18-452/18-750
Wireless Networks and Applications
Lecture 14: MIMO and WiFi Deployments

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Fall Semester 2018

http://www.cs.cmu.edu/~prs/wirelessF18/

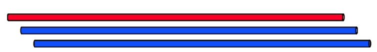
Outline

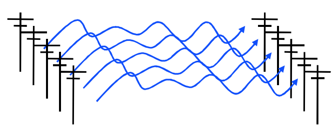
- MIMO and recent WiFi versions
  - » Refresher: spatial diversity
  - » MIMO basics
  - » Single user MIMO: 802.11n
  - » Multi-user MIMO: 802.11ac
  - » Millimeter wave: 802.11ad
- WiFi deployments
  - » Planning
  - » Channel selection
  - » Rate adaptation

How Do We Increase Throughput in Wireless?

- Wired world:

Pull more wires!

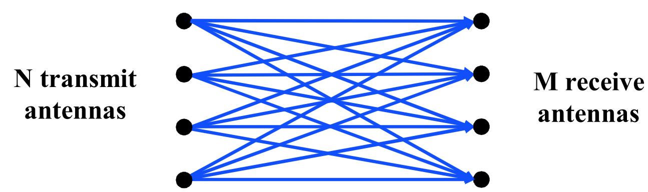




- Wireless world:

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

MIMO
Multiple In Multiple Out



- N 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

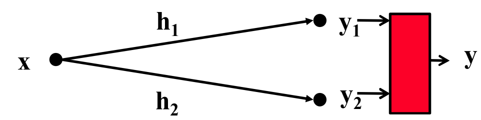
Why So Exciting?

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	$NB \log_2(1 + \rho)$

802.11 with multiple antennas for dummies, Daniel Halperin, Wenjun Hu, Anmol Sheth, David Wetherall, ACM CCR, Jan 2010

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



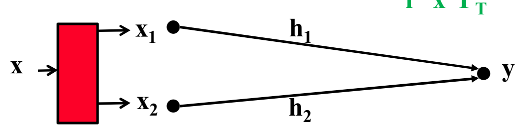
$\vec{y} = \vec{h} * x + \vec{n}$

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

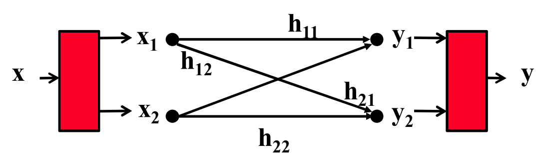
- Receiver can pick strongest signal: y_1 or y_2
- Or combines the signals: multiply $\vec{y}$ with the complex conjugate h^* of the channel vector h
  - » Can learn h based on training data (Lecture 5)

Other Diversity Options

- Transmit diversity: i x P_T x H = o

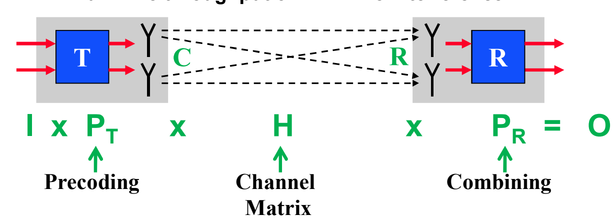


- Combined: i x P_T x H x P_R = o



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



- Combines previous techniques

Direct-Mapped NxM MIMO Only Receiver Processing (P_T=I)

