Wireless Networks

Lecture 19: MIMO

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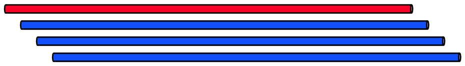
Increasing Capacity: MIMO

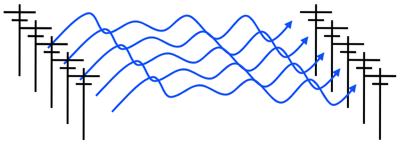
- Refresher: spatial diversity
- Multiple-In Multiple-Out basics
- MIMO in 802.11:
  - Single user MIMO: 802.11n
  - Multi user MIMO: 802.11ac

How Do We Increase Throughput in Wireless?

- **Wired world:**

Pull more wires!

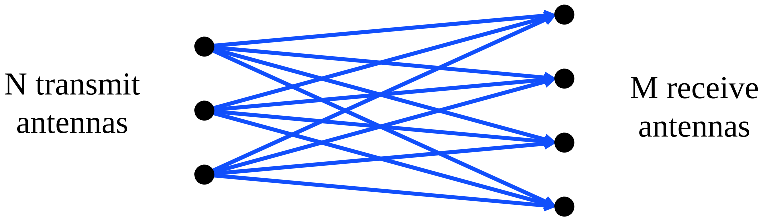




- **Wireless world:**

How about if we could do the same thing and simply use more antennas?

MIMO
Multiple In Multiple Out



N transmit antennas

M receive antennas

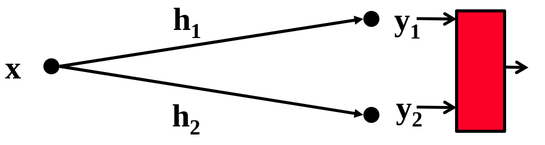
- **N x M subchannels that can be used to send multiple data streams simultaneously**
- **Fading on channels is largely independent**
  - » **Assuming antennas are separate ½ wavelength or more**
- **Combines ideas from spatial and time diversity, e.g. 1 x N and N x 1**
- **Very effective if there is no direct line of sight**
  - » **Subchannels become more independent**

Why So Exciting?

Method	Capacity
SISO	$B \log_2(1 + \rho)$
Diversity (1xN or Nx1)	$B \log_2(1 + \rho N)$
Diversity (NxN)	$B \log_2(1 + \rho N^2)$
Multiplexing	$NB \log_2(1 + \rho)$

Spatial Diversity

- Use multiple antennas that pick up the signal in slightly different locations
  - » Channels uncorrelated with sufficient antenna separation
- Receiver diversity: i x H x P_R = o



$$\vec{y} = \vec{h} * x + \vec{n}$$

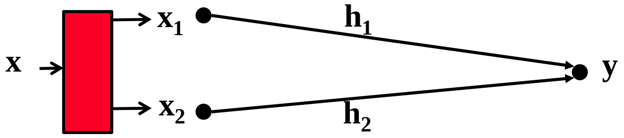
$$y = \vec{h}^* * (h * \vec{x} + \vec{n})$$

- Receiver can pick strongest signal: y_1 or y_2
- Or combines the signals: multiply y with the complex conjugate h^* of the channel vector h
  - » Can learn h based on training data

Other Diversity Options

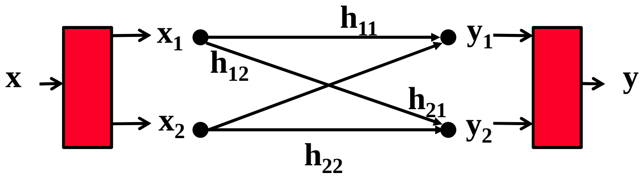
- **Transmit diversity:**

$i \ \text{x} \ P_T \quad \text{x} \quad H \quad = \ o$



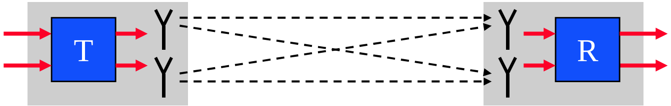
- **Combined:**

$i \ \text{x} \ P_T \quad \text{x} \quad H \ \text{x} \quad P_R \quad = \ o$



MIMO
How Does it Work?

