18-759 : Wireless Networks
Lecture 7: MIMO, UWB

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Outline

- RF introduction
- Modulation and multiplexing
- Channel capacity
- Antennas and signal propagation
- Equalization and diversity
- Modulation and coding
- Some newer technologies
  » MIMO
  » UWB
- Spectrum access

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: use more antennas?
MIMO
Multiple In Multiple Out

- N x M subchannels
- 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?

<table>
<thead>
<tr>
<th>Method</th>
<th>Capacity</th>
</tr>
</thead>
<tbody>
<tr>
<td>SISO</td>
<td>$B \log_2(1 + \rho)$</td>
</tr>
<tr>
<td>Diversity (1xN or Nx1)</td>
<td>$B \log_2(1 + \rho N)$</td>
</tr>
<tr>
<td>Diversity (NxN)</td>
<td>$B \log_3(1 + \rho N^2)$</td>
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<tr>
<td>Multiplexing</td>
<td>$NB \log_2(1 + \rho)$</td>
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Spatial Diversity

- Use multiple antennas that pick up the signal in slightly different locations
  » Channels uncorrelated with sufficient antenna separation
- Example: receiver diversity
  \[ y = h^* x + n \]
- Receiver can pick strongest signal: $y_1$ or $y_2$
- Or it combines the two signals: multiply $\bar{y}$ with the complex conjugate $h^*$ of the channel vector $h$
  » Can learn $h$ based on training data

Other Diversity Options

- Transmit diversity:
  \[ y = \bar{h}^* x + n \]
- Combined
Transmit and Receive Diversity Revisited

- Receive diversity:
  $$Y^x_i H x P_R = 0$$

- Transmit diversity:
  $$Y x P_T x H = 0$$

MIMO How Does it Work?

- Transmit and receive multiple data streams
- Coordinate the processing at the transmitter and receiver to overcome channel impairments
  » Maximize throughput or minimize interference

- Combines previous techniques

Mechanisms Supported by MIMO

- Diversity for improved system performance
- Beam-forming for improved coverage (few cells to cover a given area)
- Spatial division multiple access ("NI-MIMO") for improved capacity (more bits per cell)
- Multilayer transmission ("SU-MIMO") for higher data rates in a given bandwidth

An Example of Space Coding
A Math View

- Transmitted Code Vector:
  \[ c_I = [c_1(i), c_2(i), \ldots, c_N(i)]^T \]

- Channel Matrix:
  \[ H = \begin{bmatrix}
  \alpha_{11} & \alpha_{12} & \cdots & \alpha_{1M} \\
  \alpha_{21} & \alpha_{22} & \cdots & \alpha_{2M} \\
  \vdots & \vdots & \ddots & \vdots \\
  \alpha_{M1} & \alpha_{M2} & \cdots & \alpha_{MM}
\end{bmatrix} \]

- Received Signal Vector:
  \[ r(I) = H \cdot c_I + n(I) \]

Direct-Mapped NxM MIMO

Effect of transmission
\[ \hat{R} = H \cdot \hat{C} + \hat{N} \]

Decoding
\[ \hat{O} = P_R \cdot \hat{R} \quad \hat{C} = \hat{I} \]

Results
\[ \hat{O} = P_R \cdot H \cdot \hat{I} + P_R \cdot \hat{N} \]

- 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

Precoded NxM MIMO

Effect of transmission
\[ \hat{R} = H \cdot \hat{C} + \hat{N} \]

Coding/decoding
\[ \hat{O} = P_R \cdot \hat{R} \quad \hat{C} = P_T \cdot \hat{I} \]

Results
\[ \hat{O} = P_R \cdot H \cdot P_T \cdot \hat{I} + P_R \cdot \hat{N} \]

- How do we pick \( P_R \) and \( P_T \)?
- Singular value decomposition of \( H = U \cdot S \cdot V \)
  - \( U \) and \( V \) are unitary matrices – \( U^H \cdot U = V^H \cdot V = I \)
  - \( S \) is diagonal matrix
- Set \( P_R \) and \( P_T \) to \( U^H \) and \( V^H \)
  - Similar to approach for transmit and receive MRC
- Equations suggest that we can view MIMO as a set of independent paths with strength given by the singular values of \( S \)
  - Suggests giving more power to the stronger paths
  - Water filling algorithm allocates power while maximizing throughput
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 - will get back to this later!
- 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

How is this Different?
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?

