This lecture is being recorded

18-452/18-750
Wireless Networks and Applications
Lecture 11: MIMO and WiFi Deployments

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Spring Semester 2022

http://www.cs.cmu.edu/~prs/wirelessS22/

Announcements

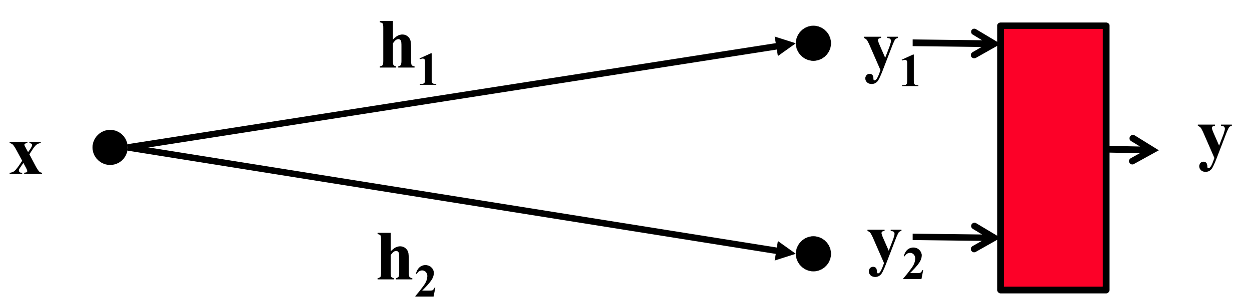
- Project 2 teams and topics due on Tuesday:
  - » I am mostly looking for topics, but
  - » If you have specific ideas of <u>what</u> you would like to do, please include it
  - » This will allow me to give better feedback
  - » 2-3 topics are fine as well
    - – Prioritized if possible
- HW 2 will be released soon!
- The recording of the Friday lectures does not have sound
  - » I am looking into how we can fix this
- I may have to move Friday office hours …

Outline

- How do further increase bit rates?
  - » Refresher: spatial diversity
  - » MIMO basics
  - » Single user MIMO: 802.11n
- How about short data short transfers?
  - » OFDMA
  - » Multi-user MIMO
- 802.11n through ax
- WiFi deployments
  - » Planning
  - » Channel selection
  - » Rate adaptation

Reminder: Spatial Diversity

- Use multiple antennas that pick up the signal in slightly different locations
  - » Channels uncorrelated with sufficient antenna separation
- Receiver diversity: $i \quad x \quad \vec{H} \quad x \quad \vec{P}_R = o$



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

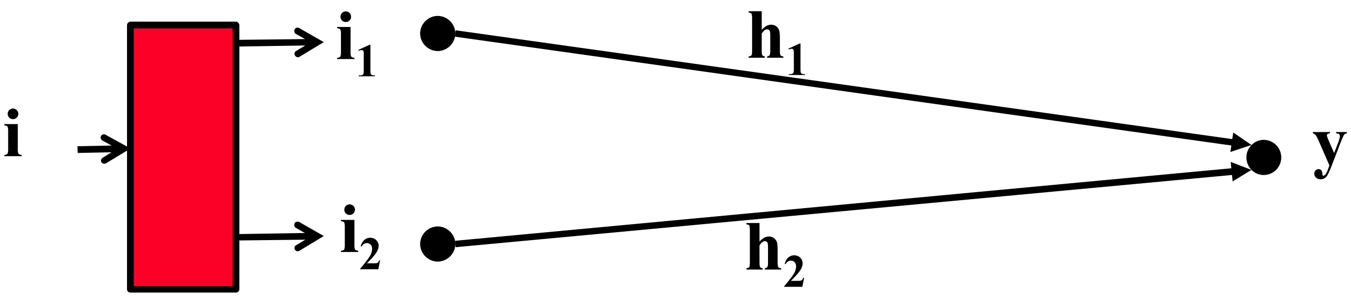
$$y = \vec{h}^* * (\vec{h} * \vec{x} + \vec{n})$$

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

Other Diversity Options

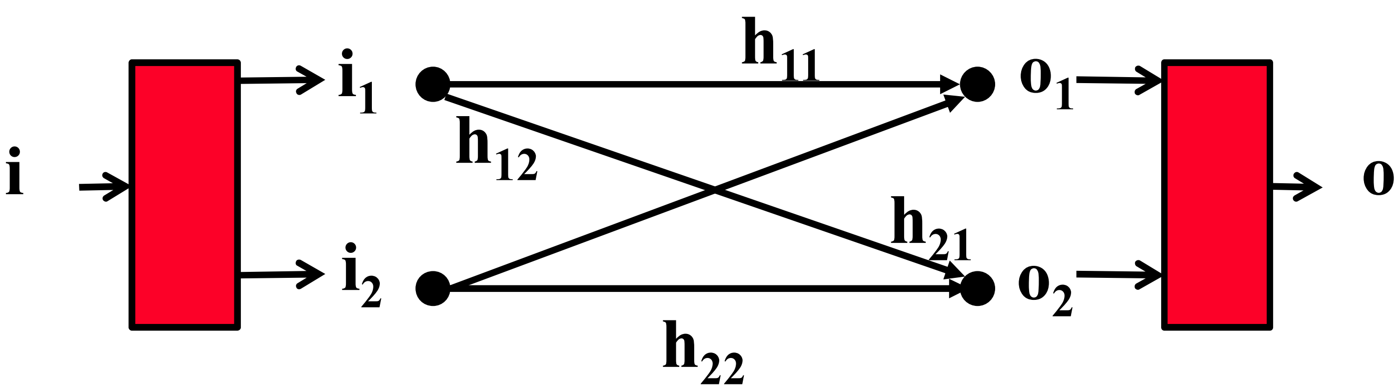
- **Transmit diversity:**

$$i \times \vec{P}_T \times \vec{H} = o$$



- **Combined:**

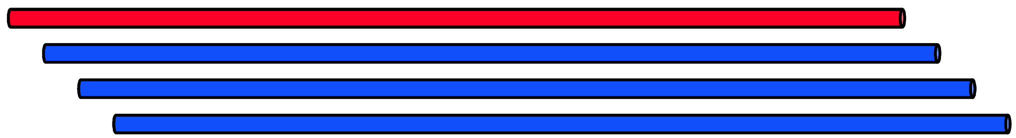
$$i \times \vec{P}_T \times H \times \vec{P}_R = o$$



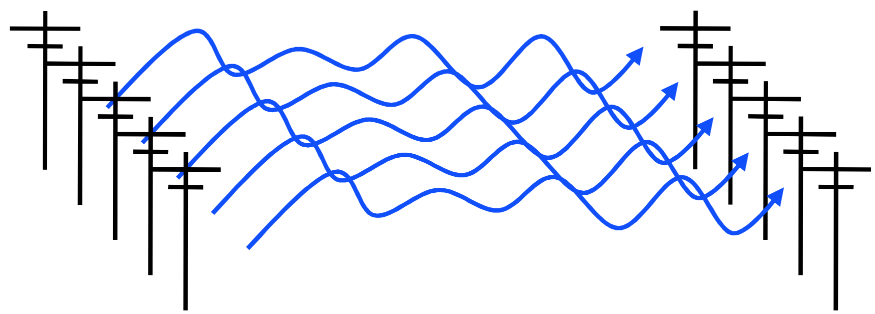
How Do We Increase Throughput in Wireless?