Effect of transmission

M MxN N M

$$\vec{R} = H * \vec{C} + \vec{N}$$

Decoding

$$\vec{O} = P_R * \vec{R} \qquad \vec{C} = \vec{I}$$

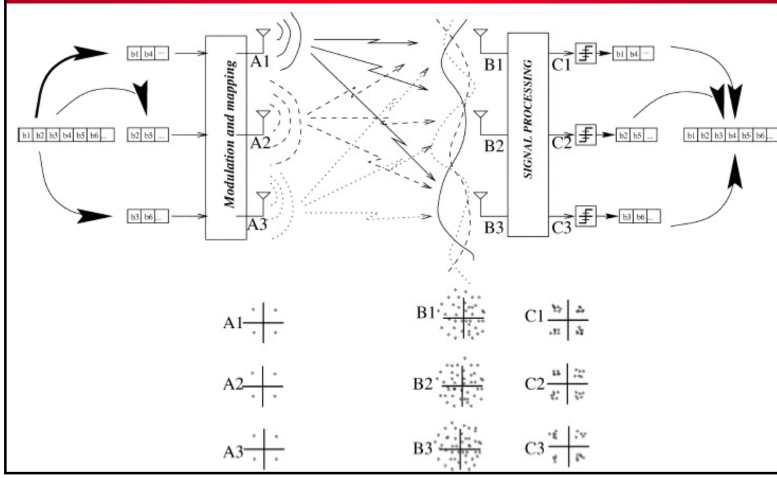
D DxM M N N

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 signals (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

An Example of Space Coding



Precoded NxM MIMO

Effect of transmission

M MxN N M

$$\vec{R} = H * \vec{C} + \vec{N}$$

Coding/decoding

$$\vec{O} = P_R * \vec{R} \qquad \vec{C} = P_T * \vec{I}$$

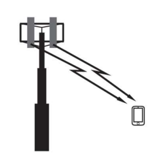
D DxM M N NxD D

Results

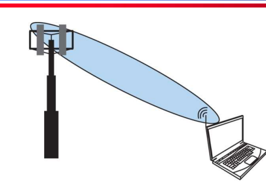
$$\vec{O} = P_R * H * P_T * \vec{I} + P_R * \vec{N}$$

- 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

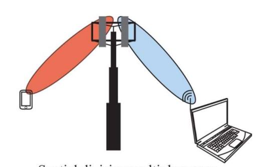
Mechanisms Supported by MIMO



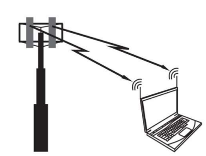
Diversity for improved system performance



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

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

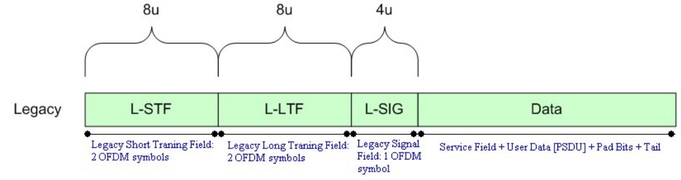
- 802.11n extends 802.11 for MIMO
  - » Supports up to 4x4 MIMO
  - » Preamble that includes high throughput training field
- Standardization was completed in Oct 2009, but, early products had long been available
  - » WiFi alliance started certification based on the draft standard in mid-2007
- Supported 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

Interoperability Uses PLC in Three Modes

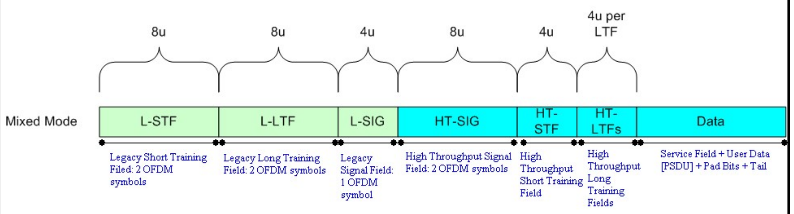
- Legacy mode: use 802.11a/g OFDM format
  - » The L-SIG field contains rate and length information



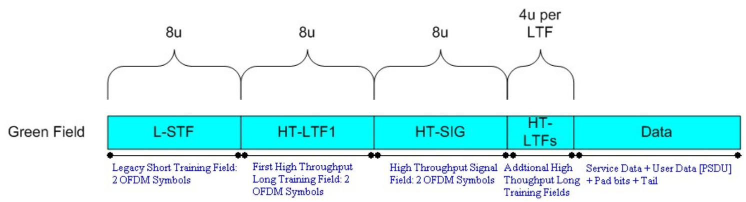
- Mixed mode:
  - » Include both an 802.11a/g and 802.11n PLC
  - » See next slide for figure
  - » 802.11n devices can interpret green field, which includes the L-SIG field (rate and length information)

 http://rfmw.em.keysight.com/wireless/helpfiles/n7617a/mimo_ofdm_signal_structure.htm

Interoperability: High Throughput (HT) Modes



- Green field mode: use 802.11n OFDM format



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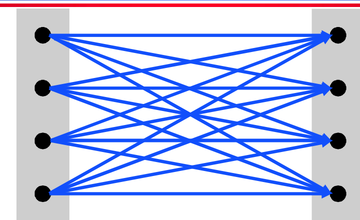
MIMO in a Network Context

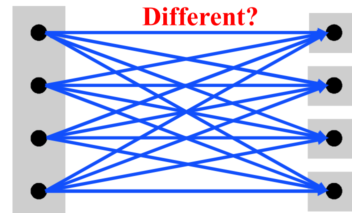
N transmit antennas



M receive Antennas - 1 receiver

How is this Different?

