:
DOWNLINK SPATIAL MULTIPLEXING

- Maximum of two code words
- Mapping to up to four layers
  - Number of layers depends on channel “rank”
  - Dynamically adjusted based on UE reports

<table>
<thead>
<tr>
<th>Layer mapping</th>
<th>Up to four layers</th>
</tr>
</thead>
<tbody>
<tr>
<td>One code word</td>
<td>Two code words</td>
</tr>
<tr>
<td>One layer</td>
<td>Two layers</td>
</tr>
<tr>
<td>(No MIMO)</td>
<td>Three layers</td>
</tr>
</tbody>
</table>

- Transport format (modulation scheme and code rate) may differ between the code words
- Same number of symbols on each layer
- Note:
  - In Tx-diversity one code-word gets mapped to 2 or 4 layers (special case)
  - A single code-word can be mapped to two layers in case of 4 Tx antennas (special case)

Example: \( N_L = 3, N_A = 4 \)

- One symbol from each of \( N_L \) layers linearly mapped to \( N_A \) antenna ports

\[
\bar{y} = W \cdot \bar{x}
\]

- UE reports recommended precoder matrix \( W \) (including channel rank)
  - Set of available precoder matrices = The precoder “code book”
  - Precoder matrices recommended per set of RBs
- Network
  - follows UE recommendation, or
  - overrides with a common precoder for all RBs, signaled on PDCCH
- One layer ⇒ “Closed-loop” TX diversity ⇒ “Beam forming”
MIMO TRANSMISSION SCHEMES IN LTE:
TWO DIFFERENT FORMS OF PRE-CODING

- Closed-loop spatial multiplexing mode:
  - Precoder $W_f$ focuses transmission in "strong directions" towards the UE
  - $W_f$ selected from finite codebook
  - Track the channel in time as well as in frequency
  - Targeting scenarios with accurate CSI at eNodeB
  - Typically low mobility (unless highly spatially correlated channel)

**Track instantaneous channel to achieve array gain!**

- Open-loop spatial multiplexing mode:
  - Transmit in "all directions" by cycling through a sequence of four different pre-coders $W_f$ during the transmission of a single subframe
  - Transmission rank one utilizes transmit diversity
  - Targeting scenarios with inaccurate CSI at eNodeB
  - Typically high mobility

**Go for diversity to achieve robustness!**

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### Table 1: Precoding codebook for transmission on two antennas.

<table>
<thead>
<tr>
<th>Codebook index</th>
<th>Number of layers $M$</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>1</td>
</tr>
<tr>
<td>0</td>
<td>$\frac{1}{\sqrt{2}} [1 1]$</td>
</tr>
<tr>
<td>1</td>
<td>$\frac{1}{\sqrt{2}} [1 -1]$</td>
</tr>
<tr>
<td>2</td>
<td>$\frac{1}{\sqrt{2}} [1 i]$</td>
</tr>
<tr>
<td>3</td>
<td>$\frac{1}{\sqrt{2}} [-i]$</td>
</tr>
</tbody>
</table>

Each column vector is in the form: $\frac{1}{\sqrt{2}} [\cos\theta, \sin\theta]$
### MIMO Transmission Schemes in LTE: 4 TX Precoding Codebook

