MIMO IN LTE AND LTE-ADVANCED

2009-10-05

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ERICSSON RESEARCH

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

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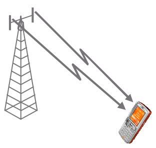
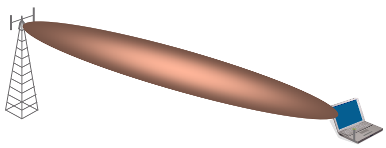
GENERAL INTRODUCTION:

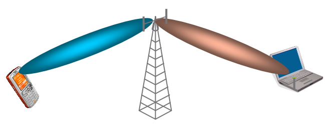
MULTI-ANTENNA TRANSMISSION TECHNIQUES



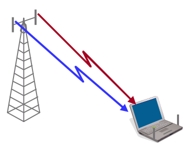
Diversity for improved system peformance



Beam-forming for improved coverage (fewer cells to cover a given area)



SDMA for improved capacity (more users per cell)



Multi-layer transmisson (”MIMO”) for higher data rates in a given bandwidth

The multi-antenna technique to use depends on what to achieve

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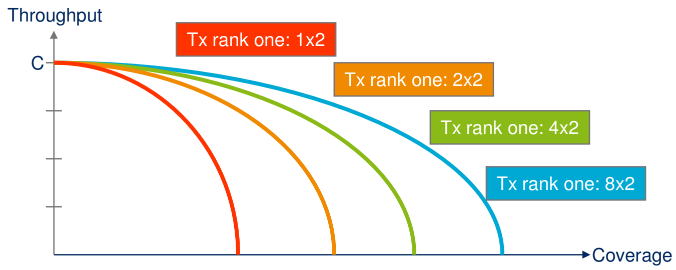
GENERAL INTRODUCTION:

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)

$$\mathbf{x} = \mathbf{w}s_1 = \begin{bmatrix} w_1 \\ w_2 \\ \vdots \\ w_{n_t} \end{bmatrix} s_1$$



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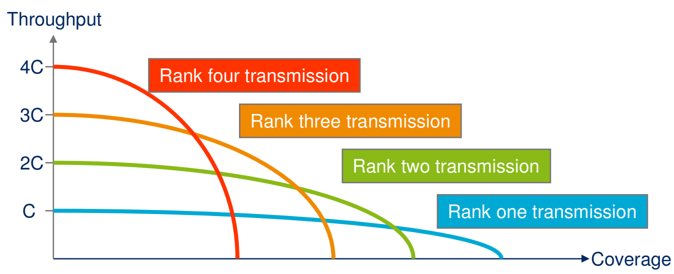
GENERAL INTRODUCTION:

MIMO IN CELLULAR SYSTEMS



- Throughput versus coverage tradeoff
  - Large path loss and high interference at cell edge Ł *Beam-forming*
  - Low path loss and low interference at cell center Ł *Spatial multiplexing*

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GENERAL INTRODUCTION:

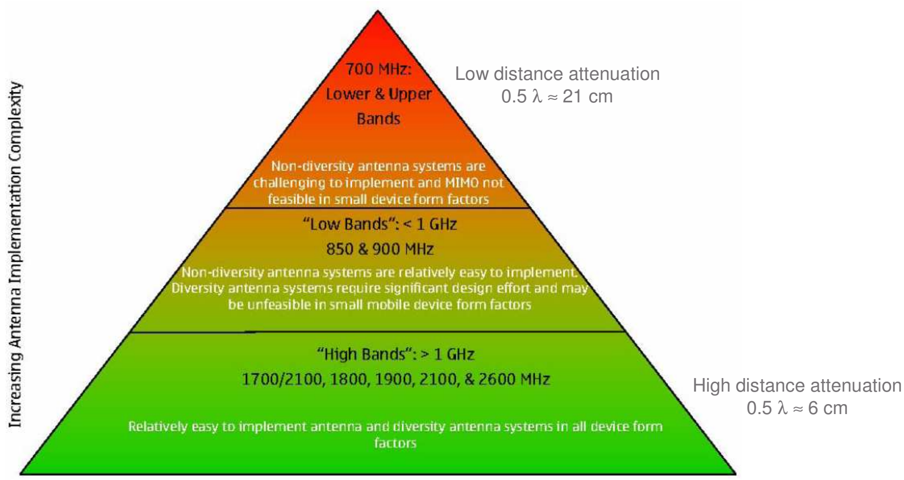
ANTENNA DESIGN

- 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

Scenario	*Difficulty*	*Antenna requirements*	*Practical effects*
Interference mitigation	Low	Envelope correlation < 0.7 Antenna BPD ≈10 dB	Diversity antenna does not have to perform nearly as well as the main antenna
Spatial multiplexing	Medium/ high	Envelope correlation ≈ 0.3–0.5 Medium BPD required	Difficult in low frequency bands (< 1GHz)
Range extension	High	Low BPD required (0 dB)	Diversity antenna as good as main antenna

GENERAL INTRODUCTION:

UE ANTENNA DESIGN



Hand-held multi-stream MIMO is not feasible at large distance

EXTREMELY BRIEF INTRODUCTION TO LTE

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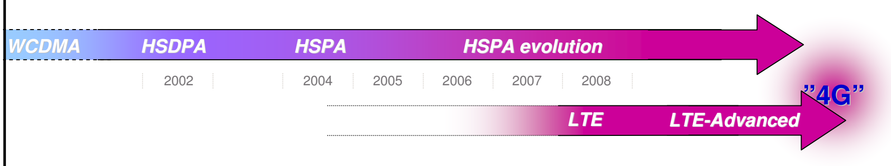
INTRODUCTION TO LTE:

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")



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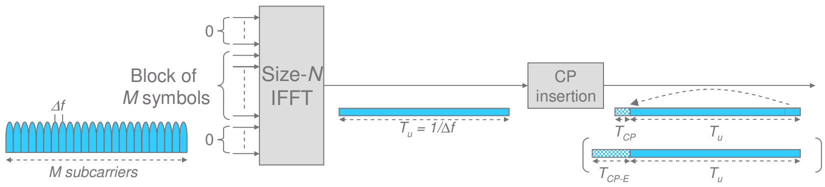
INTRODUCTION TO LTE:

