MIMO Technologies
Past, Present, and Future

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Wireless Communications

- Without wire: reachable anywhere
- Various topologies (one to one, one to many, many to one, etc.)
- Interference problem
- Fading
Wireless = Freedom
Wireless Systems - Antennas

- Transform wire propagated waves into space propagated waves and vice versa.

- Means to achieve degree of freedom (DOF) of wireless systems (spatial, temporal, spatio–temporal, etc.)
Benefits of Multiple Antennas in Wireless Communications

- Provide more resolvable signal paths
  - diversity gain $d$ ($P_{err} \propto SNR^{-d}$)
Benefits of Multiple Antennas in Wireless Communications

- Supports more data streams
- multiplexing gain $r$ ($R \propto r \log \text{SNR}$)
Benefits of Multiple Antennas in Wireless Communications

- Higher chance to select good quality mobile: opportunistic gain (also called multiuser diversity)

- When the number of users in a cell is large, almost surely there exists a user whose channel strength is much larger than the average. By allocating system resources to that user, multiuser diversity is fully capitalized.
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Benefits of Multiple Antennas in Wireless Communications

- Cooperation among multiple transmitters/receivers: cooperative gain
- Information sharing via backhaul link
MIMO - Some Statistics

- Google: MIMO (31,300,000 results)
- Google scholar: MIMO (629,000 papers)
- 6 billion cell phone users in 2012 (80% of world population)
- Expect 7.3 billion by 2014 (more than world population)
- 1.1 billion smart phone users in 2012 (Expect 2 billion by 2014)
MIMO - Brief History

- Rudimentary concept in 70s (Bell Labs)
- Seminal works by Foschini (96) and Telatar (99)
- Adopted in 3G cellular standard (HSPA) in 2006
- Part of key technologies in 4G and beyond (LTE, WiMAX, WiFi, ⋯)
- Time to market (information theoretic concept to commercialization) : about 10 yrs.
Multiple Antennas in 3G Wireless Communications (WCDMA, HSDPA, HSPA)

System model: $y_n = h_n * x_n + v_n$ ($x_n$ is transmitted chip)

- Temporal diversity: rake receiver
- Tx diversity
  - Alamouti coding: ML-detection with only linear processing
    \[
    \begin{bmatrix}
    y_1 \\
    y_2
    \end{bmatrix}
    = \begin{bmatrix}
    h_1 & h_2 \\
    h_2^* & -h_1^*
    \end{bmatrix}
    \begin{bmatrix}
    x_1 \\
    x_2
    \end{bmatrix}
    + \begin{bmatrix}
    w_1 \\
    w_2^*
    \end{bmatrix}
    \]

- Rx diversity
  - Equalization using CIR with best power $h_n^i$
    \[
    i = \text{arg max}\{|h_n^1|, |h_n^2|\}
    \]
  - Joint equalization $\hat{x}_n = E[x_n y_n^H] R_{y_n y_n}^{-1} y$

- System model is ugly
Multiple Antennas in 3G Wireless Communications (WCDMA, HSDPA, HSPA)

Complicated system model: $y = HCWGd + v$ (C: scrambling matrix, W: ovsf matrix, G: gain matrix)

- Latest release of HSPA system adopts 2x2 MIMO system
- Hard to implement
  - Frequency domain processing (may use circular approximation of H)
- SINR after equalization

$$SINR = \frac{P}{I_{\text{inter}} + I_{\text{intra}} + N_0} = \frac{P}{\alpha P + N_0}$$
(interference limited)
Multiple Antennas in 3G Wireless Communications (WCDMA, HSDPA, HSPA)

- SINR after equalization $SINR = \frac{I_{inter} + I_{intra} + N_0}{\alpha P + N_0}$ (saturation in performance $P \rightarrow \infty$)
- Solution for interference is crucial to improve spectral efficiency
Multiple Antennas in 3G Wireless Communications (WCDMA, HSDPA, HSPA)

- Type3i receiver: interference aware LMMSE receiver

- IC algorithm: successive interference cancellation and equalization (e.g., Qualcomm Q-ICE in Snapdragon)

- In short, when multiple antenna techniques are combined, system model becomes very complicated
  - Interference among stream cannot be handled nicely
LTE - OFDM based System

- Cyclic prefix + frequency domain symbol processing → free from intracell interference

\[ y = \tilde{H}x + v \rightarrow Y_i = \lambda_i X_i + V_i \]

- scalar processing per subcarrier
- New start from the simple scalar model
MIMO Technologies Past, Present, and Future

