This lecture is being recorded

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

Peter Steenkiste

Spring Semester 2021

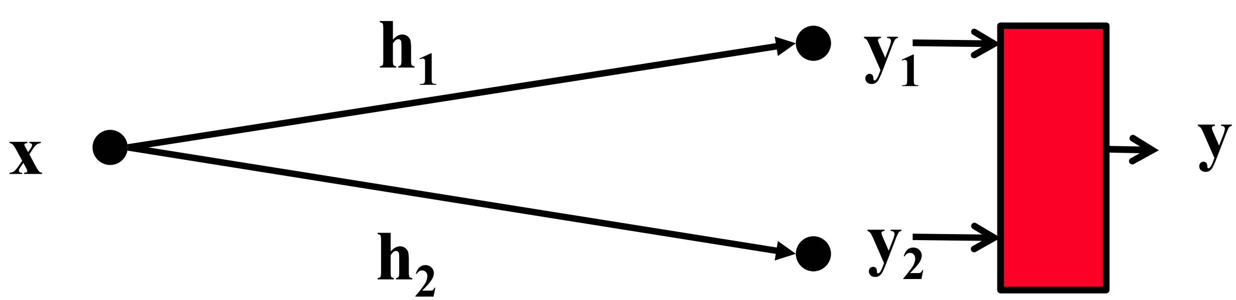
http://www.cs.cmu.edu/~prs/wirelessF21/

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

Spatial Diversity

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



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

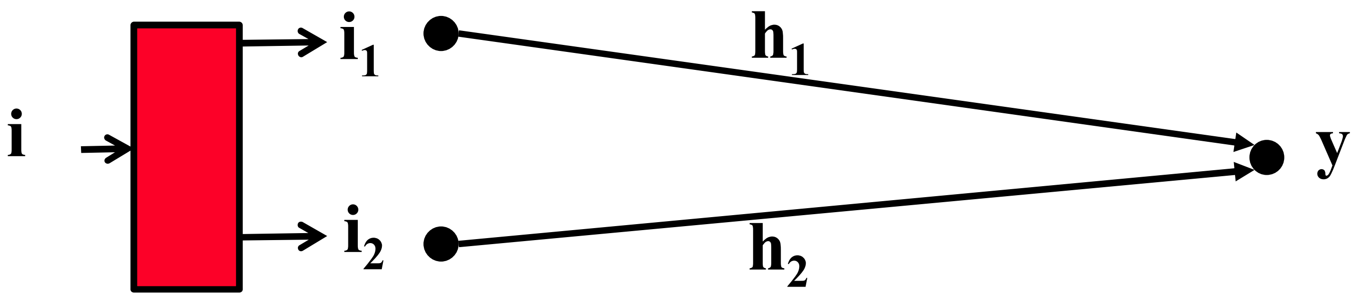
$$y = \vec{h}^* * (\vec{h} * \vec{x} + \vec{n})$$

- 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

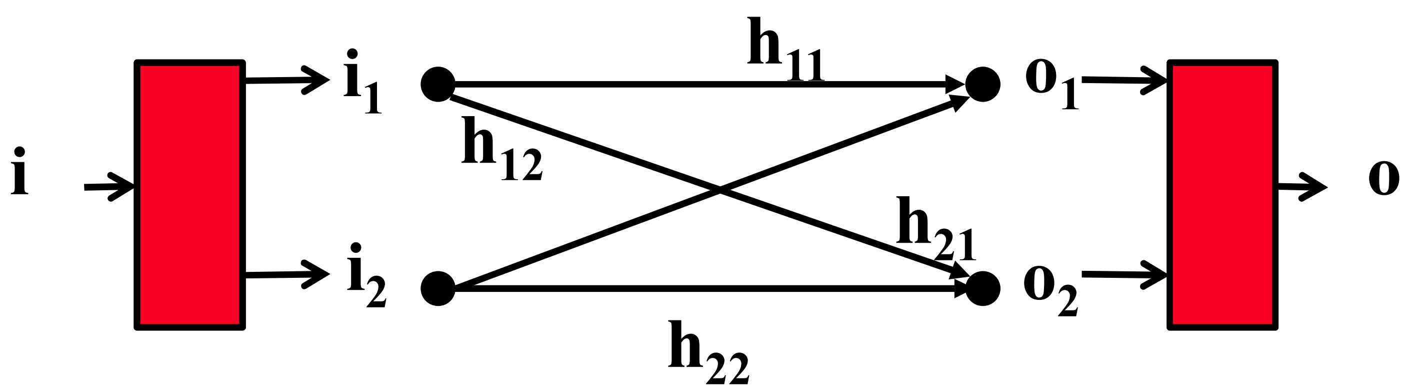
- Transmit diversity:

