Introduction to Wireless MIMO – Theory and Applications

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Why MIMO

• Motivation: current wireless systems
  – Capacity constrained networks
  – Issues related to quality and coverage
• MIMO exploits the space dimension to improve wireless systems capacity, range and reliability
• MIMO-OFDM – the corner stone of future broadband wireless access
  – WiFi – 802.11n
  – WiMAX – 802.16e (a.k.a 802.16-2005)
  – 3G / 4G
Transmission on a multipath channel

In wireless communication the propagation channel is characterized by multipath propagation due to scattering on different obstacles.

- Time variations: Fading => SNR variations
- Time spread => frequency selectivity
Transmission on a multipath channel

Fading:

- The received level variations result in SNR variations
- The received level is sensitive to the transmitter and receiver locations
MIMO Defined

- MIMO is an acronym that stands for **Multiple Input Multiple Output**.
- It is an antenna technology that is used both in transmission and receiver equipment for wireless radio communication.
- There can be various MIMO configurations. For example, a 2x2 MIMO configuration is 2 antennas to transmit signals (from base station) and 2 antennas to receive signals (mobile terminal).
MIMO vs. SIMO/MISO
(Linear vs. Logarithmic Improvement)

Channel Capacity

No. of Antenna Elements

MIMO

linear

C = log₂ (det[I+SNR/M H Hᵀ])

logarithmic

SIMO/MISO

C = log₂ (1+SNR)
How MIMO Works

- MIMO takes advantage of multi-path.
- MIMO uses multiple antennas to send multiple parallel signals (from transmitter).
- In an urban environment, these signals will bounce off trees, buildings, etc. and continue on their way to their destination (the receiver) but in different directions.
- “Multi-path” occurs when the different signals arrive at the receiver at various times.
- With MIMO, the receiving end uses an algorithm or special signal processing to sort out the multiple signals to produce one signal that has the originally transmitted data.
How MIMO Works (cont.)

Multiple data streams transmitted in a single channel at the same time

Multiple radios collect multipath signals

Delivers simultaneous speed, coverage, and reliability improvements
Types of MIMO

- MIMO involves Space Time Transmit Diversity (STTD), Spatial Multiplexing (SM) and Uplink Collaborative MIMO.

- **Space Time Transmit Diversity (STTD)** - The same data is coded and transmitted through different antennas, which effectively doubles the power in the channel. This improves Signal Noise Ratio (SNR) for cell edge performance.

- **Spatial Multiplexing (SM)** - the “Secret Sauce” of MIMO. SM delivers parallel streams of data to CPE by exploiting multi-path. It can double (2x2 MIMO) or quadruple (4x4) capacity and throughput. SM gives higher capacity when RF conditions are favorable and users are closer to the BTS.

- **Uplink Collaborative MIMO Link** - Leverages conventional single Power Amplifier (PA) at device. Two devices can collaboratively transmit on the same sub-channel which can also double uplink capacity.
Space-Time Transmit Diversity

Alamouti Code

\[ X = \begin{bmatrix} s_1 & -s_2^* \\ s_2 & s_1^* \end{bmatrix} \]
MIMO Increases Throughput
Spatial Multiplexing

Wireless throughput scales as more radio transmissions are added onto the same channel.

Only baseband complexity, die size/cost, and power consumption limits the number of simultaneous transmissions (assuming good channel conditions).
MIMO Channel Capacity
MIMO Increases Range

Each multipath route is treated as a separate channel, creating many “virtual wires” over which to transmit signals.

Traditional radios are confused by this multipath, while MIMO takes advantage of these “echoes” to increase range and throughput.
Single Radio Performance (Office)
Single Radio vs. MIMO Performance

SDTV
HDTV
30 Mbps ADSL
5-10Mbps
15-20Mbps
30-40Mbps

HDTV + SDTV + Gaming + Music + Internet + Voice

0Mbps
10-15Mbps
20-30Mbps
40Mbps

5-10Mbps
15-20Mbps
30-40Mbps
Different from Traditional Multiple Access Techniques