Multiple Antennas in LTE Systems

**LTE - New Framework to incorporate Multiple Antennas**

- \[ Y_i = \lambda_i X_i + V_i \rightarrow \text{allow per subcarrier processing without intracell interference} \]

- **Provide nice and clean framework** for building up multiple antenna techniques
  - Multiple Tx/Rx antennas can be integrated per subcarrier → [Singleuser MIMO]
LTE - New Framework to incorporate Multiple Antennas

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Multiple Antenna Technologies in LTE - A Brief History

- Rel. 8-9 (LTE System)
  - Receive diversity (RxD)
  - Transmit diversity (TxD)
  - Cyclic delay diversity (CDD)
  - SU-MIMO
  - MU-MIMO (primitive form)

- Rel. 10 and beyond (LTE-Advanced)
  - High-dimensional SU-MIMO (e.g., 8 × 8 MIMO)
  - Elaborated MU-MIMO (dual codebook, enhanced reference signal)
  - Coordinated Multipoint (CoMP) transmission and reception
  - Relay (primitive form)
  - Massive MIMO (under study)
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SU-MIMO in LTE

- The SU-MIMO scheme is applied to the physical downlink shared channel (PDSCH)
- Support both closed-loop and open-loop operation
SU-MIMO in LTE - In an Ideally Scenario...

- $C = \max_{\text{tr}(Q) \leq P} \log | I + HQH^\dagger |$
  - Low SNR: transmit on a single eigenmode (with best stream SNR) is enough
  - Mid SNR: waterfilling type transmission ($q_i = (\mu - \lambda_i^{-1})^+$)
  - High SNR: equal power transmission is close to optimal
SU-MIMO in LTE - In Reality

- Open-loop: when reliable PMI feedback is unavailable at the eNB
- Closed-loop: codebook based systems where UE feeds back the channel quality indicator (CQI), precoding matrix indicator (PMI), and rank Indicator (RI)
SU-MIMO in LTE

- Channel quality indicator (CQI)
- The CQI index is the largest index guaranteeing $BLER < 0.1$.

<table>
<thead>
<tr>
<th>CQI index</th>
<th>modulation</th>
<th>code rate x 1024</th>
<th>efficiency</th>
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<tr>
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<tr>
<td>15</td>
<td>64QAM</td>
<td>948</td>
<td>5.5547</td>
</tr>
</tbody>
</table>
SU-MIMO in LTE

- Precoding matrix indicator (PMI)
  - Indicates the preferred codebook element of the resource block.

<table>
<thead>
<tr>
<th>Codebook Index</th>
<th>Number of layers $\nu$</th>
<th>1</th>
<th>2</th>
</tr>
</thead>
<tbody>
<tr>
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<td>$\frac{1}{\sqrt{2}} \begin{bmatrix} 1 \ 0 \end{bmatrix}$</td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>$\frac{1}{\sqrt{2}} \begin{bmatrix} 1 \ -1 \end{bmatrix}$</td>
<td>$\frac{1}{2} \begin{bmatrix} 1 \ 1 \end{bmatrix}$</td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>$\frac{1}{\sqrt{2}} \begin{bmatrix} 1 \ j \end{bmatrix}$</td>
<td>$\frac{1}{2} \begin{bmatrix} 1 \ j \end{bmatrix}$</td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>$\frac{1}{\sqrt{2}} \begin{bmatrix} 1 \ -j \end{bmatrix}$</td>
<td>-</td>
<td></td>
</tr>
</tbody>
</table>

- Rank indicator (RI) : the number of layers supported
  - Open loop MIMO : the RI decides transmit diversity ($RI = 1$) or open-loop spatial multiplexing ($RI > 1$).
  - Single RI represents whole bandwidth (very rough)
SU-MIMO in LTE

- RI = 1 and RI = 2 operations (TxD, MIMO)
Limitations of SU-MIMO

- Capacity of SU-MIMO is scaled by $\min\{M, N\}$ at high SNR. However...