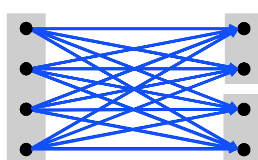
N transmit antennas



M receive antennas - M receivers

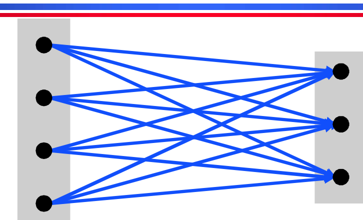
Multi-User MIMO Discussion

- 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
  » Cannot cancel interference – limits ability to extract useful data
  » Can only do transmit-side preprocssing
- MU-MIMO versus MIMO is really a tradeoff between TDMA and use of space diversity
  » MIMO: send packets to two destinations sequentially and efficiently
  » MU-MIMO: send packet to destination simultaneously, but interference cancelation is limited



How about This?

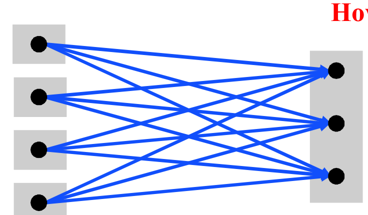
N transmit antennas



M receive Antennas - 1 receiver

How is this Different?

N transmit antennas



M receive antennas - M receivers

Multi-User MIMO
Up versus Down Link

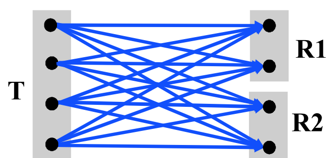
- Assume one AP with multiple clients
- Downlink: Broadcast Channel (BC)
  - Base station transmit separate data streams to multiple independent users
  - Easier to do: close to the traditional CSMA-CA model of having each client receive a packet from the base station independently
- Uplink: Multiple Access Channel (MAC)
  - Multiple clients transmit simultaneously to a single base station
  - Requires fine grain clock coordination among clients on packet transmission – hard problem!
  - Not a good for the traditional CSMA-CA protocol

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

Challenges in 802.11ac

- You must have traffic for multiple receivers!
- Channels to the receivers be "orthogonal"



$$R1: \quad O_1 = P_{R1} * H_1 * P_T * I + P_{R1} * N$$
$$R2: \quad O_2 = P_{R2} * H_2 * P_T * I + P_{R2} * N$$

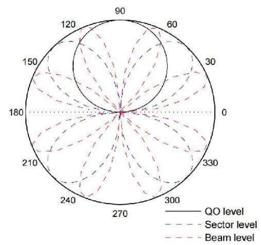
  - The signal that you create with the packet for one destination should have a "null" for the other destination(s)
  - Important since the other receivers cannot cancel out that signal
- Becomes a scheduling problem: for each "packet" transmission, identify the destinations that have traffic waiting and that are "the most" orthogonal

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; up to 7 Gbps
  - 6 channels of 2.16 GHz
- Compatible with 802.11 in 2.4 / 5 GHz bands
  - Backwards compatible MAC
  - E.g., mobile devices can switch between bands
- Has been used for point-point links for a while
  - APs now available
  - Combined with other 802.11 versions

Optimizing Communication in 802.11ad

- Transmission range in 60 GHz is limited
- Must use directional antennas to direct energy to the receiver
  - » Increases range and throughput (high signal strength)
  - » Also reduces interference at other nodes!
- Good news: antenna size scales with wave length
  - » Small antennas and narrow beams
- Bad news: how do nodes find each other?
  - » Use iterative algorithm, starting with wider beams