- **Transmit and receive <u>multiple data streams</u>**
- **Coordinate the processing at the transmitter and receiver to overcome channel impairments**
  - **Maximize throughput or minimize interference**



$I \ \text{x} \ P_T \quad \text{x} \quad H \quad \text{x} \quad P_R \ = \ O$

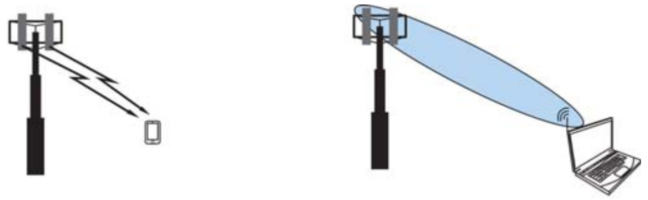
↑ Precoding

↑ Channel Matrix

↑ Combining

- **Combines previous techniques**

Mechanisms Supported by MIMO



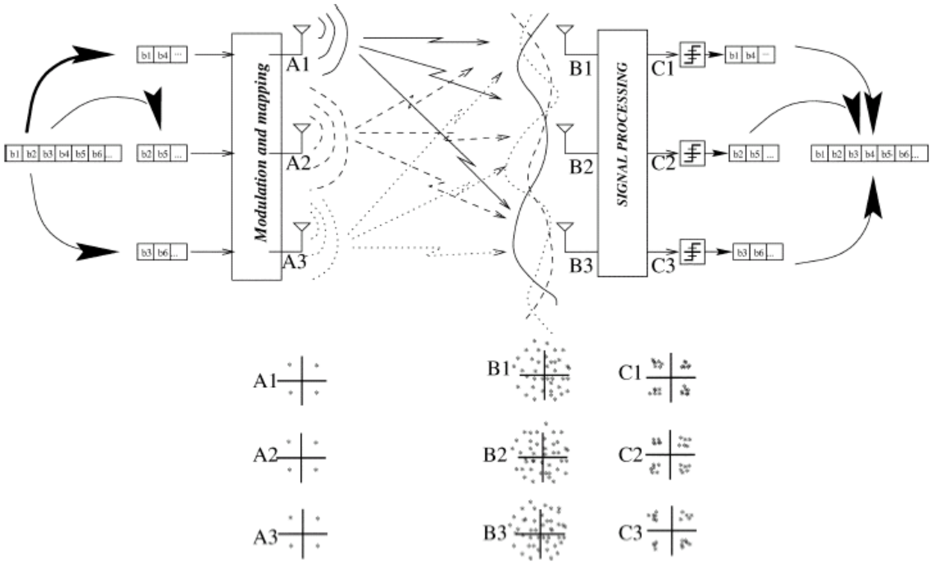
Diversity for improved system performance

Beam-forming for improved coverage (less cells to cover a given area)

Spatial division multiple access ("MU-MIMO") for improved capacity (more user per cell)

Multilayer transmission ("SU-MIMO") for higher data rates in a given bandwidth

An Example of Space Coding



Direct-Mapped NxM MIMO

Effect of transmission $\overset{M}{\vec{R}} = \overset{\text{MxN}}{H} * \overset{N}{\vec{C}} + \overset{M}{\vec{N}}$

Decoding $\underset{D}{\vec{O}} = \underset{\text{DxM}}{P_R} * \underset{M}{\vec{R}}$ $\quad \underset{N}{\vec{C}} = \underset{N}{\vec{I}}$

Results $\vec{O} = P_R * H * \vec{I} + P_R * \vec{N}$

- How do we pick P_R ? “Inverse” of H: H^{-1}
  - Equivalent of nulling the interfering possible (zero forcing)
  - Only possible if the paths are completely independent
- Noise amplification is a concern if H is non-invertible – its determinant will be small
  - Minimum Mean Square Error detector balances two effects

Precoded NxM MIMO

Effect of transmission $\overset{M}{\vec{R}} = \overset{\text{MxN}}{H} * \overset{N}{\vec{C}} + \overset{M}{\vec{N}}$

Coding/decoding $\underset{D}{\vec{O}} = \underset{\text{DxM}}{P_R} * \underset{M}{\vec{R}}$ $\quad \underset{N}{\vec{C}} = \underset{\text{NxD}}{P_T} * \underset{D}{\vec{I}}$

Results $\vec{O} = P_R * H * P_T * \vec{I} + P_R * \vec{N}$

- How do we pick P_R and P_T ?
- Singular value decomposition of H = U * S * V
  - U and V are unitary matrices – U^H*U = V^H*V = I
  - S is diagonal matrix

MIMO Discussion

- Need channel matrix H: use training with known signal
- So far we have ignored multi-path
  - Each channel is multiple paths with different properties
  - Becomes even messier!
- MIMO is used in 802.11n
  - Can use two adjacent non-overlapping “WiFi channels”
  - Raises lots of compatibility issues
  - Potential throughputs of 100s of Mbps
- Focus is on maximizing throughput between two nodes
  - Is this always the right goal?

