MIMO technologies used in latest generation of mobile communication systems

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Purposes

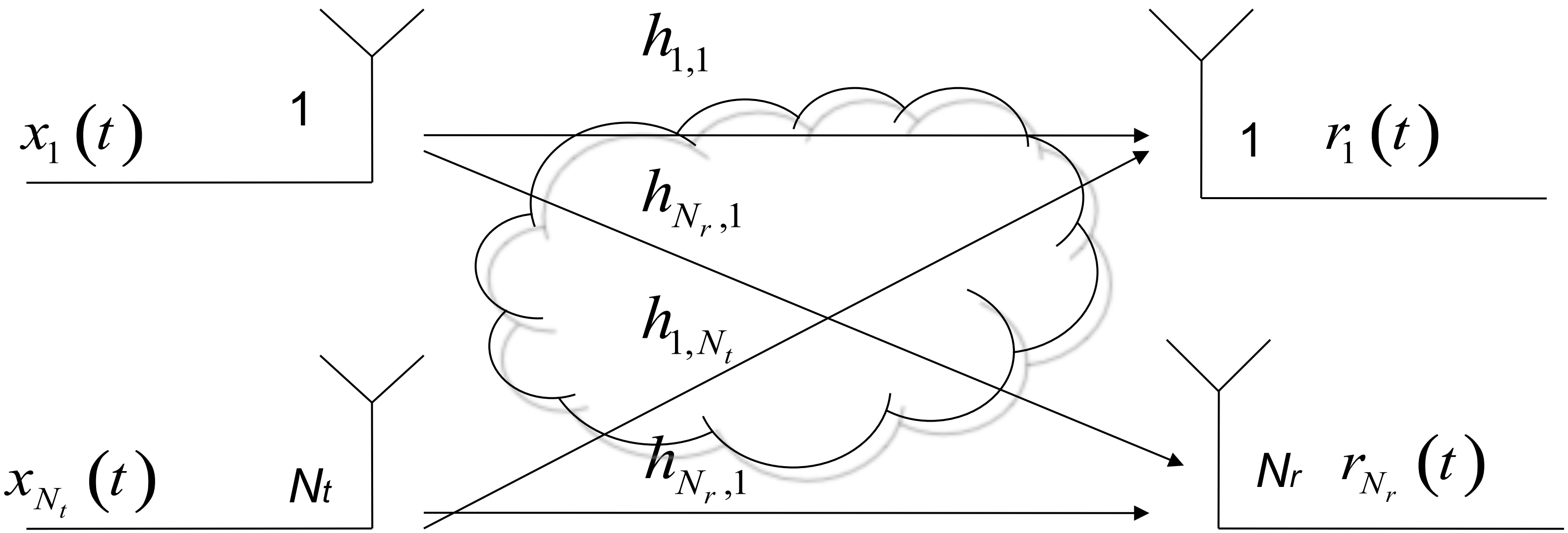
- To describe the main MIMO techniques and benefits
- To underline the constraints that exist in implementing MIMO techniques in different systems
- To give an example of the main MIMO mechanisms implemented in 4G communication systems (e.g. LTE, WiMAX)
- To propose a MIMO prototype system implemented on FPGA

Contents

- MIMO channel
- Spatial diversity
- Closed-loop MIMO
- MIMO – OFDM systems
- MIMO in WiMAX systems
- MIMO in LTE systems
- Case study: MCMA project

MIMO channel (1)

- MIMO = Multiple Input Multiple Output



$$r_i = \sum_{m=1}^{N_t} h_{i,m} x_m + z_i, \qquad i = \overline{1, N_r}$$

MIMO channel (2)

- Matrix formulation

$$\mathbf{r} = \mathbf{H}\mathbf{x} + \mathbf{z} \qquad \mathbf{r} = \begin{bmatrix} r_1 & \cdots & r_{N_r} \end{bmatrix}^T \qquad \mathbf{z} = \begin{bmatrix} z_1 & \cdots & z_{N_r} \end{bmatrix}^T$$