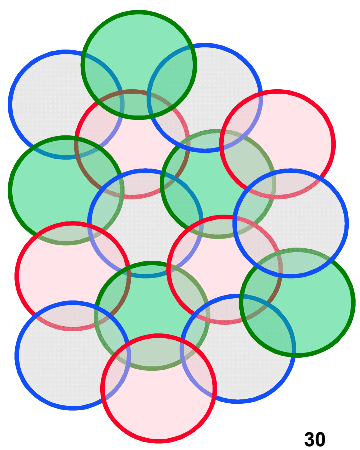


Outline

- MIMO and recent WiFi versions
  - » Refresher: spatial diversity
  - » MIMO basics
  - » Single user MIMO: 802.11n
  - » Multi-user MIMO: 802.11ac
  - » Millimeter wave: 802.11ad
- WiFi deployments
  - » Planning
  - » Channel selection
  - » Rate adaptation

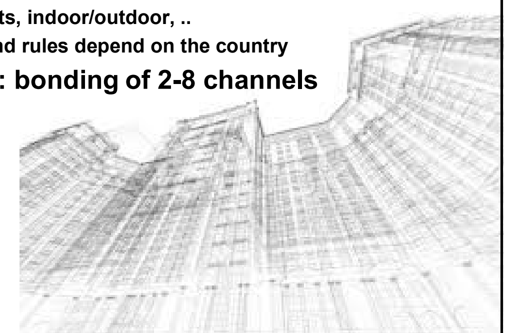
Infrastructure Deployments Frequency Reuse in Space

- Set of cooperating cells with a base stations must cover a large area
- Cells that reuse frequencies should be as distant as possible to minimize interference and maximize capacity
  - » Hidden and exposed terminals are also a concern



Frequencies are Precious

- 2.4 Ghz: 3 non-overlapping channels
  - » Plus lots of competition: microwaves and other devices
- 5 GHz: 20+ channels, but with constraints
  - » Power constraints, indoor/outdoor, ..
  - » Exact number and rules depend on the country
- 802.11n and ac: bonding of 2-8 channels
- And the world is not flat!

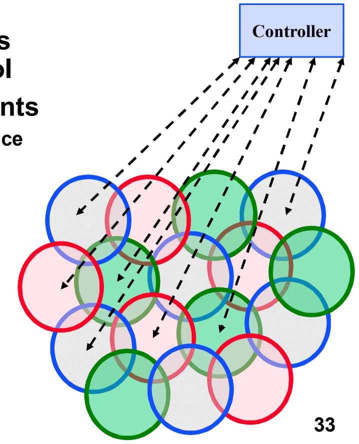


Frequency Planning

- Campus-style WiFi deployments are very carefully planned:
- A lot of measurements to determine where to place the AP
  - » What is the coverage area?
  - » What set of APs has good coverage with few "dead spots"
  - » What level of interference can we expect between cells
  - » What traffic loads can we expect, e.g., auditorium vs office
- Frequencies are very carefully assigned
  - » Can use the above measurements
- Must periodically re-evaluate infrastructure
  - » Furniture is moved, remodeling, …

Centralized Control

- Many WiFi deployments have centralized control
- APs report measurements
  - » Signal strengths, interference from other cells, load, …
- Controller makes adjustments
  - » Changes frequency bands
  - » Adjusts power
  - » Redistributes load
  - » Can switch APs on/off
  - » Very sophisticated!



Monitoring the Spectrum

- FCC (in the US) controls spectrum use
  - » Rules for unlicensed spectrum, licenses for other spectrum, what technologies can be used
- … but there is an special clause for campuses
  - » They have significant control over unlicensed spectrum use on the campus
  - » They can even use some "licensed" spectrum if it does not interfere with the license holder
- Network management carefully monitors spectrum use to make sure it is used well
  - » Shut down rogue APs – interference, security
  - » Non-approved equipment - interference
  - » Discourages outdated standards - inefficient

How about Small Networks?

- Most WiFi networks are small and (largely) unmanaged
  - » Home networks, hotspots, …
- Traditional solution: user-chosen frequency of their AP or a factory set default
  - » How well does that work?
- Today, APs pick a channel automatically in a smart way
  - » Monitors how busy channels are or how strong the signals are and then picks the best channel
  - » Can periodically check for better channels