- It is not FDMA – multiple users using the same frequency
- It is not TDMA – multiple users communicate simultaneously
- It is not CDMA/Spread Spectrum – frequency band occupied is similar to that of conventional QAM system
- It is not SDMA – there are no directed steered/switched beams in space (e.g., smart antennas)
- *It is ECDMA (Environmental CDMA): like CDMA without having to spread the signal through space-time coding; here the code is the imprint of the environment on the signal and it comes free…*

Exploiting Multipath Rather than Mitigating It
MIMO Channel

\[ H(4\times4) \]
The “Magic”:
Separating the self-coded signals

- using laser diodes
- using radio frequency
MIMO Channel Matrix

Example for 3 X 4 system:

Number of spatial streams equals $\text{rank}(H) \leq \min(M, N)$

$h_{ij}$ are complex numbers: $a+jb$ (amplitude & phase) and frequency selective
How It Works

Example for 3 X 3 system:

\[
\begin{bmatrix}
  x_1 \\
  x_2 \\
  x_3
\end{bmatrix}
= 
\begin{bmatrix}
  h_{11} & h_{12} & h_{13} \\
  h_{21} & h_{22} & h_{23} \\
  h_{31} & h_{32} & h_{33}
\end{bmatrix}
\begin{bmatrix}
  b_1 \\
  b_2 \\
  b_3
\end{bmatrix}
+ \text{Noise}
\]

\[
\begin{bmatrix}
  \hat{b}_1 \\
  \hat{b}_2 \\
  \hat{b}_3
\end{bmatrix}
= H^{-1}
\begin{bmatrix}
  x_1 \\
  x_2 \\
  x_3
\end{bmatrix}
\]
Impact of Channel Model

MIMO performance is very sensitive to channel matrix invertibility.

The following degrades the conditioning of the channel matrix:
- Antenna correlation caused by:
  - small antenna spacing, or
  - small angle spread

Line of sight component compared with multipath fading component:
- multipath fading component, close to i.i.d. random, is well conditioned
- Line of sight component is very poorly conditioned.
MIMO-SM in Line-of-Site

The system is near rank one (non invertible)!

Spatial multiplexing requires multipath to work!!!
Zero-Forcing Receiver

\[
\begin{bmatrix}
  x_1 \\
  x_2 \\
  \vdots
\end{bmatrix} =
\begin{bmatrix}
  h_{11} & h_{12} & \cdots \\
  h_{21} & h_{22} & \cdots \\
  \vdots & \vdots & \ddots
\end{bmatrix}
\begin{bmatrix}
  s_1 \\
  s_2 \\
  \vdots
\end{bmatrix} + \mathbf{n}
\]

Zero Forcing implements matrix (pseudo)-inverse (ignores noise enhancement problems):

\[
\hat{s} = \mathbf{H}^\# \mathbf{x}
\]

Where,

\[
\mathbf{H}^\# = (\mathbf{H}^* \mathbf{H})^{-1} \mathbf{H}^*
\]
Example
Simultaneous Transmission of 3 Different Bit-Streams

Data 001011 → Bit/symbol Mapping 0, 2, 3 → QPSK 1, -1, -i → Rayleigh Fading S₁ S₂ S₃ → AGWN → R₁ R₂ R₃

Scatter plot for 3x3, N=100

Scatter plot for 3x3, N=100
Downstream Signals

all signals sent at same frequency and same time
Mixed Signals
Downstream

\[ R = H \cdot S + n \]

Channel mixing matrix

Noise

e.g., \( R_1 = h_{11}S_1 + h_{12}S_2 + h_{13}S_3 + h_{14}S_4 + n_1 \)
The Received Signals

\[ R_1 = h_{11}S_1 + h_{12}S_2 + h_{13}S_3 + h_{14}S_4 + n \]
\[ R_2 = h_{21}S_1 + h_{22}S_2 + h_{23}S_3 + h_{24}S_4 + n \]
\[ R_3 = h_{31}S_1 + h_{32}S_2 + h_{33}S_3 + h_{34}S_4 + n \]
\[ R_4 = h_{41}S_1 + h_{42}S_2 + h_{43}S_3 + h_{44}S_4 + n \]

\[ R = H \cdot S + n \]
\[ H = \begin{pmatrix} h_{11} & h_{12} & h_{13} & h_{14} \\ h_{21} & h_{22} & h_{23} & h_{24} \\ h_{31} & h_{32} & h_{33} & h_{34} \\ h_{41} & h_{42} & h_{43} & h_{44} \end{pmatrix} \]

\[ \hat{S} \leftarrow H^{-1} \cdot R \approx H^{-1} \cdot H \cdot S \]