- **Wired world:**

Pull more wires!



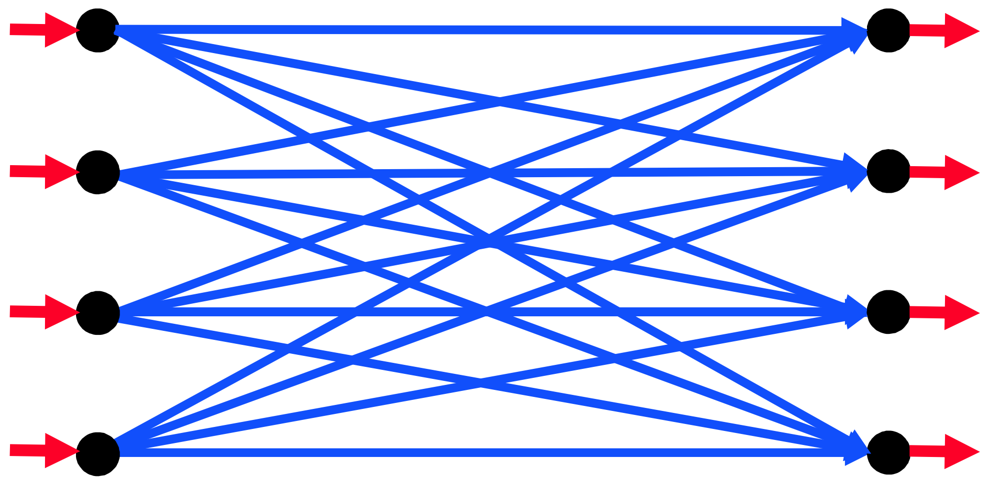
- **Wireless world:**



How about if we could do the same thing as with wires: send parallel data streams!

MIMO
Multiple In Multiple Out

N transmit
antennas
sending
N bit stream



M receive
antennas
receiving
N bit streams

- N x N subchannels that can be used to send multiple data streams simultaneously (general case: N x M)
- Fading on channels is largely independent
  - » Assuming antennas are separate ½ wavelength or more
- Is this even possible?
  - » Each receive antenna will receive weighted sum of all transmitted signals!
- Yes it is - MIMO
- Build on ideas from space diversity

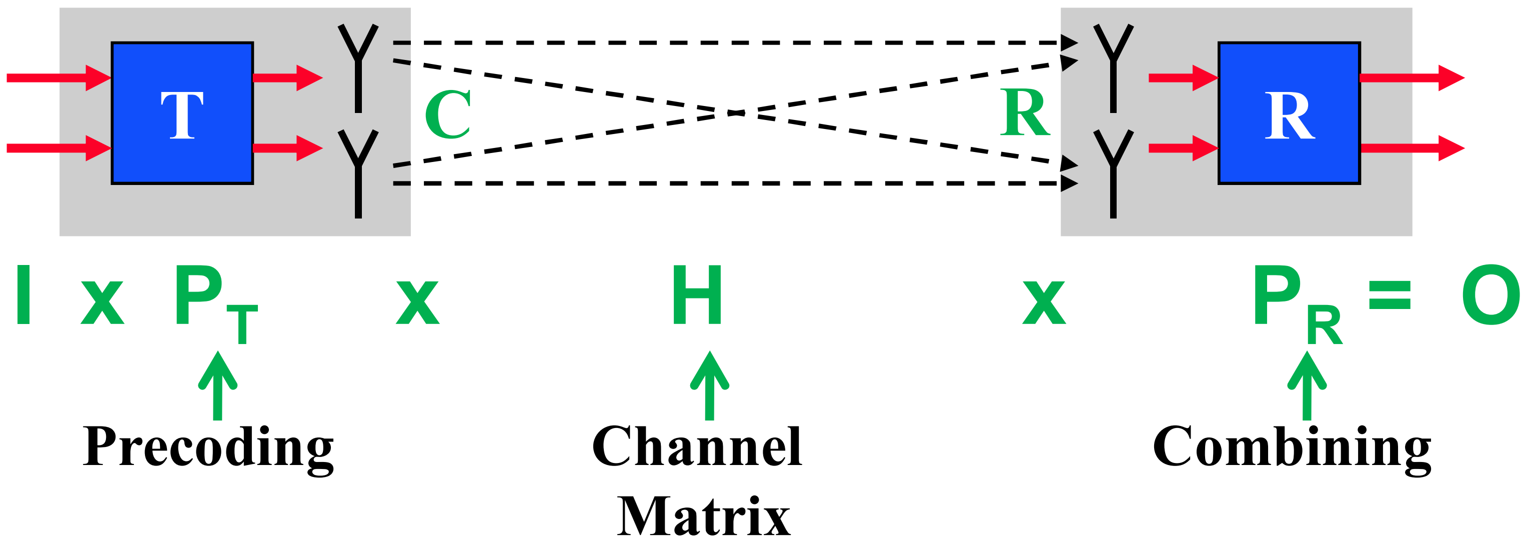
Why Is this So Exciting?

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

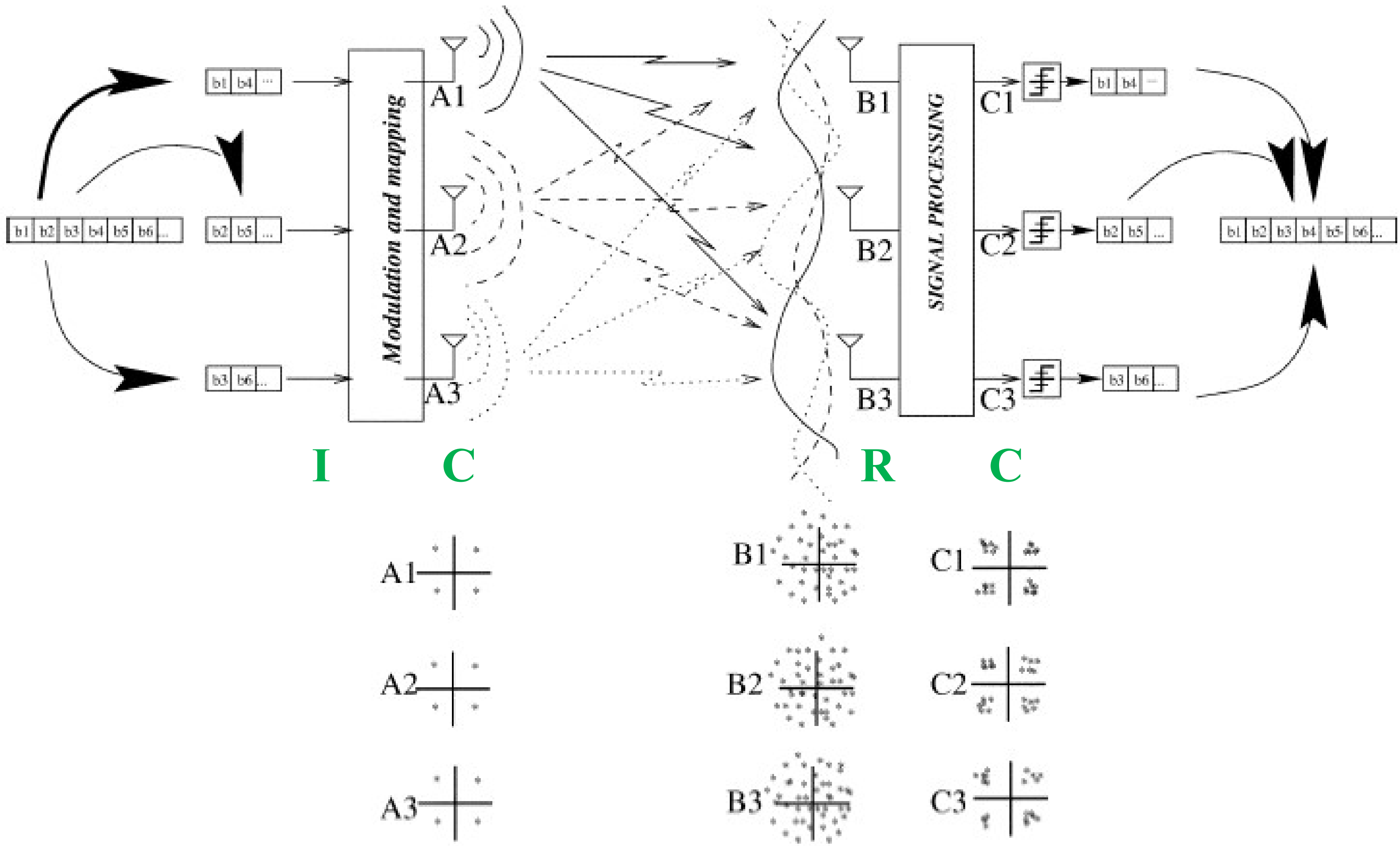
MIMO
How Does it Work?