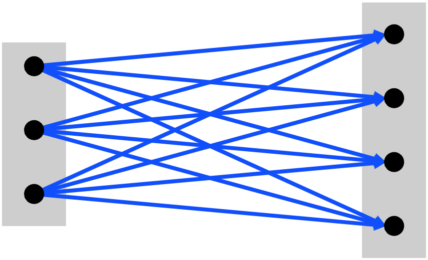
802.11n Overview

- 802.11n extends 802.11 for MIMO
  - Supports up to 4x4 MIMO
  - Preamble that includes high throughput training field
- Standardization was completed in Oct 2009, but, early products have long been available
  - WiFi alliance started certification based on the draft standard in mid-2007
- Supported in both the 2.4 and 5 GHz bands
  - Goal: typical indoor rates of 100-200 Mbps; max 600 Mbps
- Use either 1 or 2 non-overlapping channels
  - Uses either 20 or 40 MHz
  - 40 MHz can create interoperability problems
- Supports frame aggregation to amortize overheads over multiple frames
  - Optimized version of 802.11e

802.11n
Backwards Compatibility

- 802.11n can create interoperability problems for existing 802.11 devices (abg)
  - 802.11n does not sense their presence
  - Legacy devices end up deferring and dropping in rate
- Mixes Mode Format protection embeds an n frame in a g or a frame
  - Preamble is structured so legacy systems can decode header, but MIMO can achieve higher speed (training, cod/mod info)
  - Works only for 20 MHz 802.11n use
  - Only deals with interoperability with a and g – still need CTS protection for b
- For 40 MHz 802.11n, we need CTS protection on both the 20 MHz channels – similar to g vs. b
  - Can also use RTS/CTS (at legacy rates)
  - Amortize over multiple transmissions

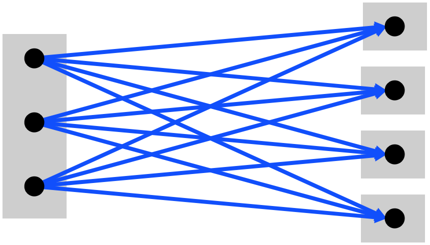
MIMO in a Network Context



N transmit antennas

M receive antennas

How is this Different?

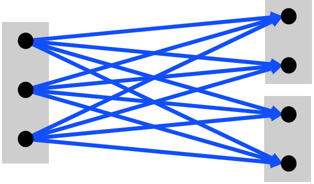


N transmit antennas

M receive antennas
-
M receivers

Multi-User MIMO
Discussion

- Math is similar to MIMO, except for the receiver processing (P_R)
  - » Receivers do not have access to the signals received by antennas on other nodes
  - » Limits their ability to cancel interference and extract a useful data stream
  - » Closer to transmit MRC
- MU-MIMO versus MIMO is really a tradeoff between TDMA and use of space diversity
  - » Sequential short packets versus parallel long packets



- Why not used in 802.11?

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Multi-User MIMO
Up versus Down Link

- Uplink: Multiple Access Channel (MAC)
  - » Multiple clients transmit simultaneously to a single base station
  - » Requires coordination among clients on packet transmission – hard problem because very fine-grained
- Downlink: Broadcast Channel (BC)
  - » Base station transmit separate data streams to multiple independent users
  - » Easier to do: closer to traditional models of having each client receive a packet from the base station independently

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802.11ac
Multi-user MIMO

- Extends beyond 802.11n
  - MIMO: up to 8 x 8 channels (vs. 4 x 4)
  - More bandwidth: up to 160 MHz by bonding up to 8 channels (vs. 40 MHz)
  - More aggressive signal coding: up to 256 QAM (vs. 64 QAM); both use 5/6 coding rate (data vs. total bits)
  - Uses RTS-CTS for clear channel assessment
  - Multi-gigabit rates (depends on configuration)
- Support for multi-user MIMO on the downlink
  - Can support different frames to multiple clients at the same time
  - Especially useful for smaller devices, e.g., smartphones
  - Besides beam forming to target signal to device, requires also nulling to limit interference

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802.11ad
60 GHz WiFi

- Uses a new physical layer definition specifically for 60 GHz band
  - Very different signal propagation properties
  - Does not penetrate walls, but does work with reflections
  - Shorter distances
  - Small antennas and good beamforming properties
- Defined up to 7 Gbps
- Has been used for point-point links for a while
  - APs now available
  - Combined with other 802.11 versions
  - 802.11ad only available for short distances