DOWNLINK TRANSMISSION SCHEME - *OFDM*



- Subcarrier spacing $\Delta f = 15$ kHz
  ⇨ $T_u \approx 66.7$ µs
  - $\Delta f = 7.5$ kHz also specified, for MBSFN transmsision only
- Two cyclic prefix lengths
  - Normal
  - Extended (for MBSFN and environments with large delay spread)
- Basic time unit T_s=1/(2048· 15000)
  - All time quantities expressed as multiples of *Ts*

Configuration, Δf		CP length	Symbols per slot
Normal	15 kHz	≈4.7 µs	7
Extended	15 kHz	≈16.7 µs	6
	7.5 kHz	≈33.3 µs	3

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

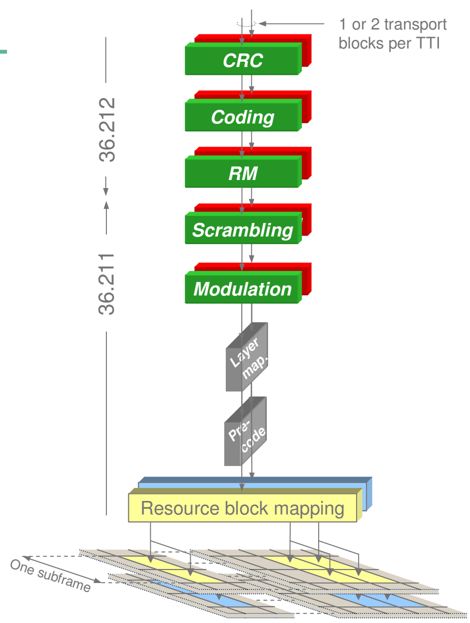
Transport-channel-specific scrambling using length-31 Gold sequences

Modulation (QPSK, 16QAM, 64QAM)

Mapping to transmission layers (for multi-layer transmission)

Precoding (for multi-rank transmission)

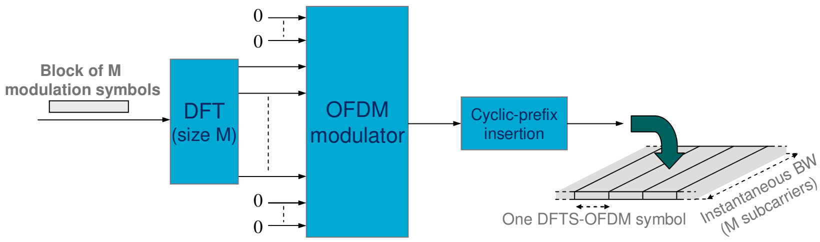
Resource block mapping (PDSCH)



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, …



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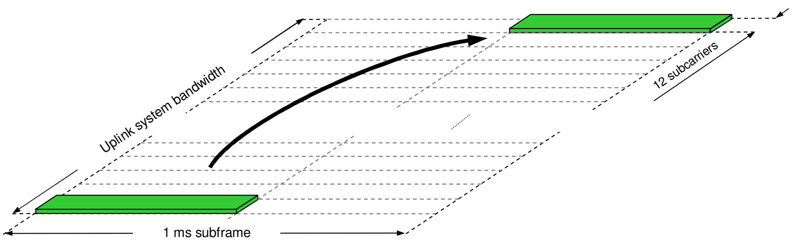
INTRODUCTION TO LTE:

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



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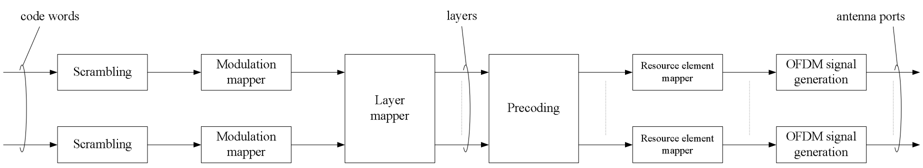
MIMO TRANSMISSION SCHEMES IN LTE

MIMO TRANSMISSION SCHEMES IN LTE:

DOWNLINK TRANSMISSION MODES

- Seven different semi-statically configured modes
  - *6 out of 7 are multi-antenna related!*
  1. Single-antenna port (port 0)
     SIMO with cell specific RS
  2. Transmit diversity (2 Tx or 4 Tx)
     SFBC based on the Alamouti code
  3. Open-loop spatial multiplexing
  4. Closed-loop spatial multiplexing
  5. Multi-user MIMO
     Classical space division multiple access (SDMA)
  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

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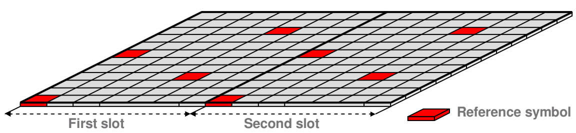
MIMO TRANSMISSION SCHEMES IN LTE:

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 subcarriers
  - 3 subcarriers staggering between symbols



- 504 different *Reference Signal Sequences*
  - Pseudo-random sequences

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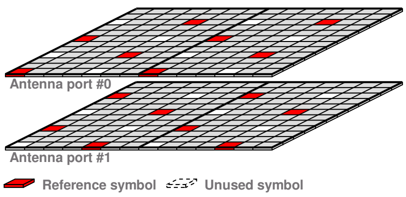
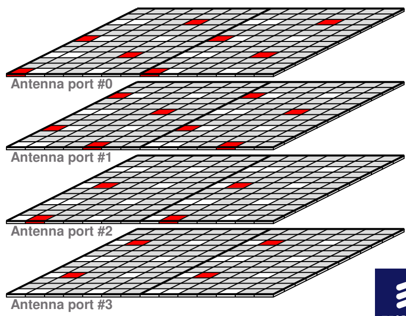
MIMO TRANSMISSION SCHEMES IN LTE:
CELL-SPECIFIC REFERENCE SIGNALS

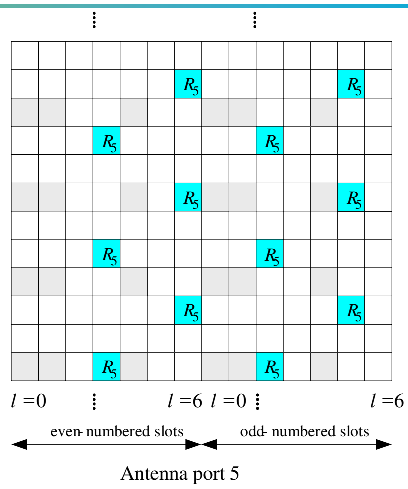
- Frequency-multiplexing between antenna port 0 and 1
  - 3 subcarriers offset
- RS resource element ”empty” on other antenna port
  ⇨ No inter-antenna RS interference
- Reduced density for antenna port 2 and 3