#### Table 2: Precoding codebook for transmission on four antennas.

<table>
<thead>
<tr>
<th>Codebook index</th>
<th>( \mathbf{u}_i )</th>
<th>( 1 )</th>
<th>( 2 )</th>
<th>( 3 )</th>
<th>( 4 )</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>( [1, -1, -1, -1]^T )</td>
<td>( \mathbf{W}_{11} )</td>
<td>( \mathbf{W}_{12}^{1/2} )</td>
<td>( \mathbf{W}_{13}^{1/2} )</td>
<td>( \mathbf{W}_{14}^{1/2} )</td>
</tr>
<tr>
<td>1</td>
<td>( [1, 1, -1, -1]^T )</td>
<td>( \mathbf{W}_{21} )</td>
<td>( \mathbf{W}_{22}^{1/2} )</td>
<td>( \mathbf{W}_{23}^{1/2} )</td>
<td>( \mathbf{W}_{24}^{1/2} )</td>
</tr>
<tr>
<td>2</td>
<td>( [1, 1, 1, -1]^T )</td>
<td>( \mathbf{W}_{31} )</td>
<td>( \mathbf{W}_{32}^{1/2} )</td>
<td>( \mathbf{W}_{33}^{1/2} )</td>
<td>( \mathbf{W}_{34}^{1/2} )</td>
</tr>
<tr>
<td>3</td>
<td>( [1, 1, 1, 1]^T )</td>
<td>( \mathbf{W}_{41} )</td>
<td>( \mathbf{W}_{42}^{1/2} )</td>
<td>( \mathbf{W}_{43}^{1/2} )</td>
<td>( \mathbf{W}_{44}^{1/2} )</td>
</tr>
<tr>
<td>4</td>
<td>( [1, -1, 1, -1]^T )</td>
<td>( \mathbf{W}_{51} )</td>
<td>( \mathbf{W}_{52}^{1/2} )</td>
<td>( \mathbf{W}_{53}^{1/2} )</td>
<td>( \mathbf{W}_{54}^{1/2} )</td>
</tr>
<tr>
<td>5</td>
<td>( [1, -1, -1, 1]^T )</td>
<td>( \mathbf{W}_{61} )</td>
<td>( \mathbf{W}_{62}^{1/2} )</td>
<td>( \mathbf{W}_{63}^{1/2} )</td>
<td>( \mathbf{W}_{64}^{1/2} )</td>
</tr>
<tr>
<td>6</td>
<td>( [1, -1, -1, -1]^T )</td>
<td>( \mathbf{W}_{71} )</td>
<td>( \mathbf{W}_{72}^{1/2} )</td>
<td>( \mathbf{W}_{73}^{1/2} )</td>
<td>( \mathbf{W}_{74}^{1/2} )</td>
</tr>
<tr>
<td>7</td>
<td>( [1, 1, -1, -1]^T )</td>
<td>( \mathbf{W}_{81} )</td>
<td>( \mathbf{W}_{82}^{1/2} )</td>
<td>( \mathbf{W}_{83}^{1/2} )</td>
<td>( \mathbf{W}_{84}^{1/2} )</td>
</tr>
<tr>
<td>8</td>
<td>( [1, 1, 1, -1]^T )</td>
<td>( \mathbf{W}_{91} )</td>
<td>( \mathbf{W}_{92}^{1/2} )</td>
<td>( \mathbf{W}_{93}^{1/2} )</td>
<td>( \mathbf{W}_{94}^{1/2} )</td>
</tr>
<tr>
<td>9</td>
<td>( [1, -1, 1, -1]^T )</td>
<td>( \mathbf{W}_{101} )</td>
<td>( \mathbf{W}_{102}^{1/2} )</td>
<td>( \mathbf{W}_{103}^{1/2} )</td>
<td>( \mathbf{W}_{104}^{1/2} )</td>
</tr>
<tr>
<td>10</td>
<td>( [1, 1, 1, 1]^T )</td>
<td>( \mathbf{W}_{111} )</td>
<td>( \mathbf{W}_{112}^{1/2} )</td>
<td>( \mathbf{W}_{113}^{1/2} )</td>
<td>( \mathbf{W}_{114}^{1/2} )</td>
</tr>
<tr>
<td>11</td>
<td>( [1, 1, 1, 1]^T )</td>
<td>( \mathbf{W}_{121} )</td>
<td>( \mathbf{W}_{122}^{1/2} )</td>
<td>( \mathbf{W}_{123}^{1/2} )</td>
<td>( \mathbf{W}_{124}^{1/2} )</td>
</tr>
<tr>
<td>12</td>
<td>( [1, 1, -1, 1]^T )</td>
<td>( \mathbf{W}_{131} )</td>
<td>( \mathbf{W}_{132}^{1/2} )</td>
<td>( \mathbf{W}_{133}^{1/2} )</td>
<td>( \mathbf{W}_{134}^{1/2} )</td>
</tr>
<tr>
<td>13</td>
<td>( [1, 1, -1, 1]^T )</td>
<td>( \mathbf{W}_{141} )</td>
<td>( \mathbf{W}_{142}^{1/2} )</td>
<td>( \mathbf{W}_{143}^{1/2} )</td>
<td>( \mathbf{W}_{144}^{1/2} )</td>
</tr>
<tr>
<td>14</td>
<td>( [1, -1, -1, 1]^T )</td>
<td>( \mathbf{W}_{151} )</td>
<td>( \mathbf{W}_{152}^{1/2} )</td>
<td>( \mathbf{W}_{153}^{1/2} )</td>
<td>( \mathbf{W}_{154}^{1/2} )</td>
</tr>
<tr>
<td>15</td>
<td>( [1, -1, -1, 1]^T )</td>
<td>( \mathbf{W}_{161} )</td>
<td>( \mathbf{W}_{162}^{1/2} )</td>
<td>( \mathbf{W}_{163}^{1/2} )</td>
<td>( \mathbf{W}_{164}^{1/2} )</td>
</tr>
</tbody>
</table>