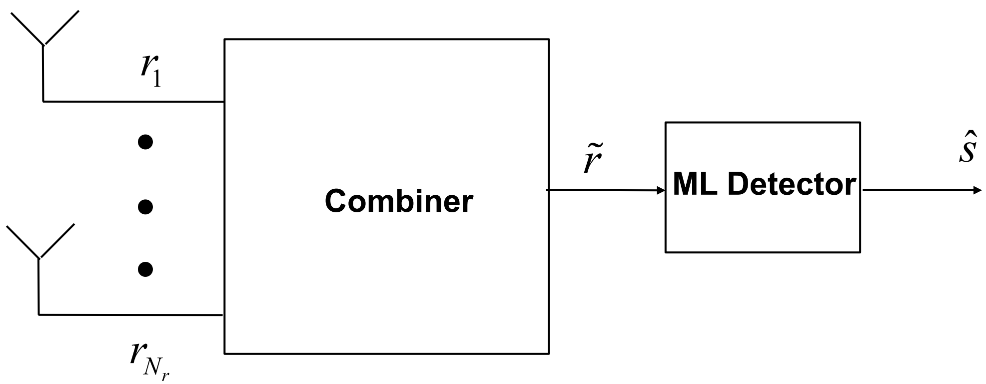
$$\mathbf{H} = \begin{bmatrix} h_{1,1} & \cdots & h_{1,N_t} \\ \vdots & \ddots & \vdots \\ h_{N_r,1} & \cdots & h_{N_r,N_t} \end{bmatrix}$$

- Formula holds only for
  - Flat fading
    - Rich scattering environment
    - Multi-carrier systems
  - Static fading
    - Fixed deployment systems

Contents

Spatial diversity (1)

- Diversity
  - Modify the channel statistics
  - Reduce the fade margin
- Receive spatial diversity
  - Compliance to a standard is not necessary
  - Requires large antenna spacing
    - It is best to be applied over uplink
    - Brings 10lg(N_r) [dB] gain for identical paths



Spatial diversity (2)

- Examples
  - Large antenna spacing ULAs
    - Radiation pattern has many lobes
  - Selection Diversity
    - Strongest received signal selected
  - Equal Gain Combining
    - Received signal are summed co-phased
  - Maximum Ratio Combining
    - Received signals are optimally combined, proportionally to their signal to noise ratio

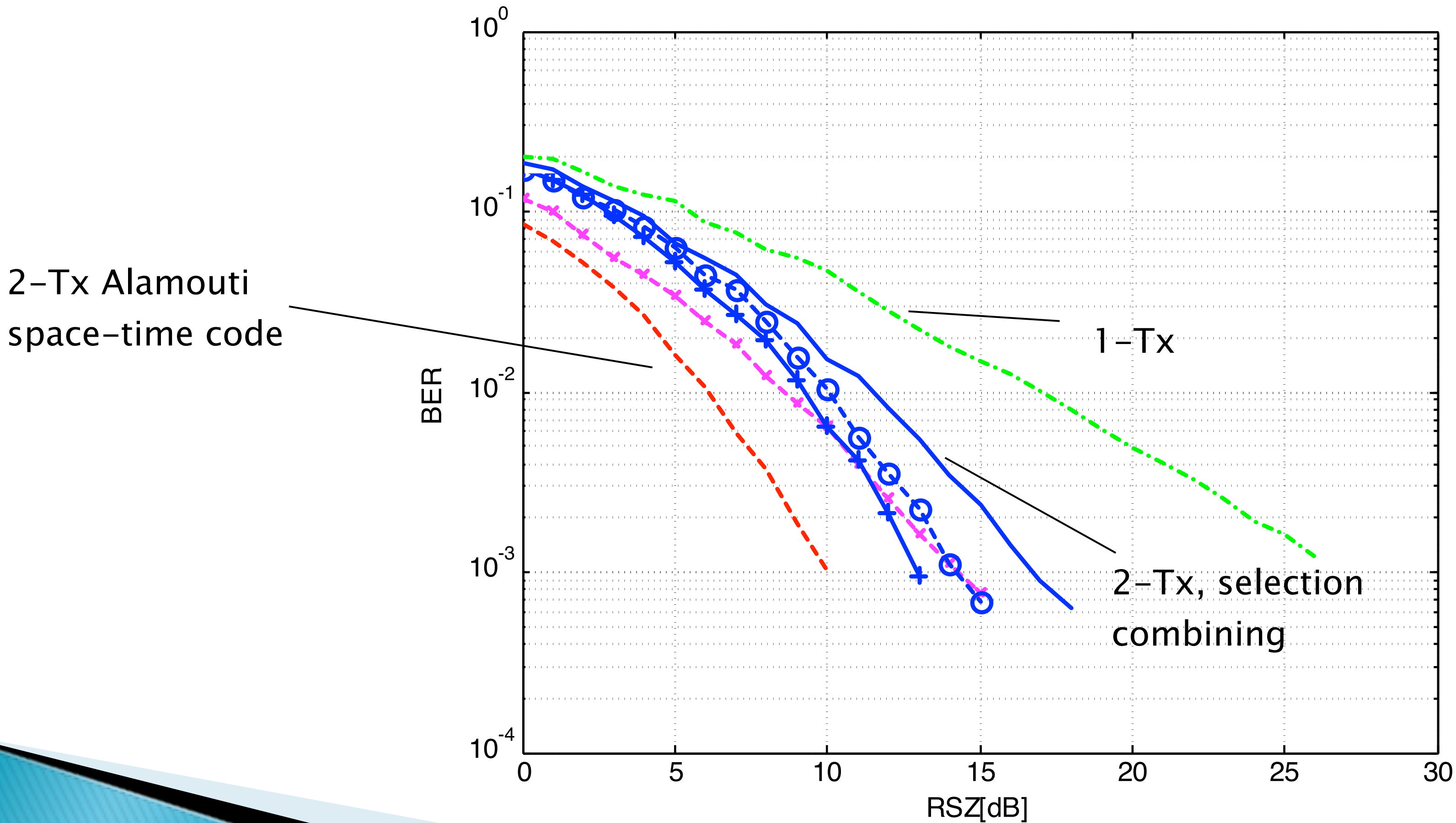
Spatial diversity (3)