802.11ac Multi-user MIMO

- Extends beyond 802.11n
  - 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)
  - MIMO: up to 8 x 8 channels (vs. 4 x 4)
  - Uses RTS-CTS for clear channel assessment
  - Multi-gigabit rates (depends on configuration)
- Support for multiuser 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

Multi-User MIMO in Practice

- 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

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
  - ad only available for short distances
Ultra WideBand

\[ C = B \log_2(1 + \text{SNR}) \]

- Can achieve high throughputs with low SNR by using a high B
- Motivation is the 802.15.3a (high rate PAN) standards effort
  - Targets high speed, short distance communication
- But where do I find this much spectrum?
- Use a transmit power that is low enough so it will not affect other users
  - Can be used in most licensed frequency bands (with FCC permission, of course)

FCC UWB Rules

- UWB technically defined as:
  - Width of signal > 500 MHz, or
  - \[ B_1 = 2 \frac{f_2 - f_1}{f_1 + f_2} > 0.2 \]

- Approved for 3.1 GHz to 10.6 GHz
- Power limit is -41.3 dBm/MHz
  - Note that the limit is not on the total signal but across the part of the spectrum that is used
- Results in a frequency mask that must be satisfied
- Certain narrow bands must be filtered out
  - E.g. certain radio astronomy bands
  - Depends on the country

FCC Regulations

Basic Impulse Information Modulation

Pulse length ~ 200ps; Energy concentrated in 2-6GHz band;
Voltage swing ~100mV; Power ~ 10uW

- Pulse Position Modulation (PPM)
- Pulse Amplitude Modulation (PAM)
- On-Off Keying (OOK)
- Bi-Phase Modulation (BPSK)
Multi-band OFDM

- Divide the spectrum into bands of 528 MHz.
  - Transmitter and receiver process smaller bandwidth signals.
  - Can spread symbols across multiple bands (FH)
  - Can avoid bands based on local regulations

- Use of OFDM offer additional advantages
  - Proven technology that is known to be efficient
  - Can selectively disable subcarriers to protect narrow band signals
  - For example: 128 tones of 5.125 MHz

So why is UWB so interesting?

- 7.5 Ghz of “free spectrum” in the U.S.
  - FCC recently legalized UWB for commercial use
  - Spectrum allocation overlays existing users, but its allowed power level is very low to minimize interference

- Very high data rates possible
  - 500 Mbps can be achieved at distances of 10 feet under current regulations

- Simple CMOS transmitters at very low power
  - Suitable for battery-operated devices
  - Low power is CMOS friendly
  - “Moore’s Law Radio” – Data rate scales with the shorter pulse widths made possible with ever faster CMOS circuits

- Low cost
  - Nearly “all digital” radio?
  - Integration of more components on a chip (antennas?)

General Frequency Ranges

- Microwave frequency range
  - 1 GHz to 40 GHz and higher
  - Directional beams possible
  - Suitable for point-to-point transmission
  - Used for satellite communications

- Radio frequency range
  - 30 MHz to 1 GHz
  - Suitable for omnidirectional applications

- Infrared frequency range
  - Roughly, 3x10^{11} to 2x10^{14} Hz
  - Useful in local point-to-point multipoint applications within confined areas

Wireless Communication Looks Pretty Easy?

- 300 GHz is huge amount of spectrum!
  - Spectrum can also be reused in space

- Not quite that easy:
  - Most of it is hard or expensive to use!
  - Noise and interference limits efficiency
  - Most of the spectrum is allocated by FCC

- FCC controls who can use the spectrum and how it can be used.
  - Need a license for most of the spectrum
  - Limits on power, placement of transmitters, coding, ..
  - Need rules to optimize benefit: guarantee emergency services, simplify communication, return on capital investment, ...
  - National Telecommunications and Information Agency (NTIA) for federal agencies
## Spectrum Allocation


- Most bands are allocated
- Industrial, Scientific, and Medical (ISM) bands are “unlicensed”
  - But still subject to various constraints on the operator, e.g. 1 W output
  - 433-868 MHz (Europe)
  - 902-928 MHz (US)
  - 2.4000-2.4835 GHz
- Unlicensed National Information Infrastructure (UNII) band is 5.725-5.875 GHz

## Different Ways of Controlling Access to Bands

- In licensed spectrum, users need a license to use that part of the spectrum
  - Cellular, radio/TV broadcast, various federal agencies
  - License typically provides exclusive use, i.e. license holder has full control over spectrum use in the band
  - Commercial entities often pay for the license, e.g. through an auction
- In unlicensed spectrum, no user license is required
  - Various constraints are placed on the radio to improve coexistence between users
    - E.g. transmit power, modulation, MAC, ...
  - Devices must be licensed

## Spectrum Use is Limited

- Most of the spectrum is mostly unused most of the time
  - E.g. 17% of spectrum used below 2 GHz in Manhattan during republican convention
  - Only a few frequencies see heavy use regularly, e.g. unlicensed, cellular
- Efforts to make spectrum use more dynamic and efficient
  - Opportunistic users, secondary markets, etc.

Snapshot of utilization of 700 MHz slice of spectrum below 1 GHz