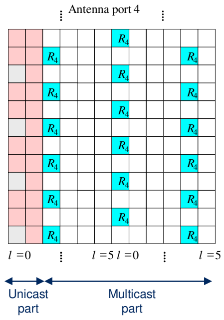
MIMO TRANSMISSION SCHEMES IN LTE:
UE SPECIFFIC RS (ANTENNA PORT 5)

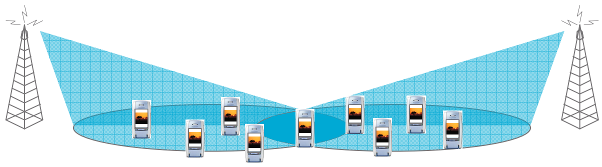
- UE-specific reference signals are supported for single-antenna-port transmission of PDSCH
- The UE is informed by higher layers whether the UE-specific reference signal is present
- UE-specific reference signals are transmitted only on the resource blocks upon which the corresponding PDSCH is mapped.
- PDSCH and antenna port 5 uses the same pre-coding



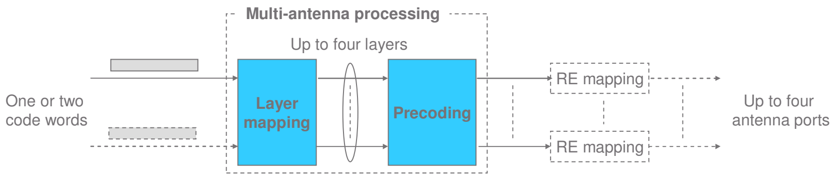
MIMO TRANSMISSION SCHEMES IN LTE:
MBSFN OPERATION (ANTENNA PORT 4)

- 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)

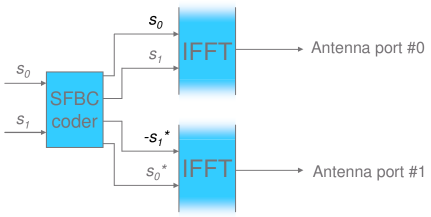
MIMO TRANSMISSION SCHEMES IN LTE:

LTE DOWNLINK TRANSMIT DIVERSITY

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

Subcarrier →

$$\begin{matrix}\text{Antenna 0} \\ \text{Antenna 1}\end{matrix}\begin{bmatrix} S_0 & S_1 \\ -S_1^* & S_1^* \end{bmatrix}$$



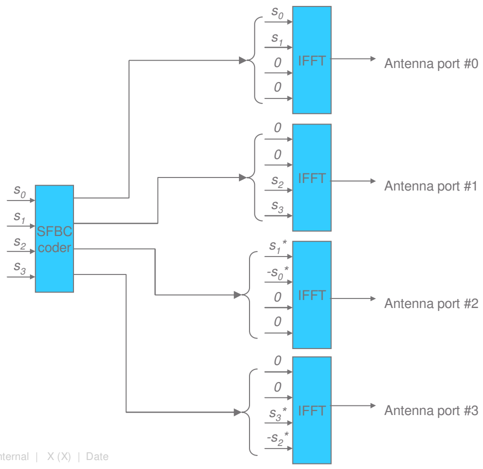
MIMO TRANSMISSION SCHEMES IN LTE:

LTE DOWNLINK TRANSMIT DIVERSITY

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

Subcarrier →

$$\begin{matrix}\text{Antenna 0}\\ \text{Antenna 1}\\ \text{Antenna 2}\\ \text{Antenna 3}\end{matrix}\begin{bmatrix} S_0 & S_1 & 0 & 0\\ 0 & 0 & S_2 & S_3\\ -S_1^* & S_0^* & 0 & 0\\ 0 & 0 & -S_3^* & S_2^* \end{bmatrix}$$



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

Subcarrier →

$$\text{Type1:}\quad \begin{matrix}\text{Antenna 0}\\ \text{Antenna 1}\\ \text{Antenna 2}\\ \text{Antenna 3}\end{matrix}\underset{\text{1st repetition}}{\begin{bmatrix} S_0 & S_1 & S_2 & S_3\\ 0 & 0 & 0 & 0\\ -S_1^* & S_0^* & -S_3^* & S_2^*\\ 0 & 0 & 0 & 0 \end{bmatrix}},\underset{\text{2nd repetition}}{\begin{bmatrix} 0 & 0 & 0 & 0\\ S_0 & S_1 & S_2 & S_3\\ 0 & 0 & 0 & 0\\ -S_1^* & S_0^* & -S_3^* & S_2^* \end{bmatrix}},\underset{\text{3rd repetition}}{\begin{bmatrix} S_0 & S_1 & S_2 & S_3\\ 0 & 0 & 0 & 0\\ -S_1^* & S_0^* & -S_3^* & S_2^*\\ 0 & 0 & 0 & 0 \end{bmatrix}}$$

(a)

Subcarrier →

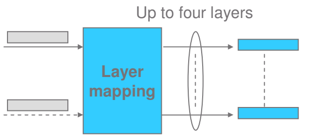
$$\text{Type2:}\quad \begin{matrix}\text{Antenna 0}\\ \text{Antenna 1}\\ \text{Antenna 2}\\ \text{Antenna 3}\end{matrix}\underset{\text{1st repetition}}{\begin{bmatrix} 0 & 0 & 0 & 0\\ S_0 & S_1 & S_2 & S_3\\ 0 & 0 & 0 & 0\\ -S_1^* & S_0^* & -S_3^* & S_2^* \end{bmatrix}},\underset{\text{2nd repetition}}{\begin{bmatrix} S_0 & S_1 & S_2 & S_3\\ 0 & 0 & 0 & 0\\ -S_1^* & S_0^* & -S_3^* & S_2^*\\ 0 & 0 & 0 & 0 \end{bmatrix}},\underset{\text{3rd repetition}}{\begin{bmatrix} 0 & 0 & 0 & 0\\ S_0 & S_1 & S_2 & S_3\\ 0 & 0 & 0 & 0\\ -S_1^* & S_0^* & -S_3^* & S_2^* \end{bmatrix}}$$