- Transmit diversity
  - Compliance to a standard is necessary
  - Requires large antenna spacing
    - It is best to be applied over downlink
  - Large antenna spacing ULAs
  - Space–time codes
    - Orthogonal space–time codes provide $N_t x N_r$ order diversity
    - They exist only for 2–Tx systems (Alamouti codes)

$$\mathbf{C} = \begin{bmatrix} s_1 & -s_2^* \\ s_2 & s_1^* \end{bmatrix}$$

Spatial diversity (4)

- Diversity effects (QPSK, Rayleigh fading)



10

Contents

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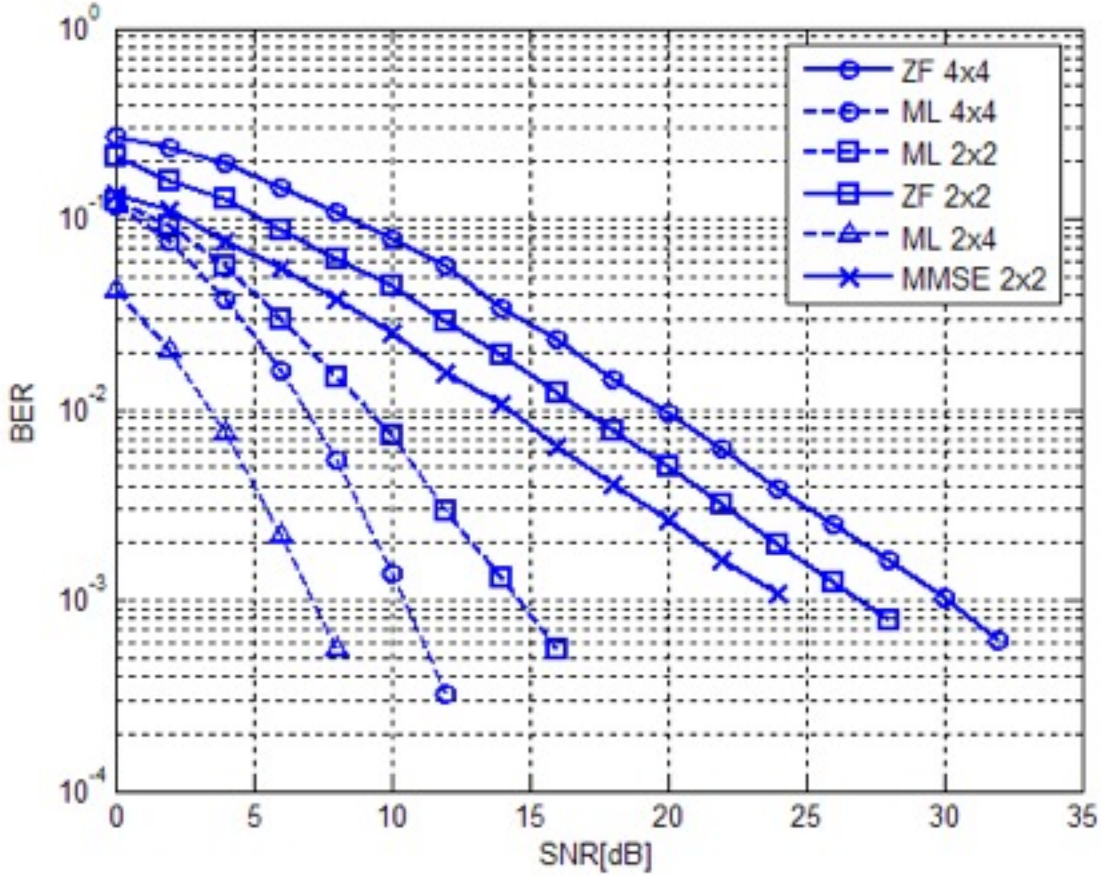
Spatial multiplexing (1)