\( \mathbf{W}_{k(1-2)} \) Denotes the matrix defined by the columns \( c_1 \ldots c_m \) of the matrix

\[
\mathbf{W}_i = \mathbf{I}_{4\times4} - 2\mathbf{u}_i\mathbf{u}_i^H/\mathbf{u}_i^H\mathbf{u}_i
\]

### MIMO Transmission Schemes in LTE: Pre-Coder Design

- **Constant modulus:**
  - All physical antennas keep the same transmit power
  - Maximizes PA utilization efficiency
- **Nested property:**
  - Each pre-coder matrix in a higher rank sub-codebook can find at least one pre-coding matrix in a lower rank sub-codebook
  - Ensures proper performance if eNB selects a lower rank than what UE reported
  - Reduced CQI calculation complexity for the UE; calculations can be shared for different ranks (up to a scaling factor)
- **Constrained alphabet:**
  - Two antennas: QPSK alphabet \( \{ \pm 1, \pm j \} \)
  - Four antennas: 8-PSK alphabet for the vector \( \mathbf{u}_i \) elements \( \{ \pm 1, \pm j, \pm (1+j)/\sqrt{2}, \pm (1-j)/\sqrt{2} \} \)
  - Reduces complexity of CQI calculations and in pre-coder
- **4Tx-precoders are based on the Housholder transformation**
  - Reduces complexity of finding out suitable pre-coding matrices
MIMO TRANSMISSION SCHEMES IN LTE:
TRANSMIT PRE-CODING MATRIX INDICATION (TPMI)

- In closed-loop spatial multiplexing eNB must send information about what pre-coding is used to the UE
- The default is that the eNB uses what the UE reported in the latest PMI report
  - Enables frequency selective pre-coding without excessive DL signaling
- TPMI is sent as part of downlink control information (DCI)
  - Two antennas: 3 bits
    - One code-word: tx-diversity + 4 pre-coders + reported PMI (left or right)
    - Two code-words: tx-diversity + 2 pre-coders + reported PMI
  - Four antennas: 6 bits
    - tx-diversity + 16 pre-coders per rank + reported PMI
- If the TPMI indicates a pre-coding matrix then it is applied to all frequency resources allocated to that UE

MIMO TRANSMISSION SCHEMES IN LTE:
OPEN-LOOP SPATIAL MULTIPLEXING

- Open loop spatial multiplexing is used if reliable PMI feedback is not available at the eNB
  - High UE speed
  - High cost of UL feedback
- Open-loop spatial multiplexing also uses UE feedback
  - Link adaptation: CQI (one value)
  - Rank adaptation: R (1, 2, 3, or 4)
- A fixed set of pre-coding matrices are applied cyclically across all the scheduled sub-carriers i

\[ y(i) = W(i)D(i)Ux(i) \]
MIMO TRANSMISSION SCHEMES IN LTE:
OPEN-LOOP SPATIAL MULTIPLEXING

- Large-delay cyclic-delay-diversity (CDD)
  - D(i)U ensures that the modulation symbols of each codeword are mapped onto different layers for each i
  - Each code-word experiences all the transmitted layers

\[ y(i) = W(i)D(i)Ux(i) \]