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



- Combined:

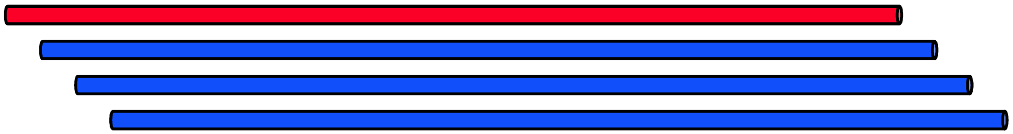
$$i \times \vec{P}_T \times H \times \vec{P}_R = o$$



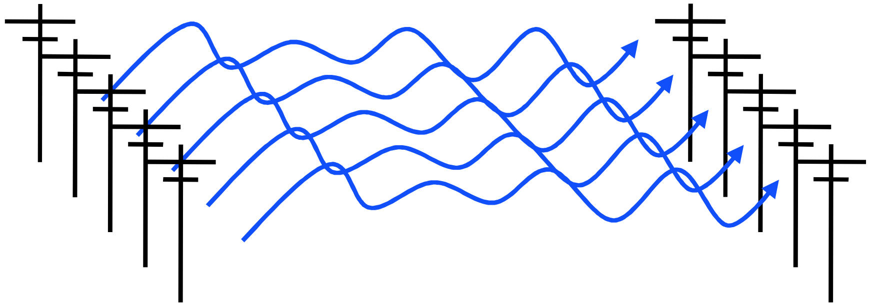
How Do We Increase Throughput in Wireless?

- Wired world:

Pull more wires!



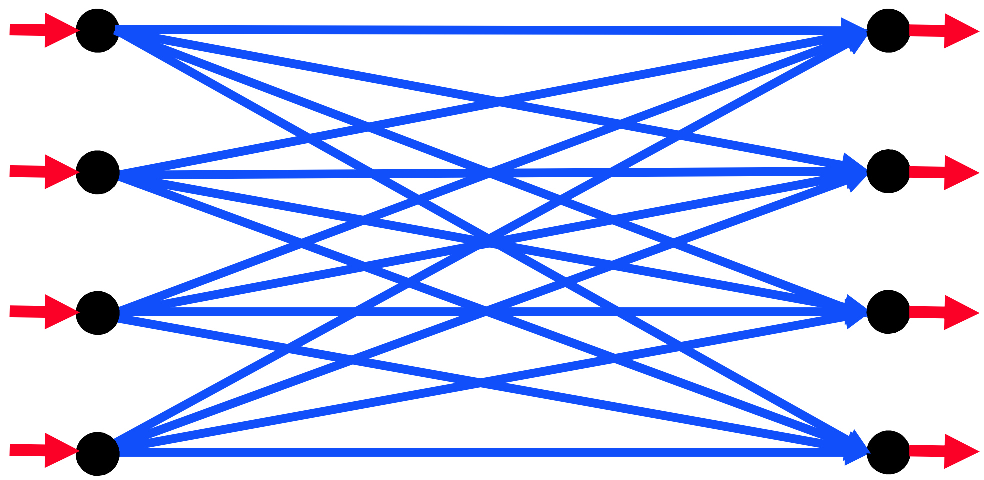
- Wireless world:



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 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
- Build on ideas from space diversity, e.g. 1 x N and N x 1
- Very effective if there is no direct line of sight
  - » Subchannels become more independent

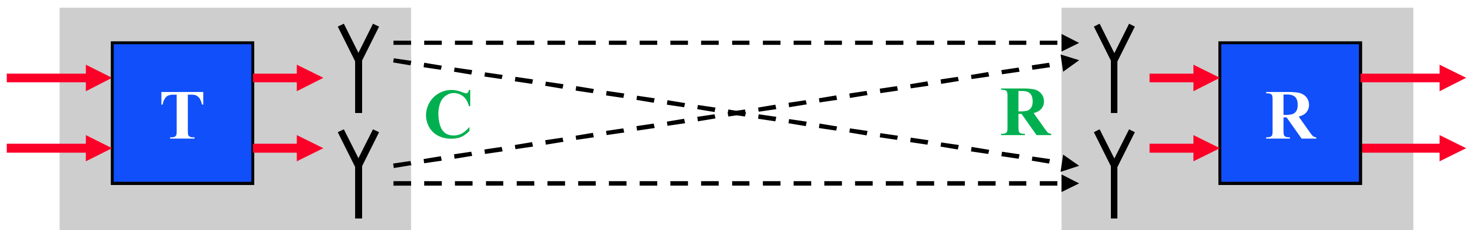
Why So Exciting?