- Transmit antennas carry independent streams
  - Throughput increases N_t times
- Requires low correlation between propagation paths (full-rank channel matrix)
  - Large antenna spacing
- A N_t x N_r SM system achieves:
  - N_t times greater throughput
  - Spatial diversity according to the decoding algorithm
    - ML algorithm or equivalent: N_r-order
    - MMSE algorithm: approximately N_r – N_t – order

Spatial multiplexing (2)

- SM decoders performances (BPSK)



Spatial multiplexing (3)

- ML-based decoders
  - Exhaustive search (e.g. 64QAM, 4x4 => 4M candidates)
  - Quasi-ML: sphere decoders (Fixed, K-Best)
- Sub-optimal
  - Zero Forcing
    - Noise enhancement
  - MMSE
    - Takes noise power into account
  - Interference cancellation (SIC, PIC)

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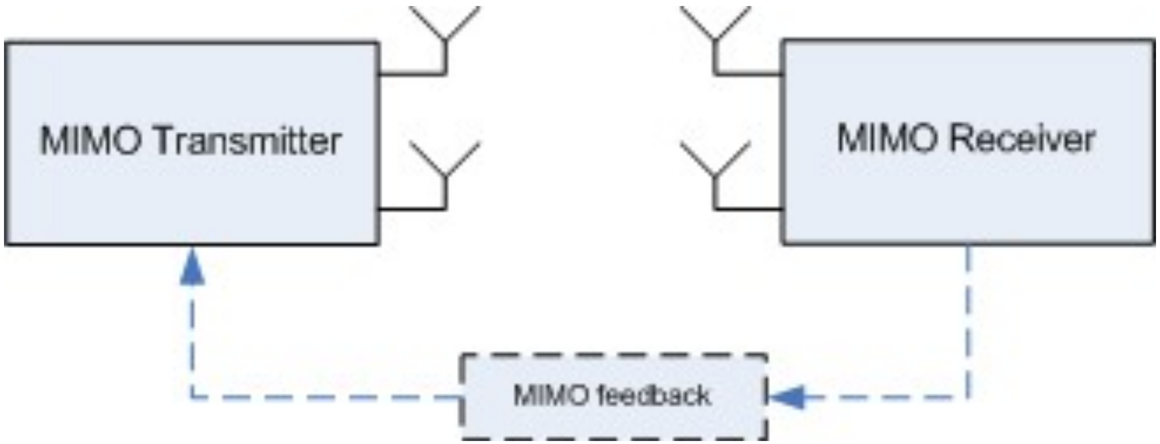
Why closed-loop MIMO?

- Choosing the right MIMO technique strongly depends on the type of channel
  - Mobile channel
    - Diversity 2x2, 4x4
  - Static fading, high SNR
    - Spatial multiplexing
    - How many layers: 2, 4 or 8?
      - Depends on the channel matrix rank

Closed-loop MIMO (1)

- CSI (Channel State Information) is provided as a feedback
  - Channel matrix coefficients
  - Channel matrix eigenvalues
  - Channel matrix rank number



Closed-loop MIMO (2)

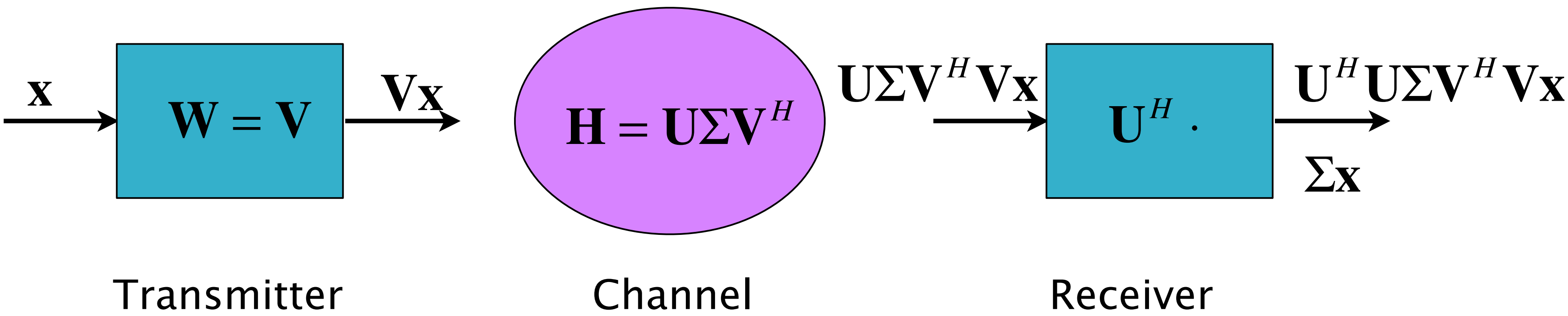
- MIMO mechanism selection
  - According to CSI feedback:
    - Mobile channel / low-rank channel => spatial diversity (3dB gain at least)
    - Static channel / full-rank channel => spatial multiplexing
- Antenna grouping
  - Different time-frequency resources use different transmit antenna pairs for space-time coding
- Antenna selection
  - Only N_t antennas are chosen from all transmit antennas for MIMO, according to CSI
- Precoding
  - Precoding matrix W is applied according to the estimated matrix channel

