ECE/CS 707
Mobile and Wireless Networking

Introduction to MIMO

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Today’s agenda

• Overview of MIMO communications
• Single-user MIMO
• Multi-user MIMO
• Network MIMO
MIMO: an Overview

- MIMO (Multiple-Input Multiple-Output)
  - Transmitter/receiver can have multiple antennas
  - A modern wireless communication technology
    - Theory: late 1980’s
    - Standards and products: after 2000’s
    - Now: core feature in WLAN (802.11 WiFi) and cellular (3G LTE, WiMax)
  - Two benefits, simply put
    - Improve link SINR
    - Improve link concurrency
MIMO: an Overview

- **MIMO network architectures**
  - Single-user MIMO (in 802.11n-2009, LTE)
    * One TX, one RX. Either TX or RX or both can have multiple antennas
  - Multi-user MIMO (in 802.11ac-2014, LTE-Advanced)
    * One TX, multiple RX. Parallel transmissions.
  - Network MIMO (expected in near-future)
    * Multiple TX, multiple RX. Parallel transmissions.
Single-user MIMO

- Basic communication modes

- **SISO**
  - Single Input Single Output
  - Single data stream

- **MISO**
  - Multiple Input Single Output
  - Single data stream

- **SIMO**
  - Single Input Multiple Output
  - Single data stream

- **MIMO**
  - Multiple Input Multiple Output
  - Multiple data streams
MIMO benefits: an audio metaphor

- **SISO**
- **SIMO**
- **MISO**
- **MIMO**

Song

Song1

Song2
Single-user MIMO benefits: capacity gains

- Diversity gain
  - Receiver diversity
  - Transmit diversity

- Multiplexing gain
  - Spatial multiplexing
Receiver diversity

- Receiver coherently combines signals received by multiple antennas

- Asymptotic gain: Increasing SNR proportionally to Nr (#of receive antennas)
  * Intuition: received signal power adds up

- What’s the capacity gain?
  * Logarithmically, according to Shannon’s equation: \( C = B \log(1+\text{SNR}) \)
  * When SNR is low, \( \log(1+\text{SNR}) \approx \text{SNR} \), so gain is almost linear w.r.t. Nr
Implementing receiver diversity

* Selection combining

\[ \text{Improves SNR to} \quad \text{avg}SNR \cdot \left(1 + \frac{1}{2} + \ldots + \frac{1}{N_r}\right) \]

* Maximum Ratio combining

\[ \text{Improves SNR to} \quad \sum_{i=1}^{N_r} SNR_i \]
Multiple receive antennas allow compensation of by non-notches in the other
Transmitter diversity

- Transmitter sends multiple versions of the same signal, through multiple antennas

- Two modes of transmit diversity
  * Open-loop transmit diversity
  * Closed-loop transmit diversity
Open-loop transmit diversity

- **Principle**
  - Send redundant versions of the same signal (symbol), over multiple time slots, and through multiple antennas
  - Encode the symbols differently for different time slots and TX antennas
    - Space-Time Block Code (STBC)
Open-loop transmit diversity

- Example: 2 TX antenna STBC
  - Send two data symbols, $s_1$ and $s_2$

Time slot 1:

- Received signals:

\[ r(t_1) = h_1 s_1 + h_2 s_2 \]

\[ r(t_2) = -h_1 s_2^* + h_2 s_1^* \]
Open-loop transmit diversity

- Example: 2 TX antenna STBC
  - Diversity combining
    \[ y_1 = h_1^* r(t_1) + h_2 r(t_2) = (|h_1|^2 + |h_2|^2)s_1 \]
  - i.e., signal power is boosted from \(|h_1|^2\) to \(|h_1|^2 + |h_2|^2\)
  - Open-loop transmit diversity gain:
    In general, open-loop transmit diversity increases SNR \textbf{linearly} with the number of transmit antennas
  - What’s the capacity gain?
Closed-loop transmit diversity

- **Principle**
  - Send redundant versions of the same signal (symbol), over the same time slot
  - Encode the symbols differently for different TX antennas
    - i.e., weight the symbols on different antennas, following a precoding algorithm
    - Precoding design requires feedback of channel state information (CSI)
Closed-loop transmit diversity

- Why precoding?
  - Signals from different antennas need to sync (align) their phases
  - But the different channels (between TX antennas and RX antenna) distort signals differently, causing phase offset

* e.g., both TX antennas sends $x = e^{j2\pi f t}$; RX may receive $e^{j2\pi f t}$ one TX antenna, but $e^{j(2\pi f + \pi)}$ from the other, which weaken each other!
Closed-loop transmit diversity

- How does precoding help?
  
  - Precoding: TX compensates the phase offset, and aligns the phases of signals going through different channels

- Why CSI feedback is needed for precoding?
  