Pre-coding for open-loop spatial multiplexing

- 2 Tx antennas:

\[ W(i) = \frac{1}{\sqrt{2}} \begin{bmatrix} 1 & 0 \\ 0 & 1 \end{bmatrix} \]

- 4 Tx antennas:

\[ W(i) = C_i; \quad k = \left( \frac{i}{M} \right) \mod 4 + 1 \]

Pre-coding matrix \( C(i) \) is given by \( k = 1, 2, 3, 4 \) for the open-loop spatial multiplexing.

- If rank is set to 1 then transmit diversity is applied
MIMO TRANSMISSION SCHEMES IN LTE:
CLOSED LOOP SPATIAL MULTIPLEXING - CSI FEEDBACK

- UE feeds back channel state information (CSI) to assist link adaptation and scheduling
  - RI: Rank Indicator
    - Recommended transmission rank
  - PMI(s): Pre-coder Matrix Indicator(s)
    - Only for closed-loop spatial multiplexing
  - CQI(s): Channel Quality Indicator(s)
    - Recommended transport format giving 10% BLER
  - Wideband report (RI, PMI, CQI)
  - Frequency selective report (CQI or PMI)
    - Reporting units (sub-bands) configured by higher layer signaling

CSI sensitive to feedback delay!

MIMO TRANSMISSION SCHEMES IN LTE:
RI, PMI, AND CQI

- RI
  - One single rank value is reported (2 antennas 1 bit, 4 antennas 2 bits)
  - Encoded separately from CQI and PMI
  - The bit-width of the other fields depend on the reported RI

- PMI
  - Calculated conditioned on the reported RI
  - Bit-width
    - 2 antennas, RI = 1: 2 bits per reporting unit (sub-band or wide-band)
    - 2 antennas, RI = 2: 1 bit per reporting unit
    - 4 antennas, 4 bit per reporting unit

- CQI
  - Calculated conditioned on the reported RI and PMI
  - Frequency selective CQI
    - Differentially encoded (2 bits) with respect to the wideband CQI (4 bits)
  - Closed loop:
    - RI = 1: Only one differential CQI value (2 bits) for each sub-band
    - RI > 1: One differential CQI value per codeword (2 bits) for each sub-band
  - Open loop:
    - Only a single differential CQI value (2 bits) is reported for each sub-band
  - Wideband CQI only on PUCCH
    - RI >1: 4 bits for first codeword, 3 differential encoded bits for second code-word
MIMO TRANSMISSION SCHEMES IN LTE:
PERIODIC AND A-PERIODIC CSI

› Periodic CSI on PUCCH
  - Narrow bit pipe → small payload size → rough report
  - Wideband CSI appropriate
› A-periodic dynamically requested CSI on PUSCH
  - Request CSI when needed!
  - Wide flexible bit pipe → large payload size → detailed report
  - Frequency-selective CSI appropriate
    › Supports frequency domain scheduling
    › Array gain in frequency-selective uncorrelated channels

Periodic CSI as baseline for more detailed a-periodic reports!

MIMO TRANSMISSION SCHEMES IN LTE:
UE COMPUTATIONS FOR CSI

› Brute force search for best combination of RI and PMI
› Ideal algorithm:
  - for each RI do
    › for each PMI do
      - compute SINR per layer
      - SINRs → predicted throughput
    - Select RI and PMI that gives highest predicted throughput over relevant
      reference period and bandwidth
  - Given selected RI and PMI(s)
    › Based on SINR(s) for transport block find
      highest transport format with BLER ≤ 10% → CQI

Substantial number crunching!
MIMO TRANSMISSION SCHEMES IN LTE:
UPLINK CONTROL ON PUSCH