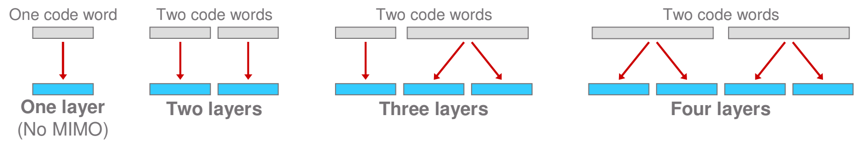
- Using both Type 1 and Type 2 simultaneously ensures uniform power distribution over the eNB antennas

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





- 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)

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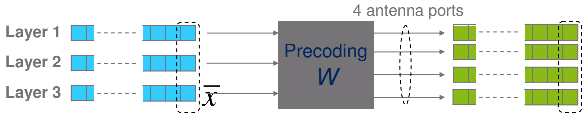
MIMO TRANSMISSION SCHEMES IN LTE:

DOWNLINK SPATIAL MULTIPLEXING

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

Example: $N_L = 3$, $N_A = 4$



$$\bar{y} = W \cdot \bar{x}$$

- 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"

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MIMO TRANSMISSION SCHEMES IN LTE:
TWO DIFFERENT FORMS OF PRE-CODING

- Closed-loop spatial multiplexing mode:
  - Precoder $\mathbf{W}_f$ focuses transmission in "strong directions" towards the UE
    - $\mathbf{W}_f$ 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 $\mathbf{W}_f$ 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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MIMO TRANSMISSION SCHEMES IN LTE:
2 TX PRECODING CODEBOOK

TABLE 1: Precoding codebook for transmission on two antennas.

Codebook index	Number of layers M: 1	Number of layers M: 2
0	$\frac{1}{\sqrt{2}}\begin{bmatrix}1\\1\end{bmatrix}$	—
1	$\frac{1}{\sqrt{2}}\begin{bmatrix}1\\-1\end{bmatrix}$	$1/2\begin{bmatrix}1 & 1\\1 & -1\end{bmatrix}$
2	$\frac{1}{\sqrt{2}}\begin{bmatrix}1\\j\end{bmatrix}$	$1/2\begin{bmatrix}1 & 1\\j & -j\end{bmatrix}$
3	$\frac{1}{\sqrt{2}}\begin{bmatrix}1\\-j\end{bmatrix}$	—

Each column vector is in the form: $\begin{bmatrix}1\\e^{j(\theta+k\pi)}\end{bmatrix}$

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MIMO TRANSMISSION SCHEMES IN LTE:
4 TX PRECODING CODEBOOK

TABLE 2: Precoding codebook for transmission on four antennas.

Codebook index	$\mathbf{u}_i$	Number of layers M: 1	2	3	4
0	$\mathbf{u}_0 = [1\ -1\ -1\ -1]^T$	$\mathbf{W}_0^{\{1\}}$	$\mathbf{W}_0^{\{14\}}/\sqrt{2}$	$\mathbf{W}_0^{\{124\}}/\sqrt{3}$	$\mathbf{W}_0^{\{1234\}}/2$
1	$\mathbf{u}_1 = [1\ -j\ 1\ j]^T$	$\mathbf{W}_1^{\{1\}}$	$\mathbf{W}_1^{\{12\}}/\sqrt{2}$	$\mathbf{W}_1^{\{123\}}/\sqrt{3}$	$\mathbf{W}_1^{\{1234\}}/2$
2	$\mathbf{u}_2 = [1\ 1\ -1\ 1]^T$	$\mathbf{W}_2^{\{1\}}$	$\mathbf{W}_2^{\{12\}}/\sqrt{2}$	$\mathbf{W}_2^{\{123\}}/\sqrt{3}$	$\mathbf{W}_2^{\{3214\}}/2$
3	$\mathbf{u}_3 = [1\ j\ 1\ -j]^T$	$\mathbf{W}_3^{\{1\}}$	$\mathbf{W}_3^{\{12\}}/\sqrt{2}$	$\mathbf{W}_3^{\{123\}}/\sqrt{3}$	$\mathbf{W}_3^{\{3214\}}/2$
4	$\mathbf{u}_4 = [1\ (-1-j)/\sqrt{2}\ -j\ (1-j)/\sqrt{2}]^T$	$\mathbf{W}_4^{\{1\}}$	$\mathbf{W}_4^{\{14\}}/\sqrt{2}$	$\mathbf{W}_4^{\{124\}}/\sqrt{3}$	$\mathbf{W}_4^{\{1234\}}/2$
5	$\mathbf{u}_5 = [1\ (1-j)/\sqrt{2}\ j\ (-1-j)/\sqrt{2}]^T$	$\mathbf{W}_5^{\{1\}}$	$\mathbf{W}_5^{\{14\}}/\sqrt{2}$	$\mathbf{W}_5^{\{124\}}/\sqrt{3}$	$\mathbf{W}_5^{\{1234\}}/2$
6	$\mathbf{u}_6 = [1\ (1+j)/\sqrt{2}\ -j\ (-1+j)/\sqrt{2}]^T$	$\mathbf{W}_6^{\{1\}}$	$\mathbf{W}_6^{\{13\}}/\sqrt{2}$	$\mathbf{W}_6^{\{134\}}/\sqrt{3}$	$\mathbf{W}_6^{\{1324\}}/2$
7	$\mathbf{u}_7 = [1\ (-1+j)/\sqrt{2}\ j\ (1+j)/\sqrt{2}]^T$	$\mathbf{W}_7^{\{1\}}$	$\mathbf{W}_7^{\{13\}}/\sqrt{2}$	$\mathbf{W}_7^{\{134\}}/\sqrt{3}$	$\mathbf{W}_7^{\{1324\}}/2$
8	$\mathbf{u}_8 = [1\ -1\ 1\ 1]^T$	$\mathbf{W}_8^{\{1\}}$	$\mathbf{W}_8^{\{12\}}/\sqrt{2}$	$\mathbf{W}_8^{\{124\}}/\sqrt{3}$	$\mathbf{W}_8^{\{1234\}}/2$
9	$\mathbf{u}_9 = [1\ -j\ -1\ -j]^T$	$\mathbf{W}_9^{\{1\}}$	$\mathbf{W}_9^{\{14\}}/\sqrt{2}$	$\mathbf{W}_9^{\{134\}}/\sqrt{3}$	$\mathbf{W}_9^{\{1234\}}/2$
10	$\mathbf{u}_{10} = [1\ 1\ 1\ -1]^T$	$\mathbf{W}_{10}^{\{1\}}$	$\mathbf{W}_{10}^{\{13\}}/\sqrt{2}$	$\mathbf{W}_{10}^{\{123\}}/\sqrt{3}$	$\mathbf{W}_{10}^{\{1324\}}/2$
11	$\mathbf{u}_{11} = [1\ j\ -1\ j]^T$	$\mathbf{W}_{11}^{\{1\}}$	$\mathbf{W}_{11}^{\{13\}}/\sqrt{2}$	$\mathbf{W}_{11}^{\{134\}}/\sqrt{3}$	$\mathbf{W}_{11}^{\{1324\}}/2$
12	$\mathbf{u}_{12} = [1\ -1\ -1\ 1]^T$	$\mathbf{W}_{12}^{\{1\}}$	$\mathbf{W}_{12}^{\{12\}}/\sqrt{2}$	$\mathbf{W}_{12}^{\{123\}}/\sqrt{3}$	$\mathbf{W}_{12}^{\{1234\}}/2$
13	$\mathbf{u}_{13} = [1\ -1\ 1\ -1]^T$	$\mathbf{W}_{13}^{\{1\}}$	$\mathbf{W}_{13}^{\{13\}}/\sqrt{2}$	$\mathbf{W}_{13}^{\{123\}}/\sqrt{3}$	$\mathbf{W}_{13}^{\{1324\}}/2$
14	$\mathbf{u}_{14} = [1\ 1\ -1\ -1]^T$	$\mathbf{W}_{14}^{\{1\}}$	$\mathbf{W}_{14}^{\{13\}}/\sqrt{2}$	$\mathbf{W}_{14}^{\{123\}}/\sqrt{3}$	$\mathbf{W}_{14}^{\{3214\}}/2$
15	$\mathbf{u}_{15} = [1\ 1\ 1\ 1]^T$	$\mathbf{W}_{15}^{\{1\}}$	$\mathbf{W}_{15}^{\{12\}}/\sqrt{2}$	$\mathbf{W}_{15}^{\{123\}}/\sqrt{3}$	$\mathbf{W}_{15}^{\{1234\}}/2$