- 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

An Example of Space Coding



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

M MxN N M

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

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

No transmit processing

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

Direct MIMO
Very Basic Example

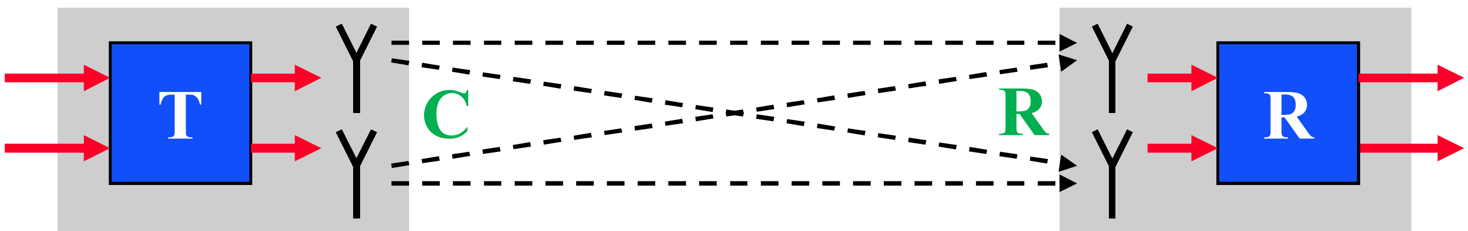
$$O = P_R * H * I + P_R * N$$

- $r_1 = (h_{11} \times i_1 + h_{12} \times i_2)$
- $r_2 = (h_{21} \times i_1 + h_{22} \times i_2)$
- $o_1 = p_{11} \times r_1 + p_{12} \times r_2$
- $o_2 = p_{21} \times r_1 + p_{22} \times r_2$

- **Simple cases can be solves as set of linear equations**
- **Reality check!**
  - » **Above values are complex number (phase, amplitude)**
  - » **The channel state matrix H changes with time and frequency – it can only be estimated**
  - » **The noise is not known**
  - » **The o_i values will not be identical to i_i!**
- **Simple examples**
  - » **What if all $h_{ij} = 1$?**
  - » **What $h_{12} = h_{21} = 1$ and $h_{11} = h_{22} = 0$?**
  - » **Conclusion: MIMO benefits depend on the channel state matrix**
    - – **Would like channels to be as uncorrelated as possible**

MIMO Basics

- 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



$I \times P_T \times H \times P_R = O$

Precoding — Channel Matrix — Combining

- Combines previous techniques

Precoded NxM MIMO

Effect of transmission (dimensions: M, MxN, N, M)

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

Coding/decoding

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

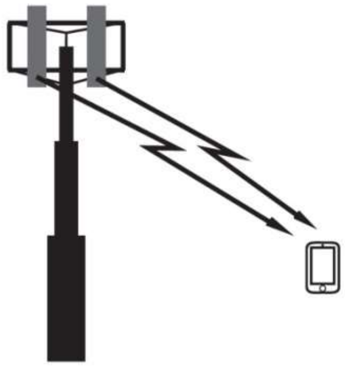
(dimensions: D, DxM, M — N, NxD, D)

Results

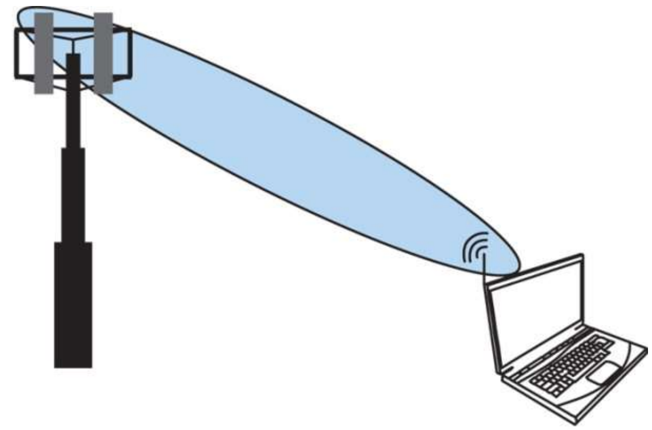
$$\vec{O} = P_R * H * P_T * \vec{I} + P_R * \vec{N}$$

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

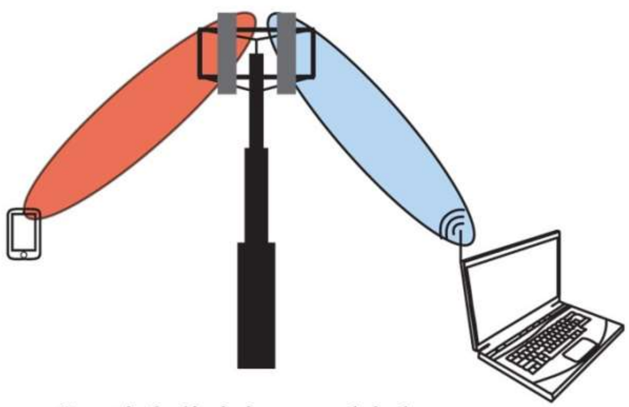
Mechanisms Supported by MIMO



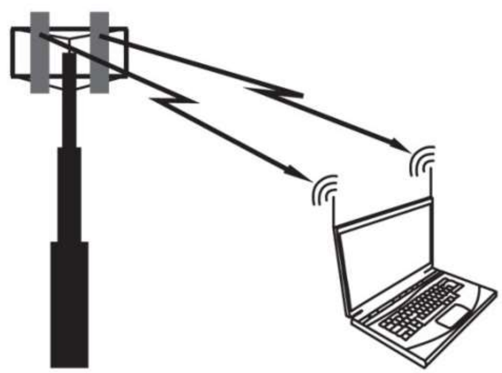
Diversity for improved system performance



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 most recent WiFi versions
  - » Is most effective in rich multi-path, non-LOS scenarios
  - » Potential throughputs of 100s of Mbps to Gbps!
- Focus is on maximizing throughput between two nodes
  - » Is this always the right goal?