- Turbo coding
- Conv. Coding
- DFT
- DFTS-OFDM modulator
- IFFT
- UL-SCH
- CQI, PMI
- Rank Indicator
- Mux
- QPSK, 16/64QAM
- Rate Matching
- MIMO transmission schemes in LTE:
  - Channel state information (CSI)
    - Wide-band or frequency selective
      - Wideband CQI + Wideband PMI
      - Frequency selective CQI + Wideband PMI
      - Wideband CQI + Frequency selective PMI
    - Transmitted on PUSCH or PUCCH
    - Periodic or a-periodic
    - Nine different CSI modes (Covers 16 pages in TS 36.213 V8.7.0 + )
      - 4 on PUCCH
      - 5 on PUSCH
      - Only a subset of modes possible for a certain transmission mode

- UL-SCH
- CQI, PMI
- Rank Indicator
- Hybrid-ARQ acknowledgment
- DFTS-OFDM indicator
- Channel-Quality Indicator, Precoding Matrix Indicator
- Rank indicator
- Hybrid-ARQ acknowledgment
- 1 ms subframe
MIMO TRANSMISSION SCHEMES IN LTE:
MULTI-ANTENNAS IN THE UPLINK

› Closed loop UE antenna selection
  - eNodeB indicates which transmit antenna the UE shall use as part of the
downlink control message
› Open loop UE antenna selection
  - TS 36.213: “If open-loop UE transmit antenna selection is enabled by higher
layers, the transmit antenna to be selected by the UE is not specified.”
› Multi-user MIMO

MIMO TRANSMISSION SCHEMES IN LTE:
TYPICAL UPLINK MU-MIMO OPERATION

› High load at least in cell of interest in order to find UEs for co-scheduling
  - Grouping UEs need careful scheduler design
› High SINRs needed
  - MU-MIMO service area close to cell center
  - Less likely that cell edge UEs use MU-MIMO
› Service area grows if surrounding cells have low load
LTE-ADVANCED CONCEPT COMPONENTS:
EXTENDED MULTI-ANTENNA SUPPORT

LTE-ADVANCED:
REQUIREMENTS AND TARGETS

- Requirements of IMT Advanced set by ITU in June/July 2008 [ITU-Rs homepage]
- Targets for LTE-Advanced set by 3GPP in May/June 2008 [36.913]

<table>
<thead>
<tr>
<th>Requirement</th>
<th>ITU Requirements</th>
<th>3GPP Targets</th>
</tr>
</thead>
<tbody>
<tr>
<td>Peak data rates</td>
<td></td>
<td>10 Gbps in DL, 500 Mbps in UL</td>
</tr>
<tr>
<td>Bandwidth</td>
<td>40 MHz</td>
<td>100 MHz</td>
</tr>
<tr>
<td>User plane latency</td>
<td>10 ms</td>
<td>10 ms</td>
</tr>
<tr>
<td>Control plane latency</td>
<td>100 ms</td>
<td>50 ms</td>
</tr>
<tr>
<td>Peak spectrum efficiency</td>
<td>[15] bps/Hz in DL</td>
<td>30 bps/Hz in DL</td>
</tr>
<tr>
<td></td>
<td>[6.75] bps/Hz in UL</td>
<td>15 bps/Hz in UL</td>
</tr>
<tr>
<td>Average spectrum efficiency</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Set for four scenarios and several antenna configurations. In ITU 3 out of 4 scenarios need to be reached.</td>
<td></td>
</tr>
<tr>
<td>Cell edge spectrum efficiency</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>See next slide for examples for Case 1.</td>
<td></td>
</tr>
<tr>
<td>VoIP capacity</td>
<td>150-250 UEs per 5 MHz</td>
<td>Improved compared to Rel 8</td>
</tr>
</tbody>
</table>
LTE-ADVANCED:
UPLINK SPATIAL MULTIPLEXING

- Up to 2 transport blocks per TTI
  - Modulation and coding scheme set individually for each transport block

- Mapping to up to four layers
  - Same mapping as for Rel-8 DL-SCH
  - Number of layers dynamically adjusted by eNB
    (to match channel "rank")
  - Layer shifting supported

- Codebook-based precoding
  - Precoded demodulation reference signals
  - Antenna-specific non-precoded sounding reference signals