$\mathbf{W}_i^{\{c_1 \ldots c_m\}}$ 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 $\{\pm1, \pm j\}$
  - Four antennas: 8-PSK alphabet for the vector $\mathbf{u}_i$ elements $\{\pm1, \pm j, \pm(1+j)/\sqrt{2}, \pm(-1+j)/\sqrt{2}\}$
  - 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

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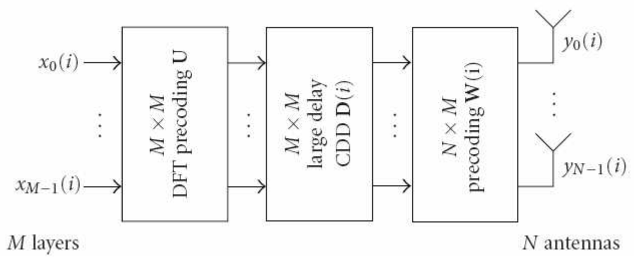
MIMO TRANSMISSION SCHEMES IN LTE:
OPEN-LOOP SPATIAL MULTIPLEXING



- 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: *RI* (1, 2, 3, or 4)
- A fixed set of pre-coding matrices are applied cyclically across all the scheduled sub-carriers *i*

$$\mathbf{y}(i) = \mathbf{W}(i)\mathbf{D}(i)\mathbf{U}\mathbf{x}(i)$$

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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*

$$\mathbf{y}(i)=\mathbf{W}(i)\mathbf{D}(i)\mathbf{U}\mathbf{x}(i)$$

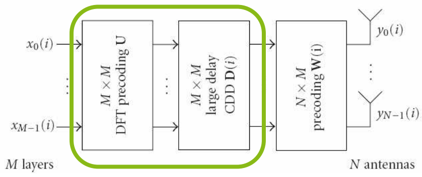

Table 4: DFT precoding matrix **U**.

Number of layers M	M × M matrix **U**
2	$\frac{1}{\sqrt{2}}\begin{bmatrix}1 & 1\\ 1 & e^{-j2\pi/2}\end{bmatrix}$
3	$\frac{1}{\sqrt{3}}\begin{bmatrix}1 & 1 & 1\\ 1 & e^{-j2\pi/3} & e^{-j4\pi/3}\\ 1 & e^{-j4\pi/3} & e^{-j8\pi/3}\end{bmatrix}$
4	$\frac{1}{2}\begin{bmatrix}1 & 1 & 1 & 1\\ 1 & e^{-j2\pi/4} & e^{-j4\pi/4} & e^{-j6\pi/4}\\ 1 & e^{-j4\pi/4} & e^{-j8\pi/4} & e^{-j12\pi/4}\\ 1 & e^{-j6\pi/4} & e^{-j12\pi/4} & e^{-j18\pi/4}\end{bmatrix}$

Table 5: Large delay CDD matrix $\mathbf{D}(i)$.

Number of layers M	$\mathbf{D}(i)$
2	$\begin{bmatrix}1 & 0\\ 0 & e^{-j2\pi i/2}\end{bmatrix}$
3	$\begin{bmatrix}1 & 0 & 0\\ 0 & e^{-j2\pi i/3} & 0\\ 0 & 0 & e^{-j4\pi i/3}\end{bmatrix}$
4	$\begin{bmatrix}1 & 0 & 0 & 0\\ 0 & e^{-j2\pi i/4} & 0 & 0\\ 0 & 0 & e^{-j4\pi i/4} & 0\\ 0 & 0 & 0 & e^{-j6\pi i/4}\end{bmatrix}$

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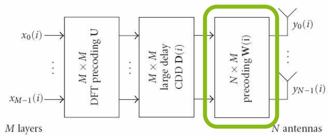
MIMO TRANSMISSION SCHEMES IN LTE:
OPEN-LOOP SPATIAL MULTIPLEXING

- **Pre-coding for open-loop spatial multiplexing**
  - 2 Tx antennas:

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



  - 4 Tx antennas:

$$\mathbf{W}(i)=\mathbf{C}_k;\quad k=\left(\lfloor i/M\rfloor \bmod 4+1\right)$$

Table 6: Precoding matrix $\mathbf{C}_k (k = 1,2,3,4)$ for the open-loop spatial multiplexing.