If \( H \) is ill-conditioned (close to singular)

\( Y \) will be far from the identity matrix

Resulting in co-channel interference
Spatial Correlation
or how well the matrix $H$ is conditioned
Spatial Correlation (cont.)

\[
\rho = \frac{E[(v_1 - E(v_1))(v_2 - E(v_2))]}{E[(v_1 - E(v_1))^2]E[(v_2 - E(v_2))^2]}
\]

Receive Antenna 1

\[
v_1 = \left( \sum_{j=1}^{L} \alpha_j e^{i\phi_j} \right) u_1
\]

Receive Antenna 2

\[
v_2 = \left( \sum_{j=1}^{L} \alpha_j e^{i\phi_j} e^{i\beta d_j} \right) u_1; \quad \beta = \omega / c; \quad d_j = D \cos \theta_j
\]
Spatial Correlation (cont.)
Correlation Drops Significantly for $D > \lambda$ When Angle Spread $> 65^\circ$
Co-Channel Interference

\[ Y = H_{est}^{-1} \cdot H_{true} \neq I \]

\[ \hat{S} \leftarrow Y \cdot S \]

\[ SINR_{S_k} = 20 \log \left| \frac{y_{kk}}{\sum_{j \neq k} y_{kj}} \right| \]
Graceful Capacity Degradation in Partially Correlated Channels

Multi-path components do not need to be fully independent.

$\overline{C}_f = \log_2 \left( \frac{\det(\mathbf{I} + \text{SNR}/\mathbf{M} \mathbf{H} \mathbf{H}^t)}{\log_2 (1 + \mathbf{h} \mathbf{h}^t \text{SNR})} \right)$
Random Capacity in MIMO Channels

Correlation Effect
Collaborative MIMO

Four 4x4 mixing matrices, one for each MU
Collaborative MIMO

Upstream

One 4x4 mixing matrix in the AP
Mixed Channels

Upstream

\[ R = H \cdot S + n \]

channel mixing matrix

noise

e.g., \( R_1 = h_{11}S_1 + h_{12}S_2 + h_{13}S_3 + h_{14}S_4 + n_1 \)
MIMO Pre-Processing at the Transmitter
A single antenna at the mobile

- AP pre-processes the signals based on channel knowledge (CSI Tx)
- No MIMO processing in the mobile
- AP sends linear combination of all signals from each antenna such that when they all arrive at the mobile all undesired signals cancel out
- Effectively AP solves the equation to each mobile
- Benefits:
  - Mobile: lower cost, power and size
  - Scalability: more MIMO channels possible resulting in higher aggregate capacity
  - Strong physical-layer security, hard to break
MIMO Pre-Processing at the Transmitter

A single antenna at the mobile

All undesired signals cancel out at the mobile
Mixed Channels
Downstream

\[ R = H \cdot S' + n \]

e.g., \( R_1 = h_{11}S'_1 + h_{12}S'_2 + h_{13}S'_3 + h_{14}S'_4 + n_1 \)
MIMO Pre-Processing at the Transmitter

Downlink

\[ R = H \cdot S + n \]

\[ S' = W \cdot S \]

\[ R' = H \cdot S' + n = H \cdot W \cdot S + n \]

\[ W = H^{-1} \cdot Y \]

\[ Y = H_{true} \cdot H_{est}^{-1} \neq I \]

\[ \hat{S} \leftarrow Y \cdot S \]
End-to-End Reciprocity

- Practically, downstream and upstream channel matrices are not reciprocal
- AP Tx/Rx chain mismatch could result in significant performance degradation
End-to-End Reciprocity (cont.)

\[
H'_D = R_{\mu} H_D T_{\mu AP} \quad \text{end-to-end downstream}
\]
\[
H'_U = R_{\mu AP} H_U T_{\mu} \quad \text{end-to-end upstream, estimated using training sequence}
\]

Note that \(R_{\mu}, T_{\mu}, R_{\mu AP} \) and \(T_{\mu AP} \) are diagonal matrices.