$$\mathbf{r} = \mathbf{HWx} + \mathbf{z} \qquad \mathbf{W} \in \{\mathbf{P}_1, \cdots, \mathbf{P}_L\}$$

MIMO Precoding

- Precoding matrix $\mathbf{r} = \mathbf{H}\mathbf{W}\mathbf{x} + \mathbf{z}$
  - Precoding matrix can be chosen in order to decouple the propagation paths
  - SUV decomposition of the channel matrix

$$\mathbf{H} = \mathbf{U}\Sigma\mathbf{V}^H \qquad \mathbf{I} = \mathbf{U}^H\mathbf{U} \qquad \mathbf{I} = \mathbf{V}^H\mathbf{V} \qquad \Sigma = diag\{\sigma_i\}$$



MIMO Precoding (2)

- Equivalent channel
- Precoding matrix decouples all propagation paths

$$\mathbf{r} = \Sigma\mathbf{x} + \mathbf{z} \qquad r_k = \sigma_k x_k + z_k$$

- SNR per virtual channel is equal to the singular value σ_k
- Physical interpretation
  - Transmitted signal:

$$\mathbf{W}\mathbf{x} = \left[\mathbf{w}_1 \cdots \mathbf{w}_{N_t}\right] \begin{bmatrix} x_1 \\ \vdots \\ x_{N_t} \end{bmatrix}$$

MIMO Precoding (3)

- Each layer is beamformed by a vector $\mathbf{w}_k$
- Beams for all N_t layers are orthogonal
  - Decorrelates channel paths for the layers
  - Optimum performance
- How do we choose matrix W from a predefined set?
  - PMI indicator
    - Minimize off-diagonal entries of $\Omega = \mathbf{W}\left(\mathbf{H}^H\mathbf{H}\right)\mathbf{W}^H$

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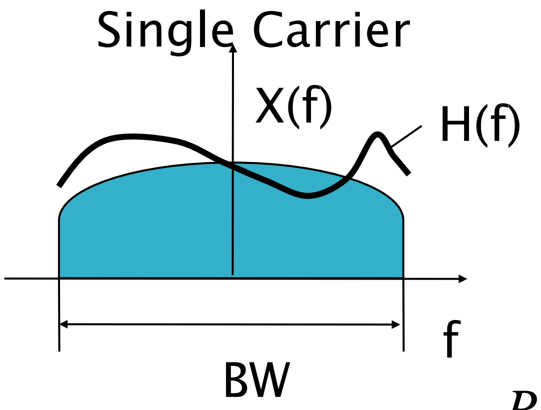
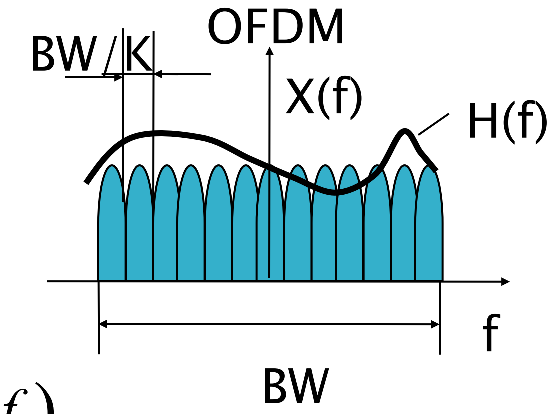
MIMO–OFDM systems (1)

- In the real–world
  - Selective fading, with coherence bandwidth $B_c >> BW$
  - MIMO channel formula will not hold
- Solution: OFDM
  - Bandwidth is divided into K independent subbands, each of $\Delta f = BW / K << B_c$
  - MIMO is applied separately for each subband
    - Large computational effort
  - Examples: LTE (DL), WiMAX (512, 1024 subcarriers)