	Number of layers M 2	3	4
$\mathbf{C}_1$	$\mathbf{W}_{12}^{\{12\}}/\sqrt{2}$	$\mathbf{W}_{12}^{\{123\}}/\sqrt{3}$	$\mathbf{W}_{12}^{\{1234\}}/2$
$\mathbf{C}_2$	$\mathbf{W}_{13}^{\{13\}}/\sqrt{2}$	$\mathbf{W}_{13}^{\{123\}}/\sqrt{3}$	$\mathbf{W}_{13}^{\{1324\}}/2$
$\mathbf{C}_3$	$\mathbf{W}_{14}^{\{13\}}/\sqrt{2}$	$\mathbf{W}_{14}^{\{123\}}/\sqrt{3}$	$\mathbf{W}_{14}^{\{3214\}}/2$
$\mathbf{C}_4$	$\mathbf{W}_{15}^{\{12\}}/\sqrt{2}$	$\mathbf{W}_{15}^{\{123\}}/\sqrt{3}$	$\mathbf{W}_{15}^{\{1234\}}/2$

  - If rank is set to 1 then transmit diversity is applied

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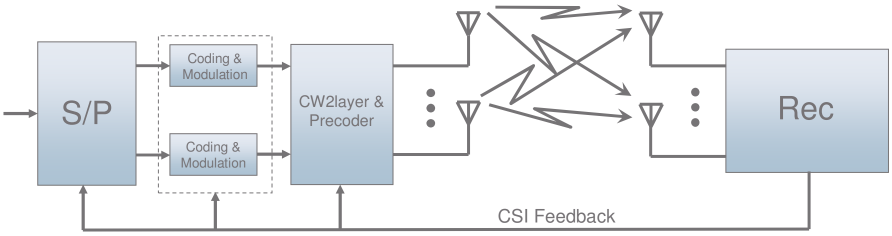
MIMO TRANSMISSION SCHEMES IN LTE:
CLOSED LOOP SPATIAL MULTIPLEXING - *CSI FEEDBACK*



- 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!

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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

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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!

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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!

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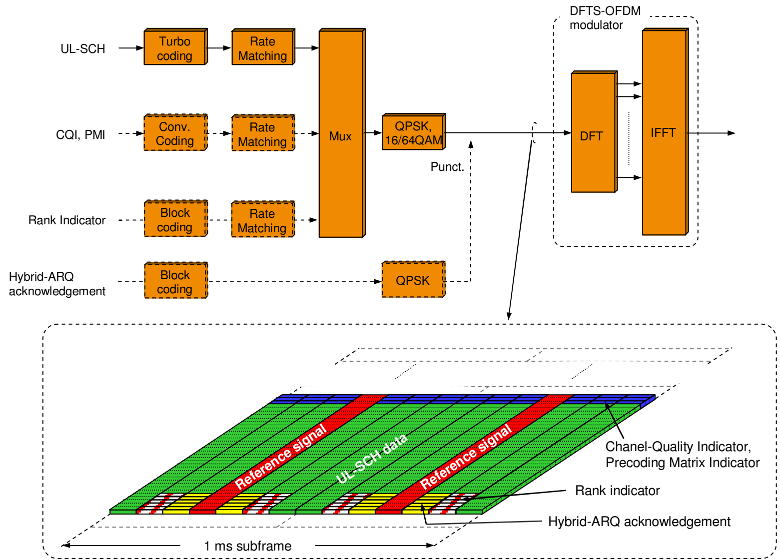
MIMO TRANSMISSION SCHEMES IN LTE :
UPLINK CONTROL ON PUSCH



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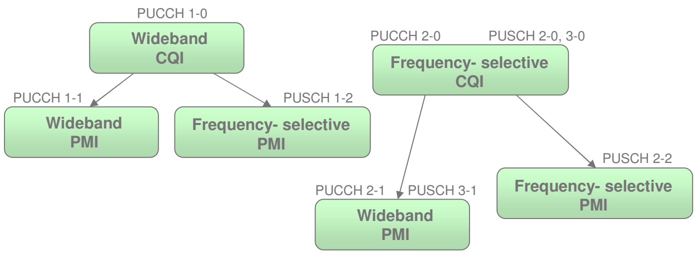
MIMO TRANSMISSION SCHEMES IN LTE:
CHANNEL STATE INFORMATION (CSI)

- 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



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MIMO TRANSMISSION SCHEMES IN LTE:

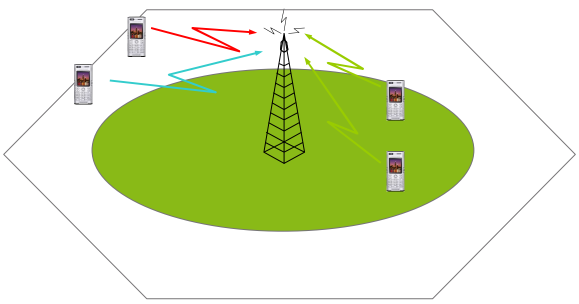
MULTI-ANTENNAS IN THE UPLINK

- 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

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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]

	ITU Requierements	3GPP Targets
Peak data-rates		1Gbps in DL 500Mbps in UL
Bandwidth	40 MHz	100 MHz
User plane latency	10 ms	10 ms
Control plane latency	100 ms	50 ms
Peak spectrum efficenvy	[15] bps/Hz in DL [6.75] bps/Hz in UL	30 bps/Hz in DL 15 bps/Hz in UL
Average spectrum efficiency	Set for four scenarios and several antenna configuartions. In ITU 3 out of 4 scenrios need to be reached. See next slide for examples for Case 1.	
Cell edge spectrum efficiency		
VoIP capacity	150-250 UEs per 5MHz	Improved compared to Rel 8

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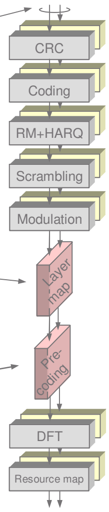
LTE-ADVANCED:
UPLINK SPATIAL MULTIPLEXING

- 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



To OFDM modulator

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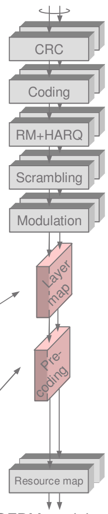
LTE-ADVANCED:
DOWNLINK SPATIAL MULTIPLEXING