  * TX must know the phase offset, in order to perform compensation
Closed-loop transmit diversity

- Asymptotic gain from closed-loop transmit diversity
  - Signal level combining, also called transmit beamforming
    * Suppose we have 2 transmit antennas, then instead of $x$, we receive: $x + x = 2x$, received power becomes $4 |x|^2$, SNR increases to 4 times!
    * More generally, with $N_t$ TX antennas, SNR increases to $N_t^2$
    * What’s the capacity gain?
Spatial multiplexing

- Spatial multiplexing concept
  - Form multiple independent links (on the same spectrum band) between TX and RX, and send data in parallel through them
  - Unfortunately, there is cross-talk between antennas
  - Cross-talk must be removed by digital signal processing algorithms
Spatial multiplexing: signal processing

- **Example 2x2 MIMO spatial multiplexing**
  - Data to be sent over two TX antennas: $x_1, x_2$
  - Data received on two RX antennas:
    
    $y_1 = h_{11}x_1 + h_{12}x_2$
    
    $y_2 = h_{21}x_1 + h_{22}x_2$

* Channel distortions: $h_{**}$ can be estimated by the receiver
* Only two unknowns: $x_1, x_2$, easily obtained by solving the equations!
Spatial multiplexing gain

- Asymptotic gain
  - In general, capacity gain from spatial multiplexing scales linearly with
    \[ \min(N_t, N_r) \]

- In practice
  - Spatial multiplexing gain also depends on channel “condition”
    * If the channels between different antennas are correlated, e.g., \( h_{**} \) are all the same, then you can’t solve the equations. Spatial multiplexing becomes infeasible!
    * Channel condition can be profiled using “condition number” (see reference)
  
  - Practical wireless devices’ multiple antennas are separated sufficiently far (further than half-wavelength), so the channel is usually uncorrelated
**Concept of Multi-User MIMO (MU-MIMO)**

* Single-antenna network

* Multi-user MIMO

* MU-MIMO enables multiple streams of data to be sent to different users in parallel, without cross-talk interference
Multi-user MIMO: how does it work?

- MU-MIMO differs from traditional MIMO
  - Data to be sent over two TX antennas: $x_1, x_2$
  - Data received on two RX nodes:
    \[
    y_1 = h_{11}x_1 + h_{12}x_2 \\
    y_2 = h_{21}x_1 + h_{22}x_2
    \]
  - Each RX only has one equation, but two variables; no way to solve it directly
    * $x_2$ causes cross-talk interference to $x_1$, and vice versa
Multi-user MIMO: how does it work?

How to remove cross-talk?

- Send a weighted mix of x1 and x2
  - TX antenna1 sends: $w_{11}x_1 + w_{12}x_2$
  - TX antenna2 sends: $w_{21}x_1 + w_{22}x_2$

- Data received on RX1:
  $$y_1 = h_{11}(w_{11}x_1 + w_{12}x_2) + h_{12}(w_{21}x_1 + w_{22}x_2)$$
  $$= (h_{11}w_{11} + h_{12}w_{21})x_1 + (h_{11}w_{12} + h_{12}w_{22})x_2$$

- RX1 only wants x1, so ideally, we should have $(h_{11}w_{12} + h_{12}w_{22}) = 0$
Multi-user MIMO: how does it work?

- **MU-MIMO precoding**
  - TX can obtain $h_{11}, h_{12}$ from RXs’ feedback, so it can tune $w_{12}, w_{22}$ to satisfy $(h_{11}w_{12} + h_{12}w_{22}) = 0$
    * This cancels the cross-talk interference from x2 to x1
    * Similarly, we can cancel that from x1 to x2
    * This is called Zero-Forcing Beamforming (ZFBF)

- **How does TX obtain channel state information $h^{**}**
  * Simplest approach in 802.11ac: CSI feedback scheduling

![Diagram of TX and RX interactions with time axis](image)
MU-MIMO capacity gain

- Asymptotic capacity gain
  - If the transmitter has $N_t$ antennas, then it can send $N_t$ streams of data simultaneously to $N_t$ users, increasing capacity to $N_t$ times compared with single-antenna transmitter

- Limitation
  - MU-MIMO is essentially a form of spatial multiplexing
  - So the channel must be well-conditioned
Limitations of existing MIMO architectures

- Only one transmitter at a time
- Simultaneous transmission from different transmitters causes collision!
- So network capacity doesn’t scale with transmitter density
A giant-MIMO comprised of many APs

- APs are tightly synchronized and share data
- Mutual interference can be cancelled
- Asymptotic gain: Network capacity scales linearly with the number of APs, theoretically
Is network MIMO practical?

A super-giant-MIMO solution?

APs need:
- Full synchronization: carrier phase, frequency, sampling-clock
- Full data sharing: large volumes of data and CSI exchange

Infeasible!
NEMOx: making network MIMO scalable

“A hierarchical architecture to realize scalable network MIMO

- **Intra-cluster**: dAPs within each cluster can TX concurrently
- **Inter-cluster**: neighboring clusters contend for channel access
- **Capacity can scale with #of dAPs within each cluster, and with #of clusters** (capacity ≈ 6 in this case)
Summary

• Take-home message:
  (1) What are the various modes of operations in MIMO?
  (2) How does each MIMO mode scale link/network capacity?

• References:
  * Book1: Fundamentals of LTE
  * Book2: Fundamentals of Wireless Communications