\(H_D\) and \(H_U\) are the channel matrices (antenna-to-antenna) for downstream and upstream, respectively.

\[
H_D = R_{\mu}^{-1} H'_D T_{\mu}^{-1} \quad \text{antenna-to-antenna downstream}
\]
\[
H_U = R_{\mu AP}^{-1} H'_U T_{\mu}^{-1} \quad \text{antenna-to-antenna upstream}
\]

\[
H_D = H_U^T \quad \text{reciprocity from EM theory}
\]
\[
R_{\mu}^{-1} H'_D T_{\mu}^{-1} = (R_{\mu AP}^{-1} H'_U T_{\mu}^{-1})^T
\]
\[
R_{\mu}^{-1} H'_D T_{\mu}^{-1} = T_{\mu}^{-1} R_{\mu AP} H_U^T
\]

\[
H'_D = R_{\mu} T_{\mu}^{-1} H_U^T R_{\mu AP} T_{\mu AP}
\]

Note that \(R_{\mu}\) and \(T_{\mu}\) are unknown.

\(H'_U, T_{\mu AP}\) and \(R_{\mu AP}\) are known.
Calibration at the AP

\[ P'_D = H'^T U R^{-1}_{AP} T_{AP} \]  \hspace{1cm} \text{matrix used for pre-processing}

\[ Y = R_{\mu} H_D T_{AP} P'^{-1}_{D} = R_{\mu} H_D T_{AP} (H'^T U R^{-1}_{AP} T_{AP})^{-1} \]
\[ Y = R_{\mu} H_D T_{AP} ((R_{AP} H_U T_{\mu})^T R^{-1}_{AP} T_{AP})^{-1} \]
\[ Y = R_{\mu} H_D T_{AP} (T_{\mu} H^T U R_{AP} R^{-1}_{AP} T_{AP})^{-1} \]
\[ Y = R_{\mu} H_D T_{AP} (T_{\mu} H_D R_{AP} R^{-1}_{AP} T_{AP})^{-1} \]
\[ Y = R_{\mu} H_D T_{AP} (T_{\mu} H_D T_{AP})^{-1} \]
\[ Y = R_{\mu} H_D T_{AP} T^{-1}_{AP} H^{-1}_{D} T^{-1}_{\mu} \]

\[ Y = R_{\mu} H_D H^{-1}_{D} T^{-1}_{\mu} \]  \hspace{1cm} \text{highly diagonal (low interference)}
No Calibration at the AP

\[ P'_D = H'^T_U \] matrix used for pre-processing

\[ Y = R_{\mu} H_D T_{AP} P'^{-1}_D = R_{\mu} H_D T_{AP} (H'^T_U)^{-1} \]
\[ Y = R_{\mu} H_D T_{AP} ((R_{AP} H_U T_{\mu})^T)^{-1} \]
\[ Y = R_{\mu} H_D T_{AP} (T_{\mu} H^T_U R_{AP})^{-1} \]
\[ Y = R_{\mu} H_D T_{AP} (T_{\mu} H_D R_{AP})^{-1} \]

\[ Y = R_{\mu} H_D T_{AP} (R^{-1}_{AP} H^{-1}_D T^{-1}_{\mu}) \]

diagonality could be spoiled resulting in interference
End-to-End Reciprocity

Conclusions

- AP Tx/Rx mismatch could result in significant performance degradation
- MU Tx/Rx mismatch has relatively small effect on performance
- Calibration in the AP is necessary and sufficient
Mobility Effects

- Motions of mobiles change the channel matrix
- Since the packet length is very short, the change of channel matrix is supposed to be negligible. Estimation of channel matrix using header (preamble) only is considered as the channel responses for decoding the entire packet.
- The SINR results are much worse than what were expected originally. The reason is: when the condition number of $H$ is very high, $H^{-1}$ is very sensitive to small changes of $H$.
- SINR for some multiplexing channels may be less than 10dB even when the displacement of a Tx or Rx is less than 2% of the wavelength
- Better estimation of channel matrix is required.
Effect of Mobility

