Outline

- MIMO and recent WiFi versions
- WiFi deployments and 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?

Spatial Diversity

- Use multiple antennas that pick up the signal in slightly different locations
  » Channels uncorrelated with sufficient antenna separation

- Receiver diversity: \( y = h^* x + n \)
  \[ y = h^* (h^* x + n) \]
  \[ y = h^* \]

- 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: \( i \times P_T \times H = 0 \)

- Combined: \( i \times P_T \times H \times P_R = 0 \)

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 (faster cells to cover a given area)
- Spatial division multiple access ("SU-MIMO") for improved capacity (more users per cell)
- Multilayer transmission ("MU-MIMO") for higher data rates in a given bandwidth

An Example of Space Coding

[Diagram showing MIMO systems and space coding mechanisms]
Direct-Mapped NxM MIMO

Effect of transmission: \( \mathbf{R} = \mathbf{H} \cdot \mathbf{C} + \mathbf{N} \)

Decoding: \( \mathbf{O} = \mathbf{P} \cdot \mathbf{R} \cdot \mathbf{R}^H \) \( \mathbf{C} = \mathbf{I} \)  

Results: \( \mathbf{O} = \mathbf{P} \cdot \mathbf{H} \cdot \mathbf{P}^H + \mathbf{P} \cdot \mathbf{N} \)

- How do we pick \( \mathbf{P} \)? “Inverse” of \( \mathbf{H} \): \( H^{-1} \)
  - Equivalent of nulling the interfering possible (zero forcing)
  - Only possible if the paths are completely independent
- Noise amplification is a concern if \( \mathbf{H} \) is non-invertible – its determinant will be small

Precoded NxM MIMO

Effect of transmission: \( \mathbf{R} = \mathbf{H} \cdot \mathbf{C} + \mathbf{N} \)

Coding/decoding: \( \mathbf{O} = \mathbf{P} \cdot \mathbf{R} \cdot \mathbf{R}^H \) \( \mathbf{C} = \mathbf{P}_T \cdot \mathbf{I} \)  

Results: \( \mathbf{O} = \mathbf{P} \cdot \mathbf{H} \cdot \mathbf{P}_T + \mathbf{P} \cdot \mathbf{N} \)

- How do we pick \( \mathbf{P} \) and \( \mathbf{P}_T \)?
- Singular value decomposition of \( \mathbf{H} = \mathbf{U} \cdot \mathbf{S} \cdot \mathbf{V}^H \)
  - \( \mathbf{U} \) and \( \mathbf{V} \) are unitary matrices – \( \mathbf{U}^H \cdot \mathbf{U} = \mathbf{V}^H \cdot \mathbf{V} = \mathbf{I} \)
  - \( \mathbf{S} \) is diagonal matrix

MIMO Discussion

- Need channel matrix \( \mathbf{H} \): 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

MIMO in a Network Context

N transmit antennas

M receive antennas

How is this Different?

M receive antennas

M receivers

Multi-User MIMO Discussion

- Math is similar to MIMO, except for the receiver processing (PR)
  » 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?

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
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”
  \[ R_1 = P_{R_1} \cdot H_1 \cdot P_T \cdot I + P_{R_1} \cdot N \]
  \[ R_2 = P_{R_2} \cdot H_2 \cdot P_T \cdot I + P_{R_2} \cdot N \]
  - The signal that you create with the packet for one destination should have a “null” for the other destination(s)
  - Important 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
  - 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

Optimizing Communication in 802.11ad

- Transmission range in 60 GHz is limited
- Can you directional antennas to direct energy to the receiver
  - Also reduces interference at other nodes!
- Good news: antenna size (roughly) scales with the wave length -> small antennas!
- Bad news: how do nodes find each other?
  - Use iterative algorithm
Outline

- WiFi deployments and channel selection
- Rate adaptation

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!

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

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

Outline

- WiFi deployments and channel selection
- Rate adaptation
  - Background
  - RRAA
  - Charm
Bit Rate Adaptation

- All modern WiFi standards are multi bit rate
  - 802.11b has 4 rates, more recent standards have 10s
  - Vendors can have custom rates!
- Many factors influence packet delivery:
  - Fast and slow fading: nature depends strongly on the environment, e.g., vehicular versus walking
  - Interference versus WiFi contention: response to collisions is different
  - Random packet losses: can confuse “smart” algorithms
  - Hidden terminals: decreasing the rate increases the chance of collisions
- Transmit rate adaptation: how does the sender pick?

Transmit Rate Selection

- Goal: pick rate that provides best throughput
  - E.g. SINR 14 dB → 5.5 Mbps
  - Needs to be adaptive

“Static” Channel

Lower signal rates enable coverage of large additional area

Mobile Channel – Pedestrian
High Level Designs

- “Trial and Error”: senders use past packet success or failures to adjust transmit rate
  - Sequence of x successes: increase rate
  - Sequence of y failures: reduce rate
  - Hard to get x and y right
  - Random losses can confuse the algorithm
- Signal strength: stations use channel state information to pick transmit rate
  - Use path loss information to calculate “best” rate
  - Assumes a relationship between PDR and SNR
    - Need to recover if this fails, e.g., hidden terminals
- Newest class: context sensitive solutions
  - Adjust algorithm depending on, e.g., degree of mobility, ...

CHARM

- Channel-aware rate selection algorithm
- Transmitter passively determines SINR at receiver by leveraging channel reciprocity
  - Determines SINR without the overhead of active probing (RTS/CTS)
- Select best transmission rate using rate table
  - Table is updated (slowly) based on history
  - Needed to accommodate diversity in hardware and special conditions, e.g., hidden terminals
- Jointly considers problem of transmit antenna selection

SINR: Noise and Interference

\[
\text{SINR} = \frac{\text{RSS}}{\text{Noise} + \sum \text{Interference}}
\]

- Noise
  - Thermal background radiation
  - Device inherent
    - Dominated by low noise amplifier noise figure
  - ~Constant
- Interference
  - Mitigated by CSMA/CA
  - Reported as “noise” by NIC

Robust Rate Adaptation Algorithm

- RRAA goals
  - Maintain a stable rate in the presence of random loss
  - Responsive to drastic channel changes, e.g., caused by mobility or interference
- Adapt rate based on short term PDR
  \[
  R_{\text{new}} = \begin{cases} 
  R^+ & P > P_{\text{RTT}} \\
  R^- & P < P_{\text{RTT}} 
  \end{cases}
  \]
  - Thresholds and averaging windows depend on rate
- Selectively enable RTS-CTS
**SINR: RSS**

\[
RSS = P_{tx} + G_{tx} - PL + G_{rx} \tag{1}
\]

\[
PL = P_{tx} + G_{tx} + G_{rx} - RSS \tag{2}
\]

- By the reciprocity theorem, at a given instant of time
  \[PL_A \rightarrow B = PL_B \rightarrow A\]
- A overhears packets from B and records RSS (1)
- Node B records \(P_{tx}\) and card-reported noise level in beacons and probes, so A has access to them
- A can then calculate path-loss (2) and estimate RSS and SINR at B

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**CHARM: Channel-aware Rate Selection**

- **Leverage reciprocity to obtain path loss**
  - Compute path loss for each host: \(P_{tx} - RSS\)
- **On transmit**:
  - Predict path loss based on history
  - Select rate & antenna
  - Update rate thresholds