Multiple-Input-Multiple-Output (MIMO) Systems

Deke Guo
National University of Defense Technology
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Future trend for wireless communications

- Future wireless applications create insatiability demand for “high data rate” and “high link quality”
- Wireless access spectrum has become a scarce and expensive resource
  - bandwidth is very limited
- Device and system capacity concerns
  - transmit power is limited
- Increases the capacity without extra bandwidth or power cost.
  - MIMO
Multi-input multi-output (MIMO) concept

- **Basic idea** of MIMO: Improve quality (BER) and/or data rate (bits/sec) by using multiple TX/RX antennas
- **Core scheme** of MIMO: space-time coding (STC)
- **Two main functions** of STC: diversity & multiplexing
- Maximum performance needs **tradeoffs** between diversity and multiplexing
Main history of MIMO techniques

- “Spatial diversity
  - Delay diversity: Wittneben, 1991 (inspired); Seshadri & Winters, 1994 (first attempt to develop STC)
  - STTC: Tarokh et al., 1998 (key development of STC)
  - Alamouti scheme: Alamouti, 1998
  - STBC: Tarokh et al., 1998

- Spatial multiplexing
  - First results hint capacity gain of MIMO: Winters, 1987
  - Ground breaking results: Paulraj & Kailath, 1994
  - BLAST: Foschini, 1996
  - MIMO capacity analysis: Telatar 1995; Foschini 1995 & 98
  - Spatio-temporal vector coding for channel with multipath
  - delay spread: Raleigh & Cioffi, 1998
Four basic models

- **Existing Technology**
  - SISO: Single Input/Single Output

- **Smart Antenna Systems**
  - SIMO: Single Input/Multiple Output
  - MISO: Multiple Input/Single Output

- **MIMO Systems**
  - MIMO: Multiple Input/Multiple Output
  - Features:
    - Smart antenna
    - Spatial Multiplexing
SISO System Model

- Single-Input-Single-Output (SISO) antenna system

  Theoretically, the 1Gbps barrier can be achieved using this configuration if you are allowed to use much power and as much BW as you so please!

- Extensive research has been done on SISO under power and BW constraints. A combination of smart modulation, coding et al. techniques have yielded good results but far from the 1Gbps barrier
MIMO System Model

\[ y = Hs + n \]

User data stream
\[ Y \]
\[ s_1 \]
\[ s_2 \]
\[ \cdot \]
\[ \cdot \]
\[ s_M \]
\[ s \]
Transmitted vector
\[ y_1 \]
\[ y_2 \]
\[ \cdot \]
\[ y_M \]
\[ y \]
Received vector

Where \( H = \) a matrix of size \( M_T \times M_R \)

\[ \begin{bmatrix}
    h_{11} & h_{21} & \cdots & h_{M1} \\
    h_{12} & h_{22} & \cdots & h_{M2} \\
    \cdots & \cdots & \cdots & \cdots \\
    h_{1M} & h_{2M} & \cdots & h_{MM}
\end{bmatrix} \]

\( h_{ij} \) is a Complex Gaussian random variable that models fading gain between the \( i \)th transmit and \( j \)th receive antenna.
MIMO Channel Capacity

- Multipath v.s. capacity
  - Multipath propagation has long been regarded as an “impairment” because it causes signal fading
  - To mitigate this problem, diversity techniques were developed
    - Antenna diversity is a widespread form of diversity
  - Recent research has shown that multipath propagation can in fact “contribute” to capacity

*Information theory* has shown that with *multipath propagation*, multiple antennas at both transmitter and receiver can establish essentially *multiple parallel channels* that operate simultaneously, on the same frequency band at the same total radiated power.
Shannon bound for SISO

- Information-theoretic capacity of a single antenna link is limited by the link’s SNR according to Shannon’s formula:

\[ C = \log_2 (1 + \gamma) \text{ (bps/Hz)} \]

- Each extra bps/Hz requires roughly a doubling of TX power (To go from 1 bps/Hz to 11 bps/Hz, the TX power must be increased by ~1000 times!)
MISO and SIMO

- Single TX array: MISO
  - A single array provides transmit diversity against fading
  - Slow logarithmic growth of capacity with no. of antennas

- Single RX array:
  - A single array provides receive diversity against fading
  - Slow logarithmic growth of capacity with no. of antennas SIMO
MIMO

- **Diversity:**
  - Dual array provides diversity at both TX and RX ends
  - Slow logarithmic growth of capacity with no. of antennas

- **Multiplexing**
  - Dual array provides parallel spatial channels
  - Linear growth of capacity with no. of antennas
MIMO Capacity

Channel Capacity

No. of Antenna Elements

linear

MIMO

C = \log_2 \left( \det \left[ I + \frac{\text{SNR}}{M} HH^T \right] \right)

logarithmic

SIMO/MISO

C = \log_2 (1+\text{SNR})
Two popular techniques in MIMO systems

- **Receive and transmit diversity** mitigates fading and significantly improves link quality.
- **Spatial multiplexing** yields substantial increase in spectral efficiency.
Spatial Diversity

- Sending the **dependent** information through different paths, multiple independently-faded replicas of the data symbol can be obtained at the receiver end. Hence, more reliable reception is achieved.
- The maximal diversity gain $d_{max}$ is the total number of independent signal paths between the transmitter and receiver.
- For an $(M_R,M_T)$ system, the total number of signal paths is $M_R M_T$.
- The higher the diversity gain, the lower $P_e$.