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

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

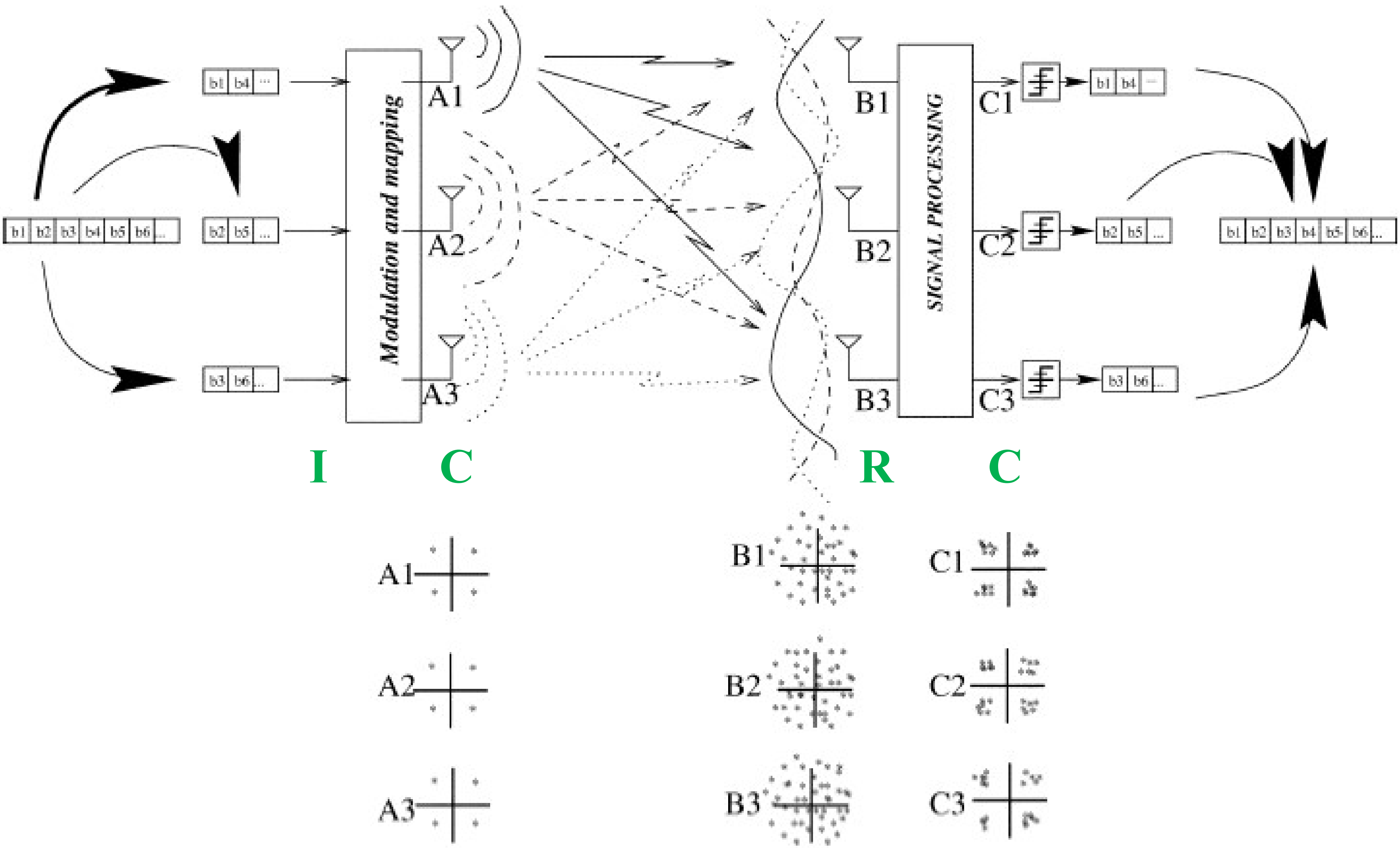


$I \times P_T \times H \times P_R = O$

Precoding — Channel Matrix — Combining

- Combines previous techniques

An Example of Space Coding



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

M MxN N M

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

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