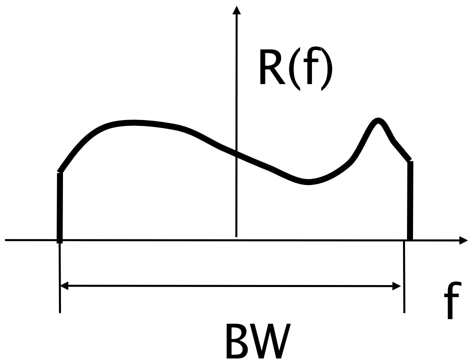
18

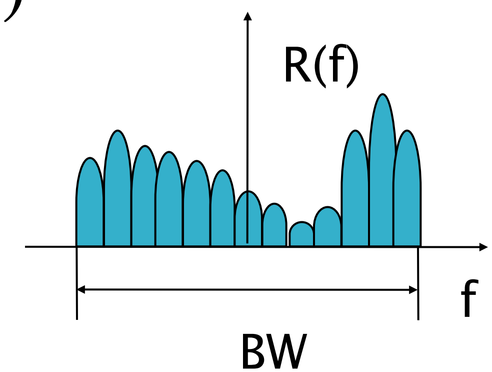
MIMO-OFDM systems (2)





$$R(f) = H(f)X(f)$$





$$r(t) = h(t) * x(t)$$

$$\hat{x}(t) = r(t) * c(t), \text{with } c(t) * h(t) = \delta(t)$$

$$r_k(t) = H(\omega_k)x_k(t)$$

$$x_k(t) = \frac{r_k(t)}{H(\omega_k)}$$

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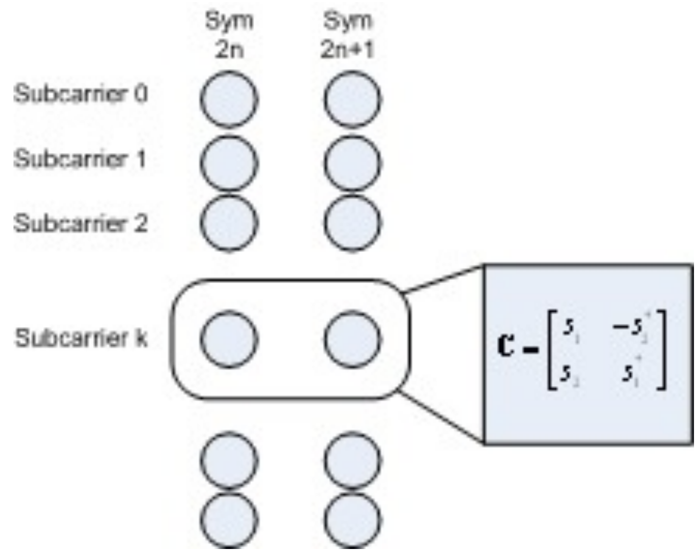
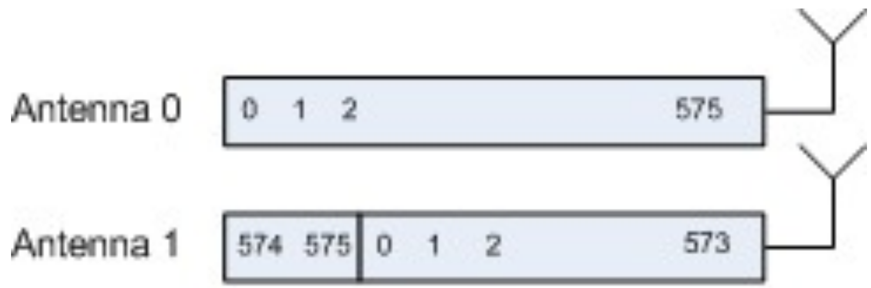
MIMO in WiMAX systems (1)

- Downlink
  - Space-time coding (Matrix A)