- The number of receive antennas $N$ at the battery powered mobile devices is smaller than $M$, which limits the capacity gain
Limitations of SU-MIMO

- Also, SU-MIMO systems are susceptible to the ill-behavior of propagation channels (strong LOS, correlations among TX/RX antenna elements)
- As an alternative option, MU-MIMO has received much attention (MIMO link between single Tx and multiple Rx)
MU-MIMO System

- Single subcarrier supports multiple distinct receivers having one or more antennas
- Receiver cannot control interuser interferences
  - MU-MIMO: Research focus is moved to Tx-side
  - SU-MIMO: Research focus was on receiver techniques: BLAST, MLD, MAP, IDD, ...
MU-MIMO - Review on Information Theory

- SU-MIMO: point-to-point MIMO channel ⇒ relatively easy to analyze

- MU-MIMO: (nondegraded) BC channel ⇒ more complicated
MU-MIMO System - Review on Information Theory

- Degraded BC channel: users are naturally ordered from strongest to weakest in their strength (e.g., Gaussian scalar BC)

WLOG $N_2 > N_1$
MU-MIMO System - Brief History on Information Theory

- Capacity region (satisfying achievability and converse) of degraded BC can be achieved via superposition coding (Tx) and successive interference cancellation (Rx) [Cover, 72]

- Nondegraded BC channels (e.g., MU-MIMO downlink): open problem for a long time!
MU-MIMO System - Dirty Paper Coding (DPC)

- System model is \( Y = X + S + Z \)
  - Note that state (e.g., interference information) is known (noncausally) to the transmitter

When the noise and interference are Gaussian, DPC achieves a capacity which is the same as if there is NO interference
\( C_{dpc} = \frac{1}{2} \log(1 + \frac{P_x}{N}) \) instead of \( \frac{1}{2} \log(1 + \frac{P_x}{P_s+N}) \) [Costa83]
MU-MIMO System - Dirty Paper Coding (DPC)

- MAC-BC duality [Vishwanath, Jindal, Goldsmith, 03]

\[
C_{dpc}(Q, H) = C_{mac}(Q_1, \cdots, Q_k; H^\dagger)
\]

- Enhanced degraded BC [Weingarten, Steinberg, Shamai, 06]

\[
C_{BC}(Q, H) = C_{dpc}(Q, H)
\]

- In summary, sum capacity of Gaussian MIMO BC is

\[
C = \max_{\sum_i \text{tr}(Q_i) \leq P} \log \left| I + \sum_i H_i Q_i H_i^\dagger \right|
\]
MU-MIMO System - Scaling Law

- \( C = \max \sum_i \text{tr}(Q_i) \leq P \log |I + \sum_i H_i Q_i H_i| \)
- Many simple schemes achieve performance close to DPC (ZF, modified VP, opportunistic RBF, ...)

Scaling law: observing the behavior of the sum rate as a function of parameters (more insightful)
Scaling Law of the MU-MIMO

- Sum rate of MU-MIMO is scaled by \( \min\{M, N_{n\text{user}}\} \)

\[
\lim_{\text{SNR} \to \infty} \frac{C_{\text{sum}}}{\log \text{SNR}} = \min\{M, N_{n\text{user}}\}
\]

- As long as \( N_{n\text{user}} \) is large, sum rate is scaled by \( M \)
- User scheduling was a hot research issue
MU-MIMO in LTE - In Reality

- CSIT inaccuracy due to finite feedback: Tradeoff between feedback accuracy and uplink resource consumption → Codebook based precoding (PMI feedback has relatively low overhead)

- Suboptimal user scheduling: user selection at the basestation (eNB) is imperfect due to the inaccurate CQI. Also, CQI in the mobile cannot be accurate due to the lack of knowledge on precoding information of other users (exacerbate problem)

- Pilot issue (overhead of common pilot is burdensome → CSIR itself can be a problem)
MU-MIMO in LTE Systems

Two types of reference signals for measuring parameters: common pilot and dedicated pilot

- **Common pilot (CRS):** \( y_p = hsp + v \) [pilot] and \( y_d = hps_d + v \) [data]
  - Common for all subcarriers; the mobile needs to obtain the precoding matrix information via the control signaling (only **codebook based precoding** is possible)

- **Dedicated pilot (DM-RS):** \( y_p = hps_p + v \) [pilot] and \( y_d = hps_d + v \) [data]
  - Specific to the user; transparent operation is possible
  - **Non-codebook based precoding** (e.g., ZF, MMSE) is possible
Spectral Efficiency for Various Cellular Systems - Past, Present, and Future

- How to further improve spectral efficiency? HetNet, CoMP, Carrier aggregation, Massive MIMO
- Why don’t we move on to new continent? Tens of GHz band (e.g., mmWave)
New World (Tens of GHz band) - Some Characteristics

- **Milimeter-wave** regime has many interesting and distinct features over **microwave**
- Early 90s, local multipoint distribution system (LMDS) concept has been introduced
  - Use millimeter wave for backhaul link, point-to-point or point-to-multipoint link
New World (Tens of GHz band) - Some Characteristics