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

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

Precoded NxM MIMO

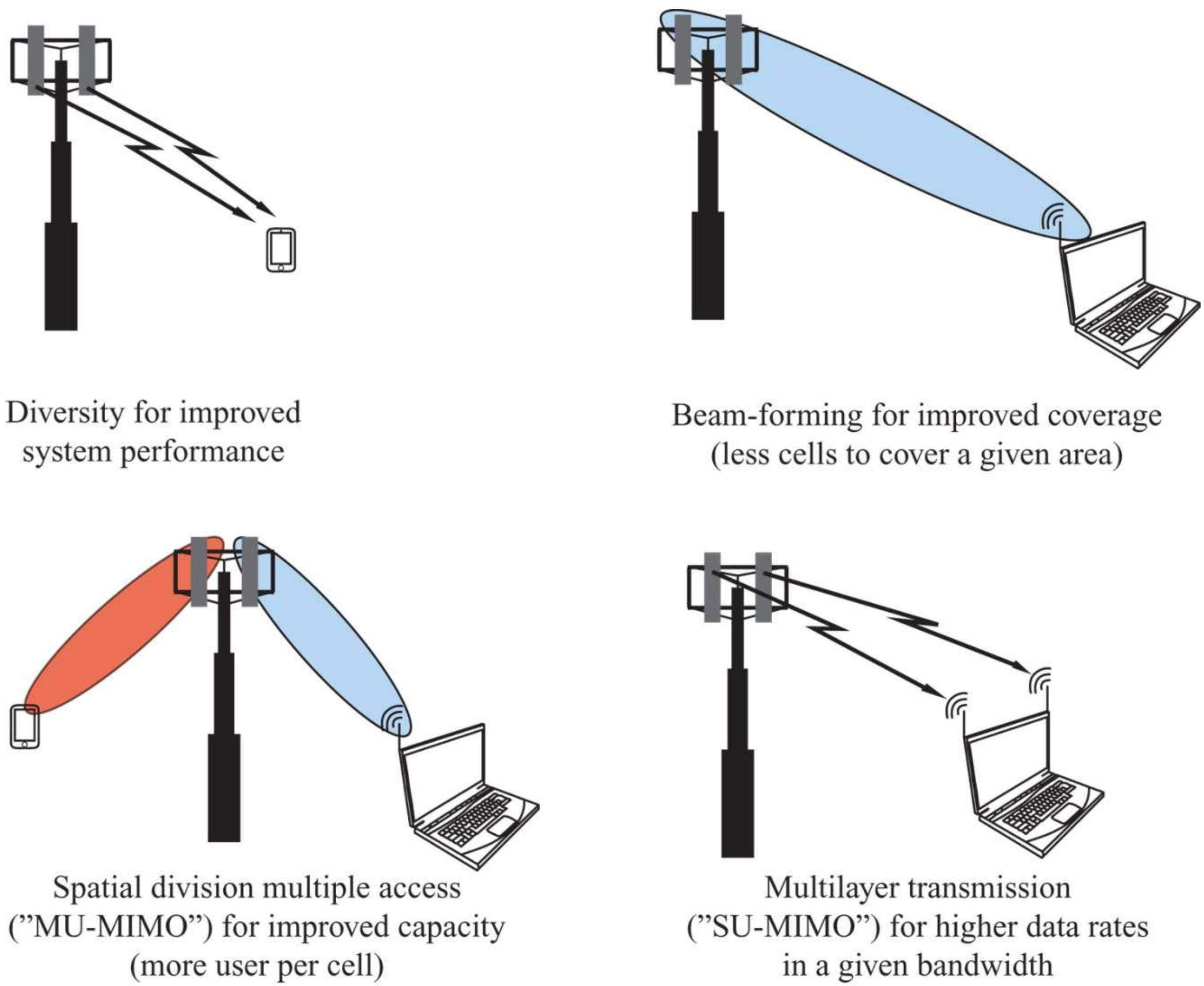
Effect of transmission: $\underset{}{\overset{M}{\vec{R}}} = \overset{MxN}{H} * \overset{N}{\vec{C}} + \overset{M}{\vec{N}}$

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

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 – $U^H * U = V^H * V = I$ ← Identity matrix
  - » S is diagonal matrix