    - Alamouti coding

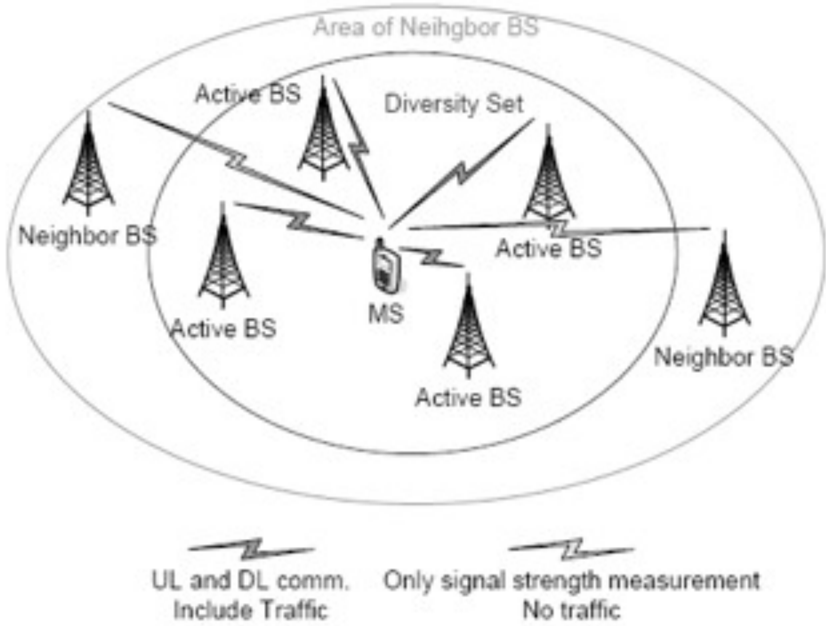
  - Cyclic Delay Diversity (CDD)



$$r_j(n) = h_{j,1}x(n) + h_{j,2}x(n-2)$$

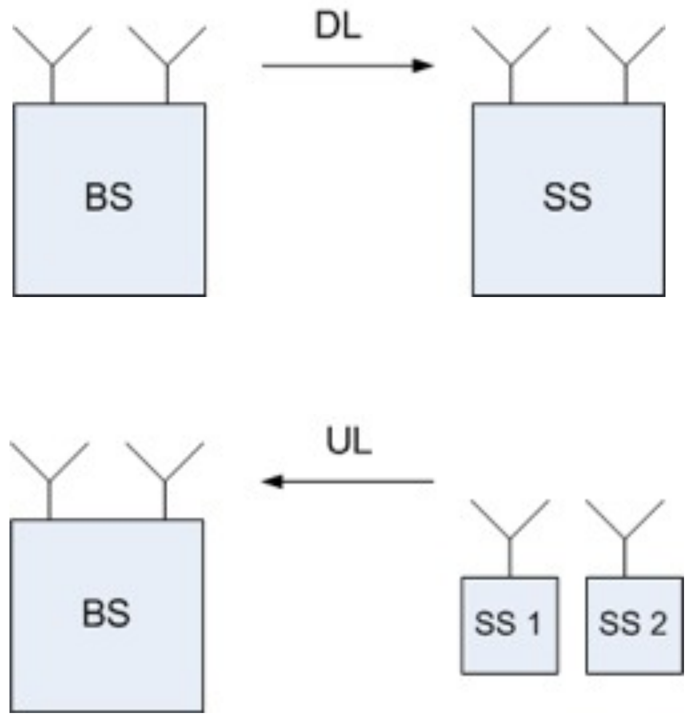
MIMO in WiMAX systems (2)

- Downlink
  - Macro Diversity HandOver (MDHO) / Fast Base Station Switching (FBSS)
    - Soft-bit combining between two base-stations during handover
    - Diversity BSs share the same MS context



MIMO in WiMAX systems (3)

- Downlink
  - Spatial multiplexing (Matrix B)
    - 2-Tx transmit antennas
    - Maximum spectral efficiency: ~4b/s/Hz
- Uplink
  - Collaborative Spatial Multiplexing (CSM)
  - MRC diversity scheme



MIMO in WiMAX systems (4)

- Optional techniques:
  - Precoding
    - Codebook indicated over Fast Feedback channel
    - Antenna grouping
      - Particular weighting matrix
  - Golden space-time code
    - Rate 2, full diversity
  - Adaptive Antenna Systems
    - Increase instantaneous signal to noise ratio
  - FHDC (Frequency Hopping Diversity Coding)
    - STC is applied in frequency, not in time
  - Up to 4Tx SM and STC

Contents

MIMO in LTE systems (1)

- Downlink
  - Spatial multiplexing using precoding (up to 4 Tx)
    - Codebook selection, based on CSI
    - MU-MIMO => SDMA
  - Transmit diversity
    - Adaptive switching between STC and SM for MIMO channel rank-one
- Uplink
  - Collaborative spatial multiplexing (MU-MIMO)
  - Antenna selection: best transmit antenna out of 2

Transmit diversity

- 2-Tx
  - CDD
  - Alamouti
  - Rotation diversity
- 4-Tx
  - CDD
  - Alamouti (x2) + rotation diversity (x2)
- DFT spreading precoding
  - Equalize SNR per virtual channels, in order to avoid unequal singular values of the channel

Closed-loop MIMO

- Precoding matrix
  - Example 4x4
    - 16 precoding matrices
  - Based on 16 orthogonal Householder vectors, u_n