Statistical Model

\[ h_{ik} = \sum_{p} a_p e^{-j\theta_p} \]

\[ \tilde{h}_{ik} = \sum_{p} a_p e^{-j(\theta_p + (2\pi / \lambda) \Delta x \cos \varphi_p)} \]

\[ \theta_p, \varphi_p \text{ iid uniformly } [0,2\pi] \]
9 Mobiles; None Move
Input SNR=20dB

SINR's constants and finite (imperfect channel estimation due to noise)
9 Mobiles; 1 Moves
Input SNR=20dB

-Uplink: ALL SINR’s are deteriorating as the displacement increases except that for the moving mobile
-Downlink: ALL SINR’s remain unchanged except that for the moving mobile
Applications

• WLAN – WiFi 802.11n
• Mesh Networks (e.g., MuniWireless)
• WMAN – WiMAX 802.16e
• 4G
• RFID
• Digital Home
High Throughput WiFi - 802.11n

General

- Using the *space* dimension (MIMO) to boost data rates up to 600 Mbps through multiple antennas and signal processing
- Target applications include: large files backup, HD streams, online interactive gaming, home entertainment, etc.
- Backwards compatible with 802.11a/b/g
High Throughput WiFi - 802.11n
Technology Overview

- 2.4 GHz and 5.8 GHz unlicensed bands
- Channel bandwidth of 20 MHz and 40 MHz
- Up to 4 spatial streams (e.g., 4x4)
- Current product offerings (pre-N) use only 2 spatial streams with 3Tx / 3Rx in the AP and 2Tx / 3Rx in the mobile supporting up to 300 Mbps
- Spatial diversity, spatial multiplexing, beamforming
- Enhancements in both PHY and MAC (e.g., frame aggregation, block-ACK, space-time coding, power save, green field mode, etc.)
MIMO in MuniWireless

- High capacity (MIMO) cross-links
- WiFi access
MIMO in Ad-Hoc Network

- A collection of wireless mobile nodes that self-configure to form a network (data rate + range)
- No fixed infrastructure is required
- Any two nodes can communicate with each other
- High capacity link are useful for scalability and multimedia services
Mobile-WiMAX 802.16e
Technology Overview

- Non line of site, up to 4-6 mbps per user for a few km
- 2.5 GHz (US) and 3.5 GHz licensed bands
- Channel bandwidth from 1.25 to 20 MHz
- QPSK, 16 QAM and 64 QAM modulation
- OFDMA access (orthogonal uplink)
- TDD for asymmetric traffic and flexible BW allocation
- Advanced Antenna Systems (AAS): Beamforming, spatial diversity, spatial multiplexing using MIMO (2x2)
MIMO in WiMAX
A 2x2 MIMO Configuration in 802.16e

• Increasing spectral efficiency (bps/Hz)
• Downlink – higher capacity and user peak rates
• Uplink – higher capacity only
MIMO in WiMAX (cont.)

OFDMA TDD Frame Structure

Time/Frequency Multi-User Diversity
MIMO in WiMAX (cont.)
Layer 3 Throughput Comparison

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<thead>
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<th>technology</th>
<th>throughput per sector/per channel</th>
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<tr>
<td></td>
<td>downlink</td>
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<tr>
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<td>-10 MHz</td>
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MIMO in RFID

- Increasing read reliability using space diversity
- Increasing read range and read throughput
- Full channel information at the reader comes for free (tag backscatter)
MIMO Enables the Digital Home

MIMO delivers whole home coverage with the speed and reliability to stream multimedia applications.

MIMO can reliably connect cabled video devices, computer networking devices, broadband connections, phone lines, music, storage devices, etc.

MIMO is interoperable and can leverage the installed base of 802.11 wireless that is already deployed: computers, PDAs, handheld gaming devices, cameras, VoIP Phones, etc.
The Ultimate Digital Home

WiFi 802.11n

Kitchen

Home Theater and Set Top Box

Bedroom

Home Office

Children’s Room

Living Room – TV Displays and Gaming

Home Service Gateway
Questions?

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Thank You!