- High pass loss $\alpha$ and narrow beam
  - Coverage gets smaller (good match with small cells)
  - Reduction of fading and multi-path interferences

- Large bandwidth
  - Possible to use relative sub-optimal multiple access schemes
    (less spectral efficiency is allowed since this regime is Montana, not New York)
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  - Easy to integrate massive antennas for Tx/Rx
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Massive MIMO: Large Tx/Rx antennas

- Employ large number of antennas in the transmitter (1D/2D-array antennas) for improving spectral efficiency.
- Strong candidate for achieving improvement in spectral efficiencies (approved study items in Rel. 12 and beyond)
- How can we support dozens of antennas → issues in various fields including antenna, RF, DSP, etc.
In an Ideal Scenario...

- Example of massive-MIMO MAC ($N_t \times K$ channel)

  - $N_t$: the number of basestation antennas
  - $K$: the number of users

$$y = Hx + n$$
In an Ideal Scenario...

- Massive-MIMO MAC: simple reconstruction via the matched filtering (MF):

\[
\frac{1}{N} H^H y = \frac{1}{N} H^H H x + \frac{1}{N} H^H n \xrightarrow{N \to \infty} x
\]

- The transmit power (per each antenna) can be made arbitrarily small
- Full DOF (proportional to the number of users) can be achieved
- Uncorrelated interference and noise vanish as \( N \to \infty \)
- Developed under the assumption that channel elements are independent
In an Ideal Scenario...

- Massive-MIMO BC: simple maximum ratio transmission (MRT) can be used (transmit signal is $x = H^H s$)

$$y = Hx + n = H(H^H s) + n$$

$N \to \infty \quad \Rightarrow \quad s + n$

- TDD is easier than FDD (no hassle for feedback)
In Reality, however, ...

- Number of reference signal increases with $N_{Tx}$
- If $N_{Tx} > T$, then orthogonality will be no longer guaranteed in the uplink
  - Often called **pilot contamination problem**
  - Also downlink has similar behavior (channel estimation quality is affected via reference signal)
- Reference signal eats out the portion of data transmission in downlink
Packing RS

- Simple packing of the RS will affect resolvability
  \[ y = h_1 + h_2 + h_3 + h_4 \]
  - Need to encode the reference signal via orthogonal code (e.g., Walsh code) \[ y(n) = h_1 c_1(n) + h_2 c_2(n) + h_3 c_3(n) + h_4 c_4(n) \]
  - Need to adapt the number of antennas depending on channel conditions
- This is way to go... but NOT enough!
A Virtual RS for Massive MIMO System

- Assumption that the reference signal should be “known” needs to be relaxed
- Reuse detected and decoded symbol for pilot purpose (we refer to it as “virtual RS”)
- Nicely integrated into the iterative detection and decoding paradigm
Channel Re-estimation via Sparse Error Detection

- After cancellation, modified observation becomes

\[ y - \hat{H}\hat{s} = H\begin{bmatrix} s_{11} \\ s_{12} \\ \vdots \\ s_{1n} \end{bmatrix} - \hat{H}\begin{bmatrix} \hat{s}_{11} \\ \hat{s}_{12} \\ \vdots \\ \hat{s}_{1n} \end{bmatrix} + v \]

\[ = He + w \]

- Only a small fraction of \( e \) is nonzero (\( e \) is the sparse vector)
Channel Re-estimation via Sparse Error Detection

- Minimize misdetection probability at the expense of slight increase in false alarm probability
Compressive sensing - A Short Summary

- From minimum energy principle ($\min \| \mathbf{x} \|_2$) to minimum sparsity principle ($\min \| \mathbf{x} \|_0$)
- Performs well even under underdetermined systems ($N_{tx} \gg N_{rx}$) as long as the sensing matrix satisfies property called **restricted isometry property**
- For practical implementation, greedy algorithm can be used instead of $L_0$ or $L_1$-optimization approach
- Generalized OMP algorithm provides improved mis-detection performance over conventional greedy algorithm
- Virtual RS improves performance as long as erroneous position can be avoided in re-estimation
Feedback of Massive MIMO - Too massive!

- Finite feedback (uplink) and reference signal (downlink) is kind of dual problem for FDD system.
- In FDD system, CSI information of all Tx antennas should be feded back → depletion of all uplink resources!
Feedback of Massive MIMO - Too massive!