- 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



To OFDM modulator

Beamforming AND Multi-layer transmission

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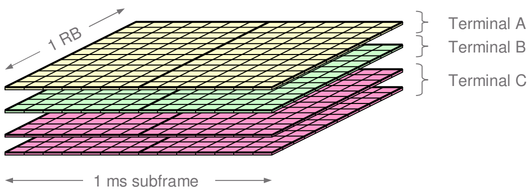
LTE-ADVANCED:
DOWNLINK MU-MIMO

- Simultaneous transmission to multiple UEs on the same time-frequency resource *using separate layers* to separate the transmissions



- 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

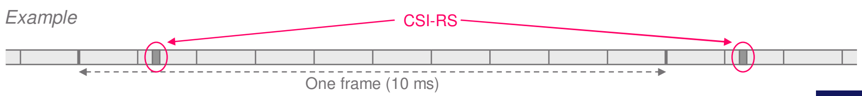
LTE-ADVANCED:
DOWNLINK REFERENCE SIGNALS

- 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

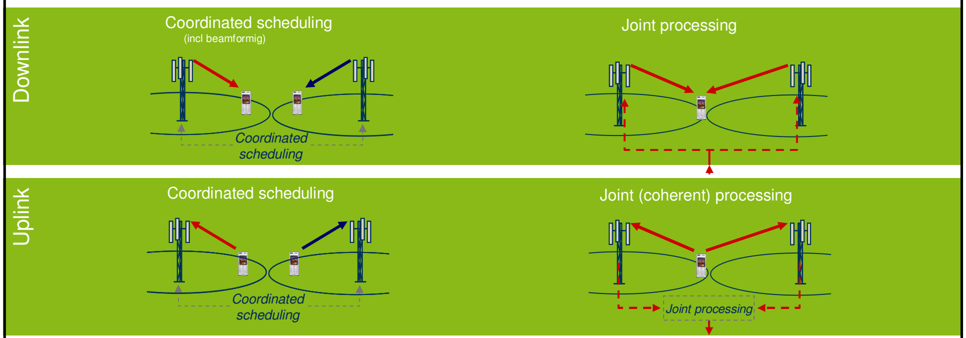
Example



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



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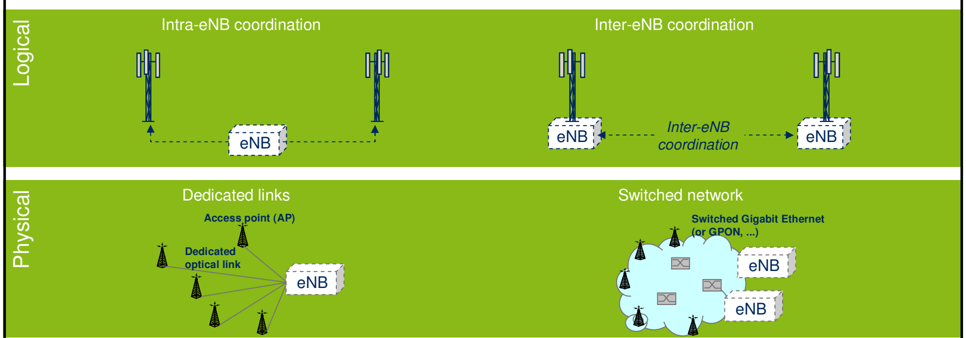
LTE-ADVANCED:

COMP – ARCHITECTURE

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



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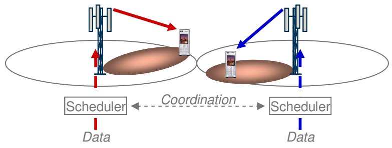
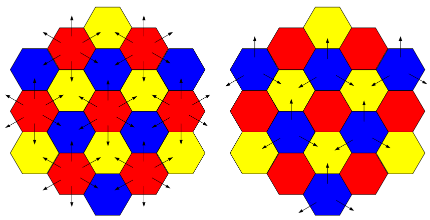
LTE-ADVANCED:
DL COORDINATED SCHEDULING

- 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
  - Ł 100% gain in cell edge throughput!
  - Ł Only 10% worse than a single centralized controller!





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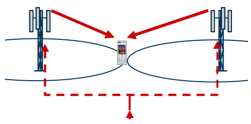
LTE-ADVANCED:
JOINT COHERENT PROCESSING

- 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



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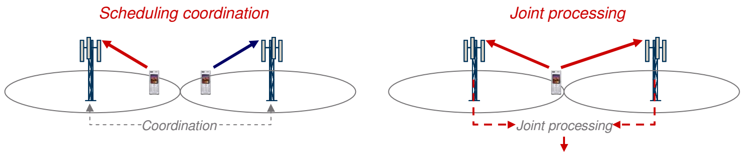
LTE-ADVANCED:
UPLINK COMP

- Coordination alternatives:
  - Dynamic coordination in UL scheduling ⇨ 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

Uplink CoMP is in principle an implementation feature

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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

Multi-antenna techniques at the heart of LTE!

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BACKUP SLIDES

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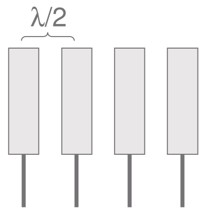
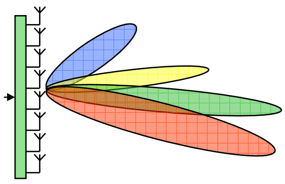
GENERAL INTRODUCTION:

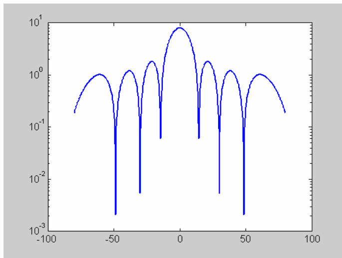
BEAMFORMING

- ”Traditional” beamforming
  - Same fading on all antennas
  - Stear beam by phase shift on antennas
    - Estimate ”direction” from UL

      OR
    - Slow feedback
- Antenna constallation do not match ”MIMO multiplexing”
- Reference symbols provided in ”beam”
  - Cannot be used by others
  - Cannot estimate CQI when not scheduled