LTE-ADVANCED:
DOWNLINK SPATIAL MULTIPLEXING

- Up to 8 layers
  - Extension of Rel-8 scheme

- UE-specific reference signals
  - Extension of Rel-8 RS to multiple layers

- Channel status reports extended to 8 layers
  - Codebook-based feedback

- Layer mapping extended to 8 layers

- Precoding extended to support 8 layers
  - No codebook standardized; precoding is transparent to the UE due to UE-specific RS
LTE-ADVANCED:
DOWNLINK MU-MIMO

- Simultaneous transmission to multiple UEs on the same time-frequency resource using separate layers to separate the transmissions
  - 1 ms subframe
  - 1 RB
  - Terminal A
  - Terminal B
  - Terminal C

- Inform the UE which layer(s) it is supposed to receive
  - The UE may not make any assumptions on contents/presence of other layers
- Certain degree of inter-user interference suppression in the UE
  - Requirements set in RAN4

LTE-ADVANCED:
DOWNLINK REFERENCE SIGNALS

- Unified reference-signals structure used for multiple features
  - CoMP, MIMO, ...
- Cell-specific reference signals (CRS)
  - Inherited and unchanged from release 8?
- UE-specific reference signals (DRS)
  - Extended to support up to 8 layers
  - Support for two-layer transmission already in Rel-9?
  - Orthogonal code-division multiplexing of RS between different layers
- Reference signals for CSI (CSI-RS)
  - New type of reference signals targeting CSI estimation only
  - Up to eight cell-specific antenna ports
  - Sparse in time and frequency,
    - e.g., every 6th subcarrier in one OFDM symbol per frame
    - ~0.12% overhead per antenna port
  - Present in Rel-8
  - New/extended in Rel-10

Example

CSI-RS

One frame (10 ms)
LTE-ADVANCED: 
COMP – BASIC PRINCIPLES

- Coordinated MultiPoint transmission and reception
- Dynamic coordination in transmission and reception between cells
- Reduce interference and/or increase desired signal

### Downlink
- Coordinated scheduling
- Joint processing

### Uplink
- Coordinated scheduling
- Joint (coherent) processing

LTE-ADVANCED: 
COMP – ARCHITECTURE

- Coordination can be centralized or distributed, proprietary or standardized
- Delay and bandwidth of backhaul and coordination links are important parameters

### Logical
- Intra-eNB coordination
- Inter-eNB coordination

### Physical
- Dedicated links
- Switched network

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LTE-ADVANCED: DL COORDINATED SCHEDULING

- Schedule UEs such that throughput versus user rate can be improved by avoiding interference
- Two mechanisms:
  - Multi-cell link adaptation and power control
  - Interference avoidance
- Example:
  - 1st TTI: Red Blue Yellow
  - 2nd TTI: Yellow Red Blue
  - 3rd TTI: Blue Yellow Red
  i. 100% gain in cell edge throughput!
  ii. Only 10% worse than a single centralized controller!

LTE-ADVANCED: JOINT COHERENT PROCESSING

- Coherent linear transmission schemes
- Network must know DL channel to UEs in coordination cluster
- Mitigate intra-cluster interference
  - Zero forcing: eliminate intra-cluster interference
  - Epsilon forcing: constrain intra-cluster interference
  - MMSE: minimize sum rx. symbol estimation error

Desired signal adds constructively
Interference cancelled
LTE-ADVANCED: UPLINK COMP

- Coordination alternatives:
  - Dynamic coordination in UL scheduling or Dynamic interference coordination
  - Reception and joint processing at multiple sites (e.g. MRC, IRC, IC, ...)