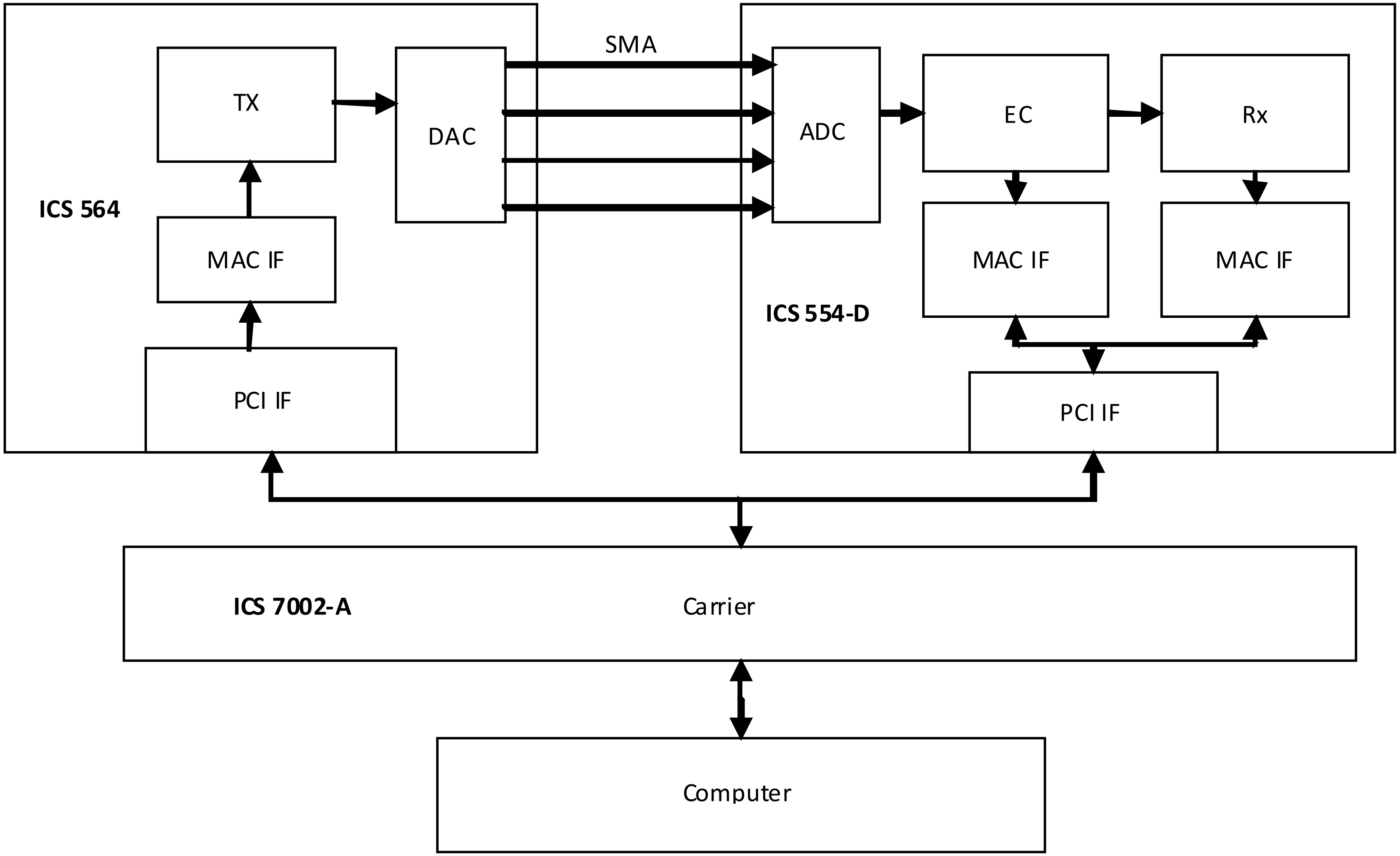
$$\mathbf{W}_n = \mathbf{I}_4 - 2\frac{\mathbf{u}_n\mathbf{u}_n^H}{\mathbf{u}_n^H\mathbf{u}_n}$$

Contents

Case study: MCMA project (1)

- Internal project, carried by a team of 6 students and 2 teachers
- Prototype system
  - App. 16Mbps . / 1.25MHz BW
  - Spectral efficiency: 12.8b/s/Hz
  - 16 subcarriers
  - 4x4 spatial multiplexing with sphere decoder, quasi-ML
  - Maximum delay spread: 1.3μs
  - Maximum Doppler frequency: 200Hz

Case study: MCMA project (2)



29

Thank you!