![Diagram of ST encoding structure](FIG7) A space-time (ST) encoding structure.
Spatial Diversity

- Number of different symbols transmitted in a symbol period is only one for Alamouti Code
Spatial Multiplexing

Spatial multiplexing concept:

- Form multiple independent links (on same channel) between transmitter and receiver to communicate at higher total data rates
Spatial Multiplexing

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- However, there are cross-paths between antennas
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Spatial multiplexing concept:

- Form multiple independent links (on same channel) between transmitter and receiver to communicate at higher total data rates
- However, there are cross-paths between antennas
- The correlation must be decoupled by digital signal processing algorithms
Spatial Multiplexing
Spatial Multiplexing

- Requires **multiple antennas at both ends** of radio link.
- **Increase in data rate** by transmitting **independent information streams** on different antennas.
- If scattering is **rich enough** (i.e. high rank channel $H$) several **spatial data pipes** are created **within the same bandwidth**.
- **Multiplexing gain** comes at **no extra bandwidth or power**.

Practical System

Channel coding \rightarrow \text{Symbol mapping} \rightarrow \text{Space-Time Coding}

- Redundancy in time
- Coding rate = r_c
- Space-time redundancy over T symbol periods
- Spatial multiplexing gain = r_s

\( r_s \): number of different symbols N transmitted in T symbol periods

\( r_s = N/T \)

** If \( r_s = M_T \), we are in spatial multiplexing

** If \( r_s \leq 1 \), we are in diversity mode
V-BLAST – Spatial Multiplexing
(Vertical Bell Labs Layered Space-Time Architecture)

- This is the only architecture that goes all out for maximum rate.

- Split data into $M_T$ streams $\rightarrow$ maps to symbols $\rightarrow$ send
- Assume receiver knows $H$
- Uses old technique of *ordered successive cancellation* to recover signals
- In one symbol period, sending $M_T$ different symbols
Linear precoding

- Precoding is a processing technique that exploits CSIT by operating on the signal before transmission.
- A linear precoder is optimal from an information theoretic view point. It splits the transmit signal into orthogonal spatial eigenbeams and assigns higher power along the beams where the channel is strong but lower or no power along the weak.

- Equal beam power

- Unequal beam power
Precoding System Structure

[FIG5] An optimal configuration for exploiting CSIT.

[FIG8] A linear precoder structure as a multimode beamformer.
Linear precoding

- Let the singular value decomposition (SVD) of the channel be $H = U_H \Sigma V_H^*$. $M$ be $V_H$ and $W$ be $U_H^*$.
- Multiplying the signal at the transmitter with $M$, in which each column is referred to as a transmitting weight vector for a symbol of $x$.
- Multiplying the signal at the receiver with $W$, in which each row is referred as a receiving weight vector.

$$z = W(HMx + a),$$
Multi-user MIMO systems

- Broadcast channel (BC): down link
- Multiple-access channel (MAC): up link
TDMA-based multiplexing

- TDMA-based multiplexing: scheduling
  - In this setting, MIMO enhances the potential network throughput via spatial multiplexing by achieving high data rates.
Spatial reuse

- Spatial reuse of the spectrum: allowing multiple simultaneous communications at the same time slot and vicinity.
Spatial reuse

- Each MIMO link only employs partial degree-of-freedoms to transmit and receive data streams.
  - Stream control: best degree-of-freedoms are selected for data transmissions, while others at the receiver are used to suppress interfering data streams
  - Interference avoidance: the transmitter selects appropriate degree-of-freedoms to transmit data streams such that the remaining degree-of-freedoms can null its data streams at undesired active receivers.
Stream Control

- If stream control and spatial multiplexing transmit the same number of data streams, stream control outperforms spatial multiplexing in terms of the network throughput.
- Although a MIMO channel can be decomposed into multiple parallel sub-channels, their capacities have quite large disparities for moderate or low SNR.
Exploiting Spatial Reuse in Multi-hop MIMO Networks

- Receiver-oriented interference suppression model (ROIS)
  - Each MIMO link with data to be transmitted is scheduled by stream control first, or by interference avoidance if stream control cannot assign the smallest time slot to it.
Performance evaluation

- The impact of number of antennas at each terminal under distributed algorithms.
Performance evaluation

- The impact of average hop length under distributed algorithms
Performance evaluation

- The impact of interference range under distributed algorithms.
Summary/Conclusions

- Point-to-Point MIMO Systems
- Multi-user MIMO systems
- Multi-hop MIMO networks