Increase Useful Aggregate Bandwidth

- OFDM and MIMO make it possible to support very high bandwidth point-to-point links, but …
- How many devices and applications really need 100s of Mbps or Gbps throughputs?
  - » Web browsing, mail, video, …?
- Also, enabling these very high throughputs introduces overhead!
  - » Wasted effort for short data transfer
- Question: can we increase network throughput for a broad range of diverse traffic loads?
  - » It is ok if it decrease the (theoretical) maximum throughput

Outline

- How do further increase bit rates?
- How about short data short transfers?
  - » OFDMA
  - » Multi-user MIMO

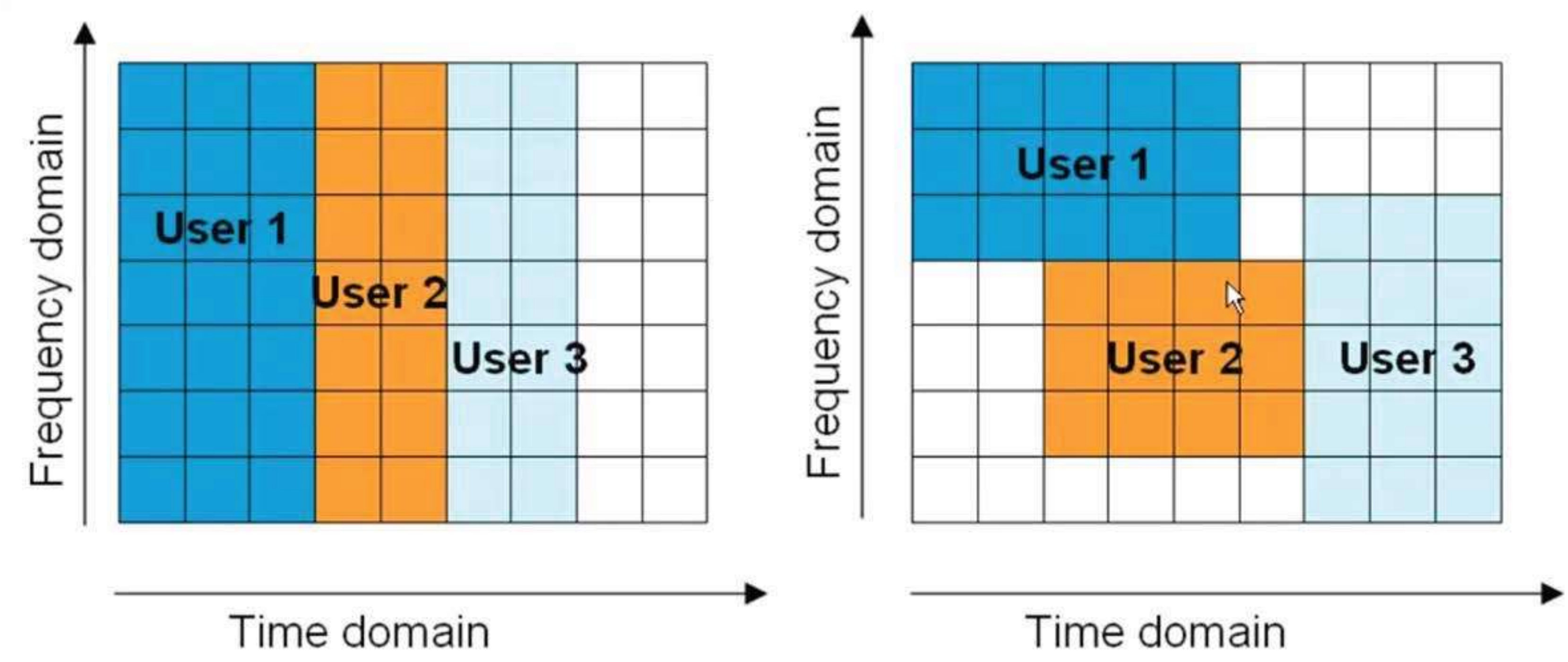
Not specific to WiFi!

- 802.11n through ax
- WiFi deployments
  - » Planning
  - » Channel selection
  - » Rate adaptation

Orthogonal Frequency Division Multiple Access (OFDMA)

- Remember Spread Spectrum?
  - » Modulation technique that allows very robust data transfers
- By using different spreading codes/hopping sequences, we can use it as a Multiple Access technique
  - » Multiple senders can transmit simultaneous
  - » Or, a cell tower/base station can communicate with multiple devices simultaneously (upstream+downstream)
- Can we do this for OFDM as well?
- Yes – OFDMA!

OFDM versus OFDMA



- **Traditional OFDM allows channel sharing by user using TDMA**
- **With OFDMA, users can use subsets of subcarriers in each time slot**
- **Remember: signals travel everywhere!**

Discussion

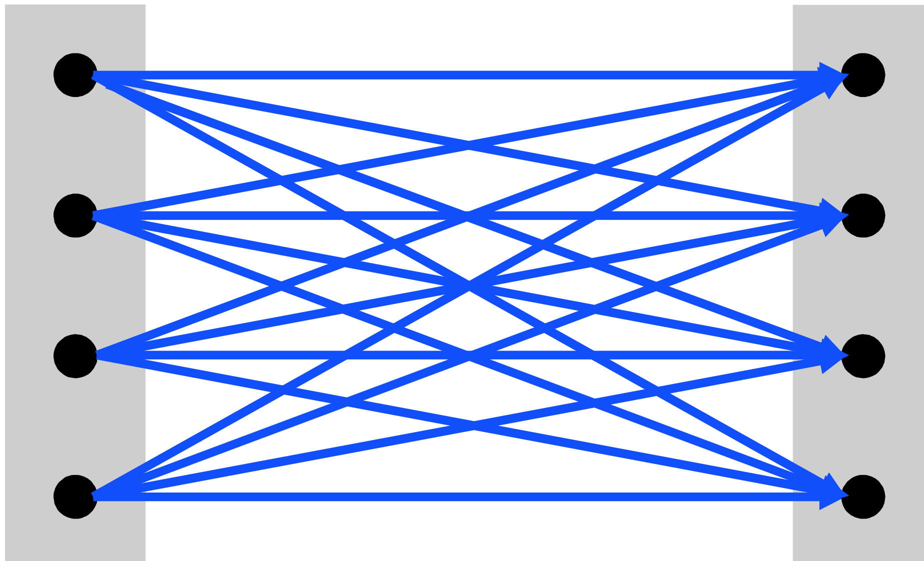
- OFDMA allows a base station to transmit data to multiple devices at the same time
  - » Different bit rates can be used for each device
- OFDMA upstream allows multiple devices to the base station at the same time
  - » Requires tight synchronization
- The advantage is that it makes it possible to use the benefit from the high OFDM bandwidth for traffic loads involving smaller transfers
- The cost is that it involves more overhead
  - » The base station and device(s) needs to agree on for each slot what device it is used by