- CSIT directly affects the multiplexing gain in MU-MIMO → 
  MU-MIMO system is interference limited under finite feedback environments

- Using ZFBF ($\mathbf{x} = \sum_i x_i \mathbf{v}_i$ and $\mathbf{h}_i^H \mathbf{v}_j = 0$ for $j \neq i$), we have
  - Perfect CSIT: $R = E_{\mathbf{h}_i} (\log(1 + \frac{P}{N} |\mathbf{h}_i^H \mathbf{v}_i|))$
  - Imperfect CSIT: $R = E_{\mathbf{h}_i} (\log(1 + \frac{P}{N} |\mathbf{h}_i^H \mathbf{v}_i|) + \sigma_v^2 - \frac{P}{M} \sum_{j \neq i} \frac{P}{M} |\mathbf{h}_i^H \mathbf{v}_j|))$
  
  since $\hat{\mathbf{h}}_i^H \mathbf{v}_j = 0$ for $j \neq i$
Feedback of Massive MIMO - Too massive!

- Under finite feedback (with RVQ), SNR loss approximates
  \[ \Delta SNR_{dB} \approx 10 \log_{10}(1 + P2^{-\frac{B_f}{N_t-1}}) \] [Jindal, TIT06]

- Loosely speaking, to ensure a constant loss in the rate, \( B_f \) should satisfy \( B_f \approx \frac{N_t-1}{3} P_{dB} \). Therefore,
  \[ B_{f,2} = \frac{N_{t,2} - 1}{N_{t,1} - 1} B_{f,1} \]

- Feedback bits \( (B_f) \) increase sharply in massive MIMO environment!
  - Suppose \( B_f = 4 \) for \( N_t = 4, N_r = 1 \) system, then \( N_{t} = 64, N_{r} = 1 \) will result in \( B_f = 84 \)
Feedback of Massive MIMO - Too massive!

- Feedback overhead scales linearly with both $N_t$ and $SNR$
Feedback Reduction in Massive MIMO

- In short, we need to reduce the feedback information as much as we can!
- Need to exploit spatial correlation in 2D array antennas
  - Channel element grouping based on correlation (e.g., modified Lloyd algorithm)
  - Select initial group vector $\mathbf{h}_1^*, \mathbf{h}_2^*, \ldots, \mathbf{h}_{N_g}^*$
  - Select Voronoi region $V_i = \{ \mathbf{h} | \angle(\mathbf{h}_i^*, \mathbf{h}) \leq \angle(\mathbf{h}_k^*, \mathbf{h}) \}$
  - Find out the representative point ($\mathbf{h}_i^* = E_{V_i}[\mathbf{h}]$) and then repeat steps
- From $\hat{\mathbf{h}} = \arg \max_{\mathbf{v}} \langle \mathbf{h}, \mathbf{v} \rangle$ to $\hat{\mathbf{h}} = \arg \max_{\mathbf{v}'} \langle \mathbf{h}^*, \mathbf{v}' \rangle$ (substantial reduction of the feedback load)
- Similar to the Rx, channel estimation (fine grain tuning of the channel) performed in the transmitter
Feedback Reduction in Massive MIMO

- Multiple receive antennas can be used deliberately for reducing quantization error, saving the required feedback load of the mobile.
- Conventional codebook selection: $\hat{h} = \arg \max_v \langle h, v \rangle$
- Receive combining for improving the codebook quantization error: $\hat{h} = \arg \max_v \max_{\beta_i} \langle \sum_i \beta_i h_i, v \rangle$
Feedback of Massive MIMO - Too massive!

- Effective MISO system achieves substantial capacity improvement over conventional MISO system
Receiver… What should we do?

- Under the finite feedback condition, interuser interference cannot be perfectly removed, causing degradation in SINR
  
  - SINR in imperfect CSIT: \( \text{SINR} = \frac{\frac{P}{N} |h_i^H v_i|}{\sigma_v^2 + \sum_{j \neq i} \frac{P}{M} |h_i^H v_j|} \)

- Same as CDMA systems, interuser interference (and also intercell interference) is major impediment → multiuser detection (MUD) is required for boosting up the SINR

- Additional signalling or classification (feedback information of co-scheduled users or precoder, co-scheduled user’s modulation information) is required for MUD
Summary of Multiple Antenna Technologies

- Multiple antenna techniques have been one of most successful story of wireless communications in the last decade

- Information theoretical concept has been commercialized into the standard (LTE, LTE-Advanced) in a short period of time

- Many exciting challenges exist in multiple antenna systems
Thanks

- Thank you very much for your attention!