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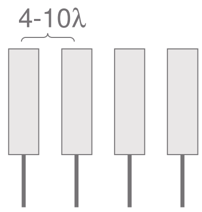
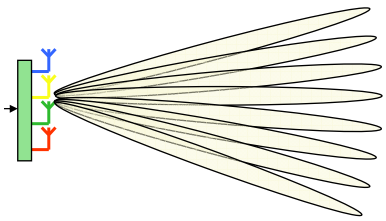
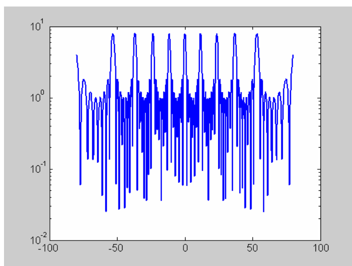
GENERAL INTRODUCTION:

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







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GENERAL INTRODUCTION:

LINEAR DISPERSION CODING

- General LDC (rank $r = Q/L$)

$$\mathbf{C} = [\mathbf{x}_1 \quad \mathbf{x}_2 \quad \dots \quad \mathbf{x}_L] = \sum_{q=1}^{Q} \mathbf{B}_q \mathrm{re}\{s_q\} + \tilde{\mathbf{B}}_q \mathrm{im}\{s_q\}$$

- Can be re-written as

$$\mathbf{X} = [\mathbf{w}_1 \quad \mathbf{w}_2 \quad \dots \quad \mathbf{w}_Q] \begin{bmatrix} s_1 \\ s_2 \\ \vdots \\ s_Q \end{bmatrix} = \mathbf{W}\mathbf{s} \qquad (L = 1, \tilde{\mathbf{B}}_q = \mathbf{B}_q)$$

- The matrix **W** is often chosen from a fixed and countable set of pre-coder matrices

$$\mathbf{W} = \{\mathbf{W}_1 \quad \mathbf{W}_2 \quad \dots \quad \mathbf{W}_K\}$$

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GENERAL INTRODUCTION:

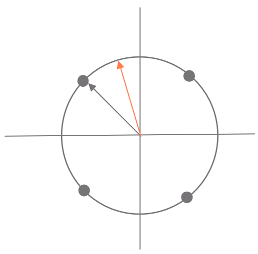
PRECODING BASED BEAMFORMING

- Code-book of pre-coding matricies
- Maximize SNR, rate, throughput, received power,... from downlink reference signals, e.g.:

$$P_k = \mathbf{w}_k^H \mathbf{H}\mathbf{H}^H \mathbf{w}_k$$

- The UE feeds back an index to the prefered pre-coding vector

$$\begin{pmatrix} 1 & 1 & 1 & 1 \\ e^{j\pi/4} & e^{j3\pi/4} & e^{j5\pi/4} & e^{j7\pi/4} \end{pmatrix}$$



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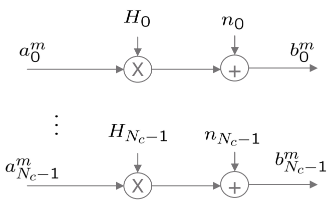
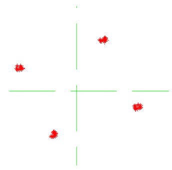
INTRODUCTION TO LTE:

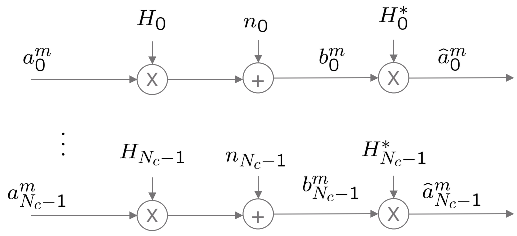
FREQUENCY DOMAIN MODEL FOR OFDM

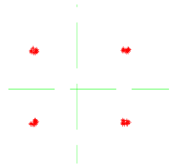
The channel can be seen as acting per subcarrier by the complex gain H_k





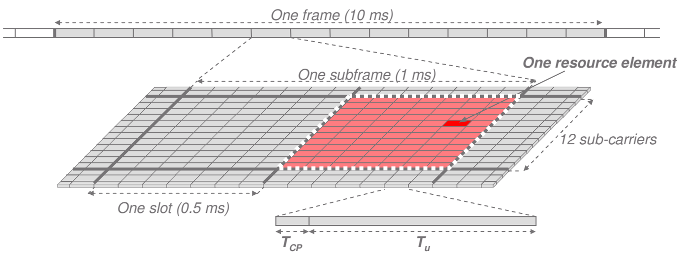
If channel estimates are at hand, this can be compensated for e.g.





INTRODUCTION TO LTE:

PHYSICAL RESOURCE

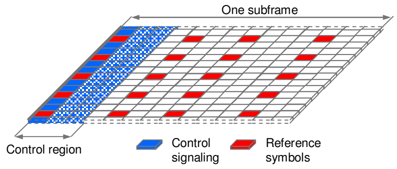


- Time domain structure:
  - 10 ms frame consisting of 10 subframes of length 1 ms
  - Each subframe consists of 2 slots of length 0.5 ms
  - Each slot consists of 7 OFDM symbols (6 symbols in case of extended CP)
- Resource element (RE)
  - One subcarrier during one OFDM symbol
- Resource block (RB)
  - 12 subcarriers during one slot (180 kHz × 0.5 ms)

INTRODUCTION TO LTE:

DOWNLINK CONTROL SIGNALING

- 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

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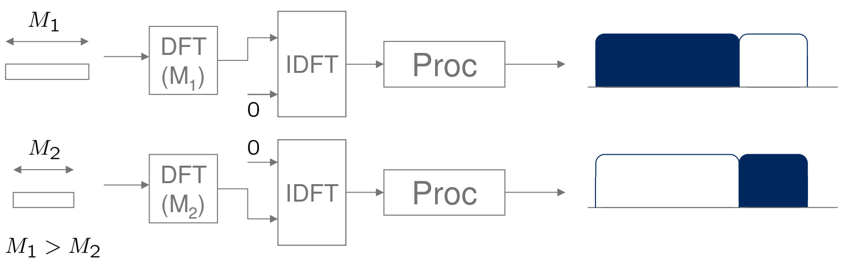
INTRODUCTION TO LTE:

DFTS-OFDM (CONT.)

- This enables flexible bandwidth sharing, restricted by a consequtive subcarrier allocation requirement.
  - Evenly distributed carrier allocation also gives single-carrier properties



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