How about MIMO

- MIMO makes it possible to achieve even higher data rates than OFDM
  - » Send multiple data streams in parallel using multiple antennas and radios on sender and receiver
- Key idea is that sender sends separate data streams to multiple receivers
  - » Idea is similar to that of OFDMA except it is applied to data streams rather than subcarriers
- Very attractive for two reasons
  - » A better fit for traffic loads consisting of smaller data transfers to multiple receivers (or from multiple senders)
  - » Mobile devices typically have fewer antennas than BS
    - – Each data stream requires an antenna/radio pair

MIMO in a Network Context

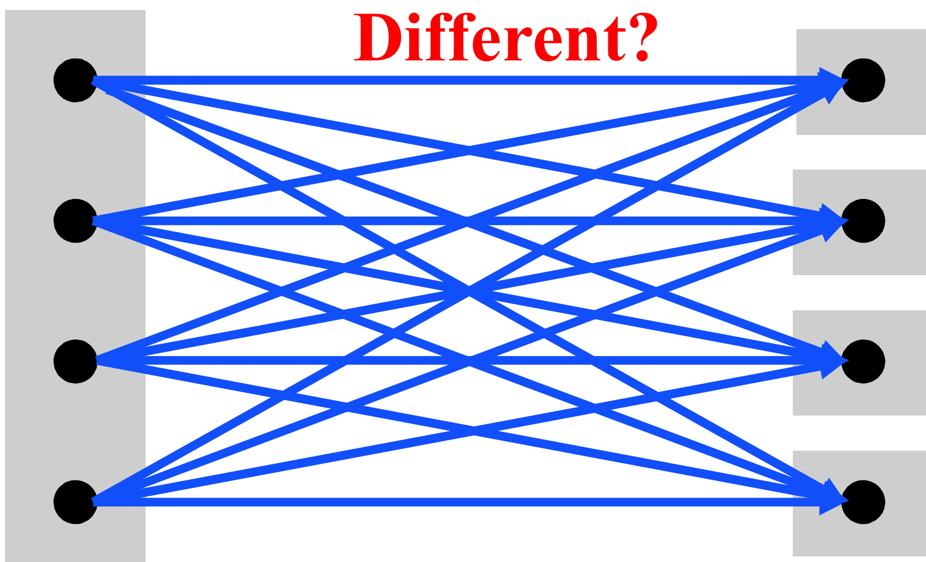
N transmit antennas



M receive Antennas
-
1 receiver

How is this Different?

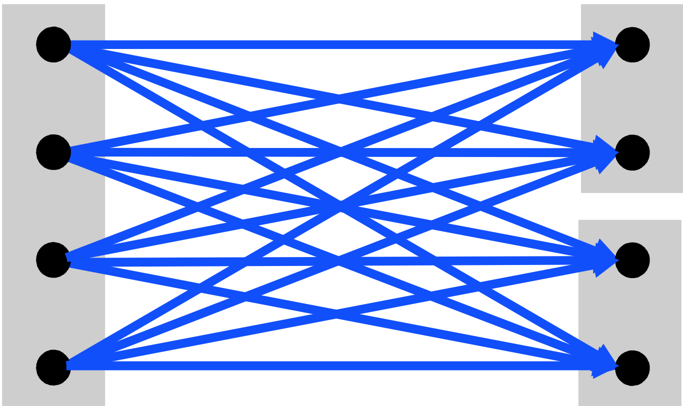
N transmit antennas



M receive antennas
-
M receivers

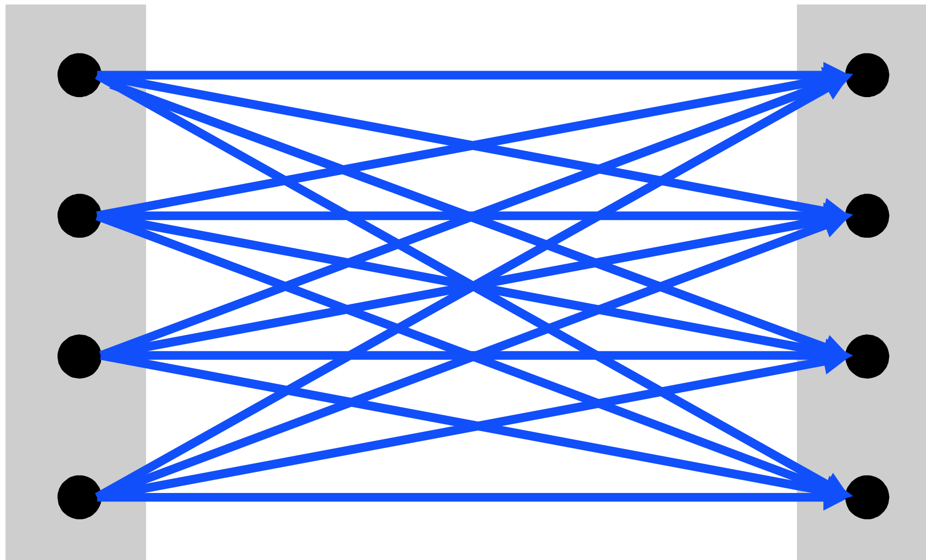
Multi-User MIMO Discussion

- 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 created by those signals – limits ability to extract useful data (e.g., lower bit rates)
- 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 more limited