- Coordination/processing can be centralized or distributed

- No impact on radio interface
  - UE does not need to be aware at what points the uplink transmission is received and how it is processed
  - Associated downlink signaling (scheduling grants, HARQ ACK/NAK, power control) from serving cell regardless of uplink reception points

- May benefit from larger number of orthogonal uplink DRS
  - Facilitates reliable interference estimates required by IRC and IC methods

MIMO IN LTE AND LTE-ADVANCED: SUMMARY

- Closed-loop and open-loop spatial multiplexing (antenna ports 0-3)
  - Covers both low and high mobility
  - Complementary peak-rate achieving transmission modes

- Diversity transmission based on Alamouti scheme
  - SFBC + FSTD

- MBSFN transmission (antenna port 4)

- Single layer beam-forming with dedicated reference symbols (antenna port 5)

- Uplink MU-MIMO for high load scenarios

- Lots of CSI
  - Periodic and a-periodic
  - Wide-band or frequency-selective
  - PUSCH or PUCCH

- Extended multi-antenna support in LTE Rel-10
  - 8 Tx antennas in downlink
  - SU MIMO in uplink (4 Tx antennas)
  - Combined beam-forming and spatial multiplexing
  - CoMP
BACKUP SLIDES
**General Introduction: Beamforming**

- "Traditional" beamforming
  - Same fading on all antennas
  - Steer beam by phase shift on antennas
  - Estimate "direction" from UL
  - Slow feedback
- Antenna constellation do not match "MIMO multiplexing"
- Reference symbols provided in "beam"
  - Cannot be used by others
  - Cannot estimate CQI when not scheduled

---

**More Beamforming**

- Pre-coded based beamforming
  - Align signals by fixed BF vectors
  - A "code-book" of vectors
  - UE pick "best" vector
  - Do not require same fading on antennas
  - Blends with "MIMO multiplexing"
  - Different fading over frequencies
  - Feedback per resource block
  - Reference symbol per "antenna"
  - Possible to estimate CQI even when not scheduled
GENERAL INTRODUCTION:

LINEAR DISPERSION CODING

- General LDC (rank $r = Q/L$)
  \[ C = [x_1 \ x_2 \ \ldots \ x_q] = \sum_{q=1}^{Q} B_q [\text{re}{e_q} + \text{im}{e_q}] \]

- Can be re-written as
  \[ X = \begin{bmatrix} w_1 \ w_2 \ \ldots \ w_q \end{bmatrix} \begin{bmatrix} s_1 \\ s_2 \\ \vdots \\ s_q \end{bmatrix} = Ws \quad (L=1, \overline{B}_q = B_q) \]

- The matrix $W$ is often chosen from a fixed and countable set of pre-coder matrices
  \[ W = \{ W_1 \ W_2 \ \ldots \ W_q \} \]

GENERAL INTRODUCTION:

PRECODING BASED BEAMFORMING

- Code-book of pre-coding matrices
- Maximize SNR, rate, throughput, received power, ... from downlink reference signals, e.g.:
  \[ P_k = w_k^H HH^H w_k \]

- The UE feeds back an index to the preferred pre-coding vector
  \[ \begin{pmatrix} 1 \\ e^{j\pi/4} \\ e^{j3\pi/4} \\ e^{j5\pi/4} \\ e^{j7\pi/4} \end{pmatrix} \]
The channel can be seen as acting per subcarrier by the complex gain $H_k$.

If channel estimates are at hand, this can be compensated for e.g.

- **Time domain structure:**
  - 10 ms frame consisting of 10 subframes of length 1 ms
  - Each subframe consists of 2 slots of length 0.5 ms
  - Each slot consists of 7 OFDM symbols (6 symbols in case of extended CP)

- **Resource element (RE)**
  - One subcarrier during one OFDM symbol

- **Resource block (RB)**
  - 12 subcarriers during one slot (180 kHz x 0.5 ms)
To support DL-SCH and UL-SCH transmission

- Mapped to first OFDM symbols of each subframe
  - Dynamically varying size;
    - 1, 2, 3 OFDM symbols
  - TDM of data and control
    - UE micro-sleep possible

- PCFICH – Physical Control Format Indicator Channel
  - Size of control region

- PHICH – Physical Hybrid ARQ Indicator Channel
  - ACK/NAK of uplink transmission

- PDCCH – Physical Downlink Control Channel
  - Scheduling assignments, scheduling grants, ...

*) 2, 3, 4 OFDM symbols for narrow BWs

This enables flexible bandwidth sharing, restricted by a consecutive subcarrier allocation requirement.

- Evenly distributed carrier allocation also gives single-carrier properties