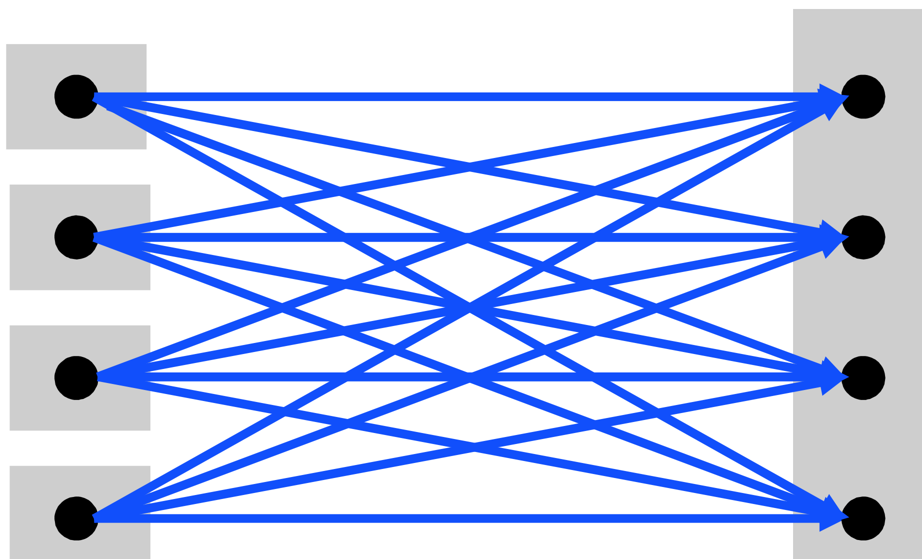
MIMO Upstream

N transmit Antennas
-
1 transmitter



M receive Antennas
-
1 receiver

N receiver



M receive antennas
-
1 receiver

802.11n Overview

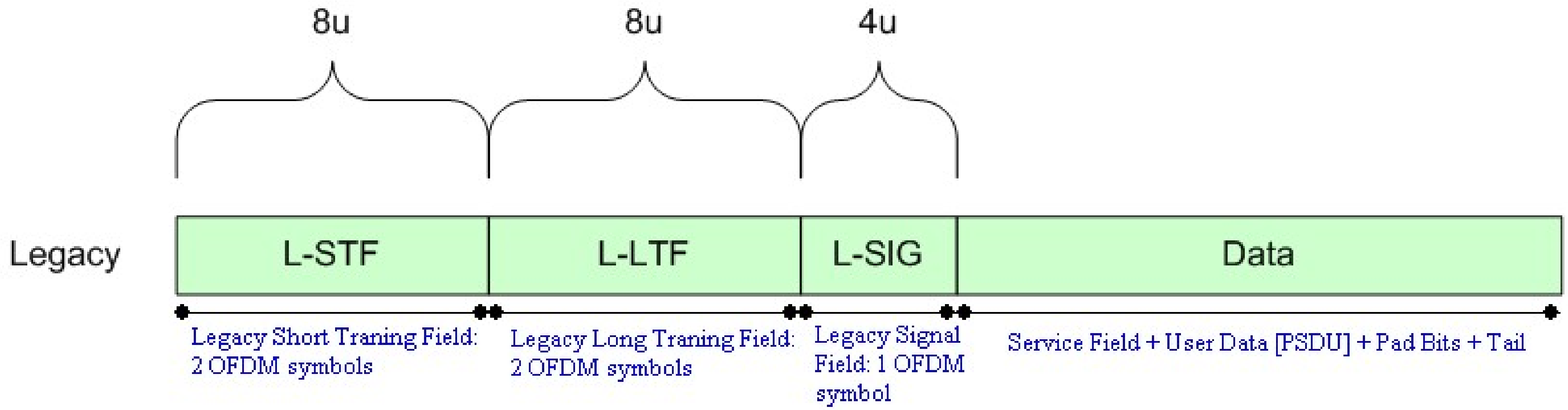
- **802.11n extends 802.11a for MIMO**
  - » Supports up to 4x4 MIMO
  - » Preamble that includes high throughput training field
- **Standardization was completed in Oct 2009, but early products had long been available**
  - » WiFi alliance started certification using draft in mid-2007
- **Supported 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 - 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
  - » Amortize over multiple transmissions

Interoperability Uses PLCP in Three Modes

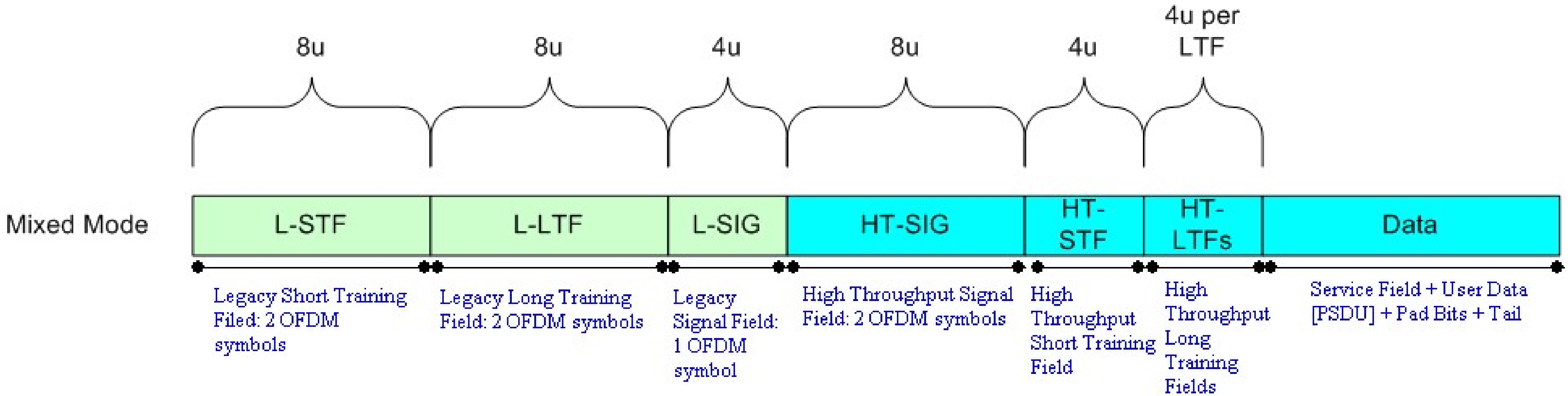
- Legacy mode: use 802.11a/g OFDM format
  - » The L-SIG field contains rate and length information
  - » Loses benefits of 802.11n!



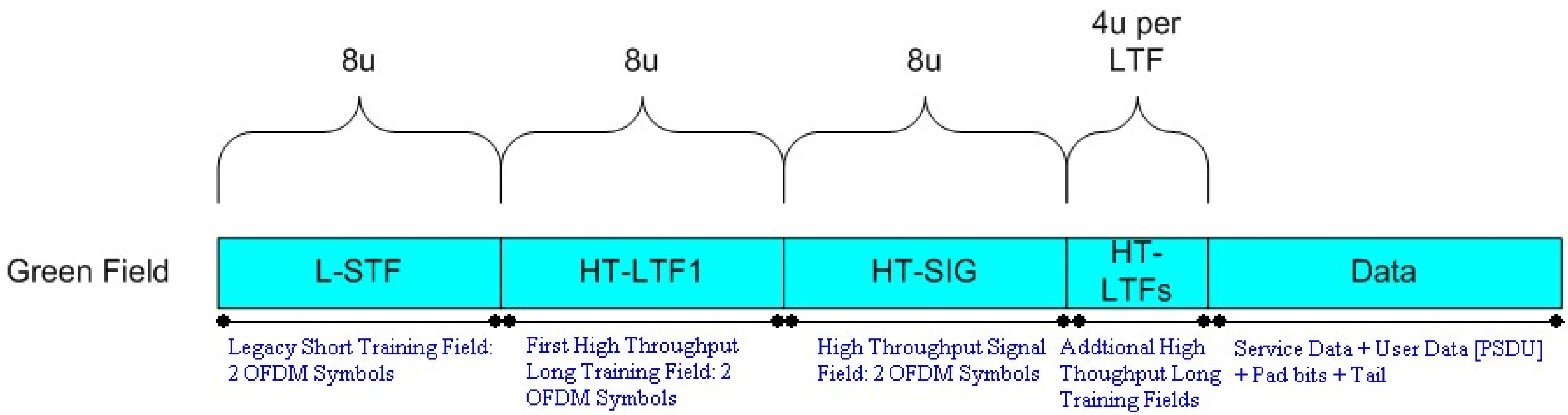
- Mixed mode:
  - » Include both an 802.11a/g and 802.11n PLC - next slide
  - » 802.11n devices can interpret green field, which includes the L-SIG field (rate and length information)

PLC – PHY Layve Convergence protocol
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**



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

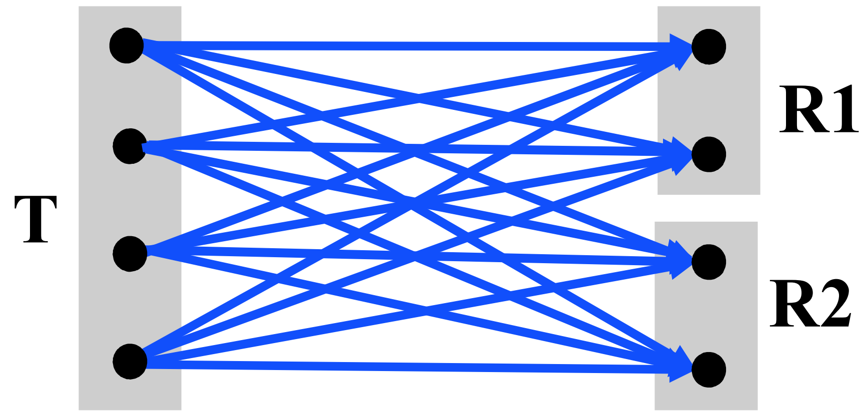
Multi-User MIMO
Up versus Down Link

- Assume one AP with multiple clients
- Downlink: Broadcast Channel (BC)
  - » Consistent with the traditional WiFi model of having each client receive a packet from the base station independently (except that it is at the same time!)
- Uplink: Multiple Access Channel (MAC)
  - » Multiple clients transmit simultaneously to a single base station
  - » WiFi is designed to avoid this!
    - – Simultaneous transmissions = collision
  - » MU-MIMO requires some changes to the standard
  - » Also requires fine grain clock coordination among clients on packet transmission – protocol support!

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
- Also supports beam forming to target signal to device – increases SNR

Challenges in 802.11ac



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

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

  » 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

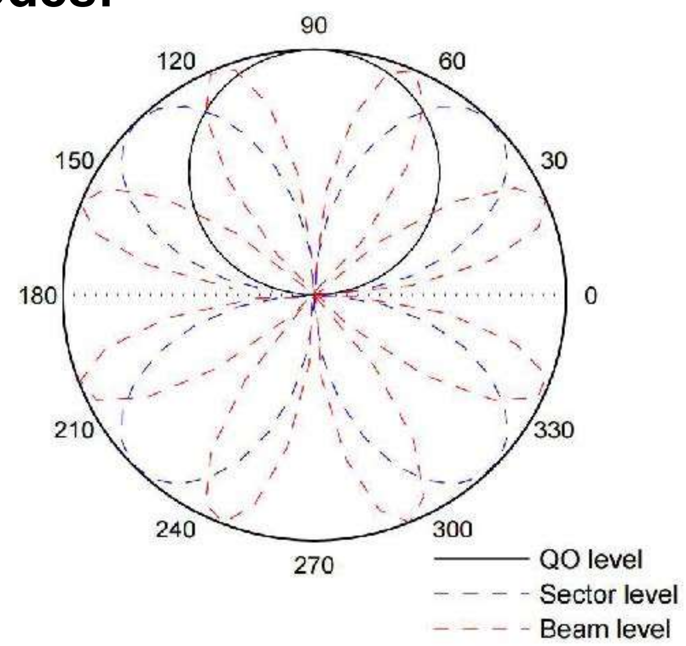
- Becomes a scheduling problem: for each "packet" transmission, identify the destinations that have traffic waiting and that are "the most" orthogonal

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 (not PHY!)
  - » E.g., mobile devices can switch between bands
- Has been used for point-point links for a while
  - » Set top box to TV screen,
  - » 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



802.11ax versus ac

- Operates in both 2.4 and 5 GHz band
- Low level modulation differences
  - » Up to 1024 QAM compared to 256 QAM
  - » Tighter packing of subcarriers and longer symbol duration
  - » Shorter gaps between symbols
- Use of OFDMA
- MU-MIMO upstream and downstream
- Power saving techniques targeting IoT

802.11ay versus ad

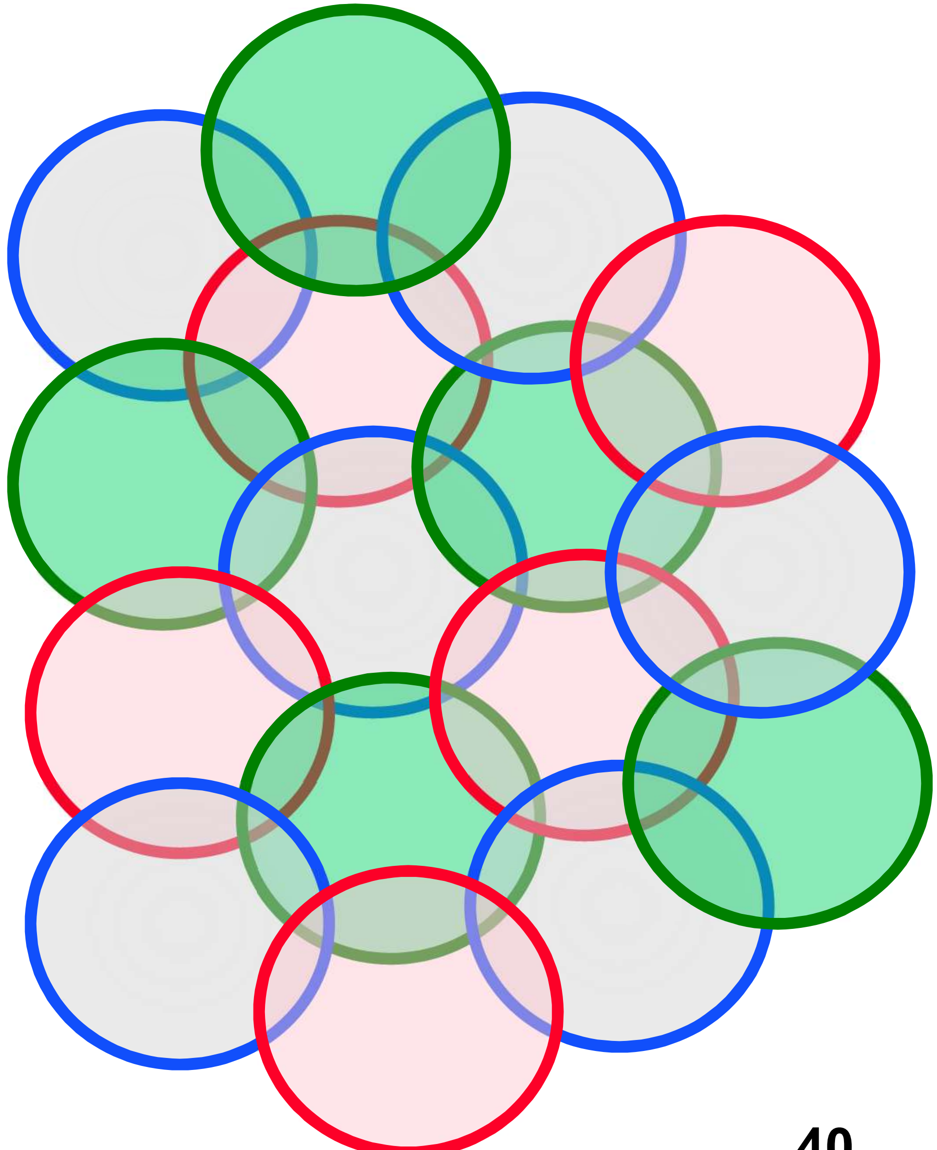
- Use of MIMO and MU-MIMO instead of beamforming
- Channel bonding: combine up to 4 2.16 GHz channels
- Increased distances to a few 100 m
- Could be used as replacement for Ethernet (indoors) or backhaul outdoors
  - Reduce cost
  - “Easy” application: no need to track mobile users

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**

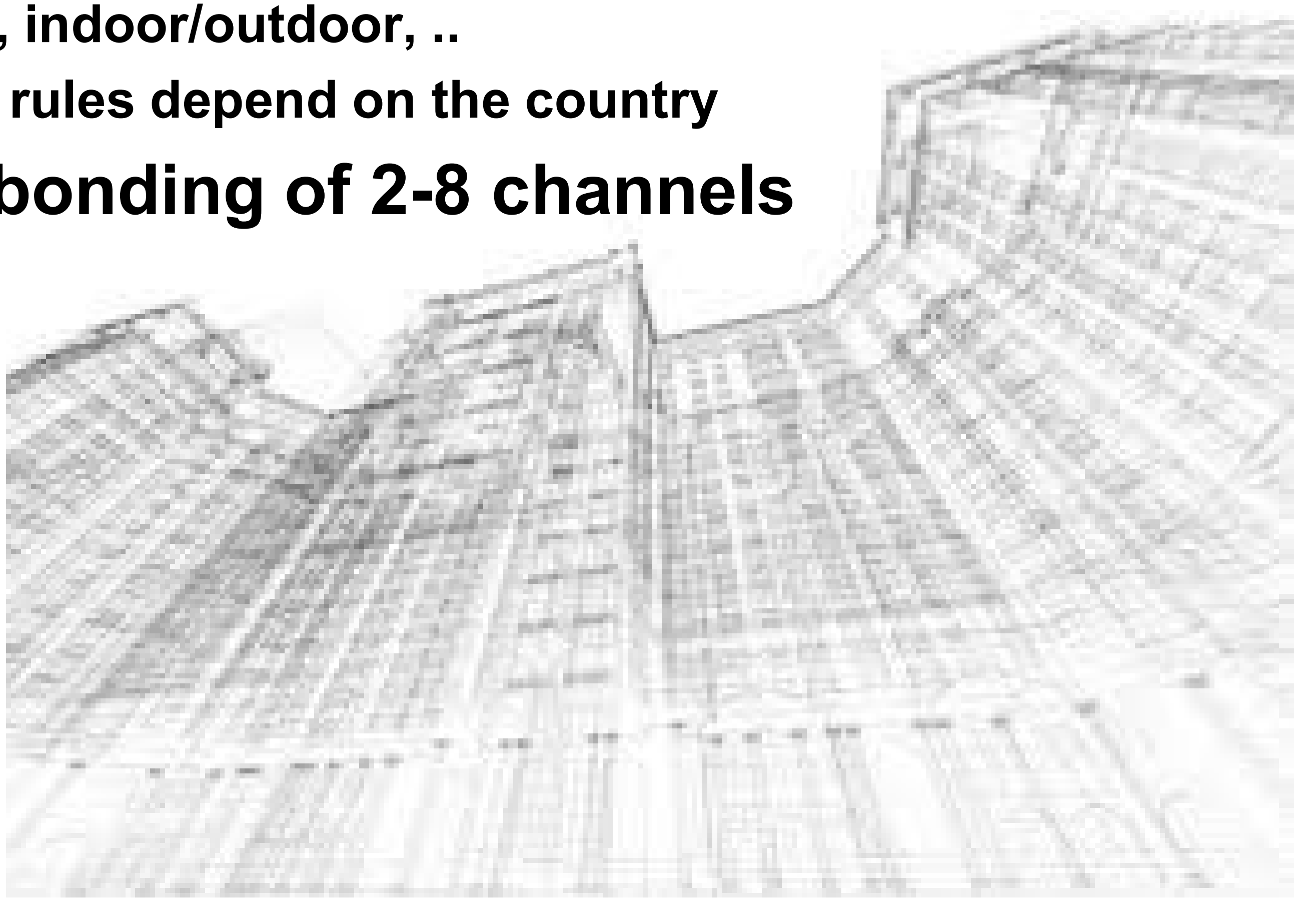
Infrastructure Deployments Frequency Reuse in Space

- **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!**

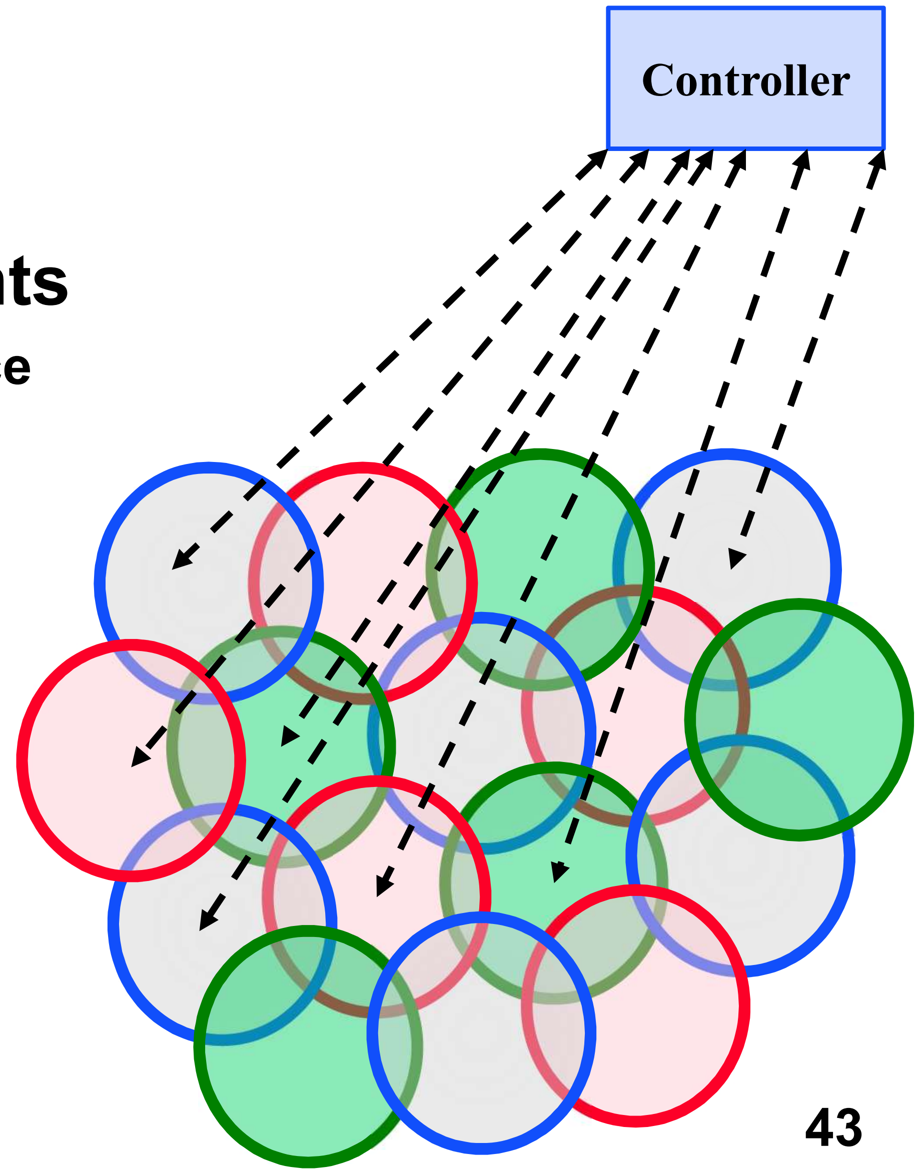


Frequency Planning

- 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 involves carefully monitoring for performance and security
  - » 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 the best channel
  - » This is done by measuring the ``channel busy time'' on all channels
  - » Can also consider signal strength from nearby APs/clients
  - » Can periodically check for better channels