Mechanisms Supported by MIMO



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

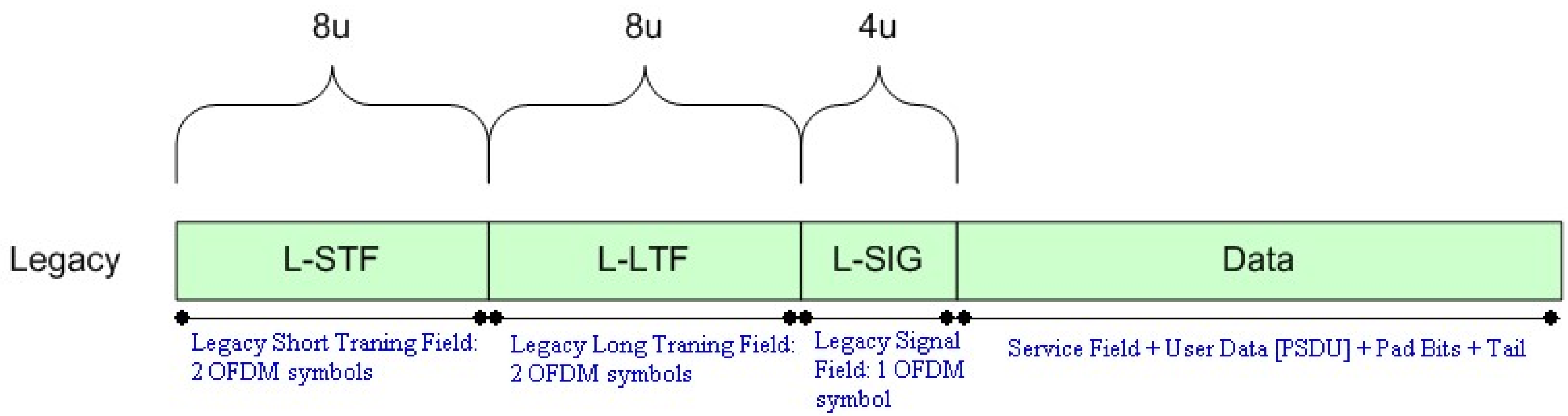
- 802.11n extends 802.11a for MIMO
  - » Supports up to 4x4 MIMO
  - » Preamble that includes high throughput training field
- Standardization was completed in Oct 2009, but early products had long been available
  - » WiFi alliance started certification using draft in mid-2007
- Supported in both the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

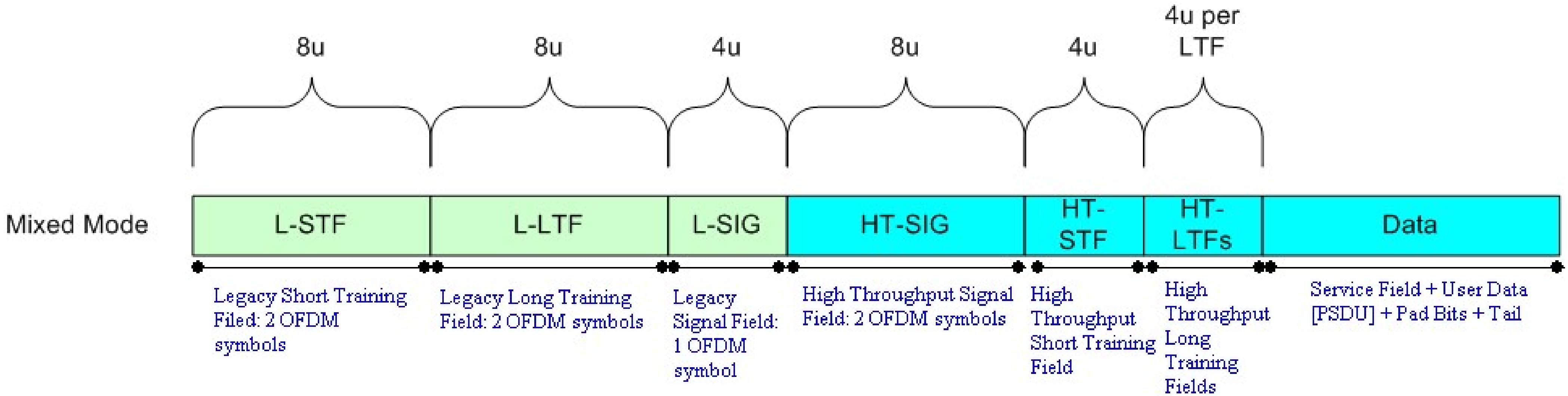


- **Mixed mode:**
  - » Include both an 802.11a/g and 802.11n PLC - next slide
  - » 802.11n devices can interpret green field, which includes the L-SIG field (rate and length information)

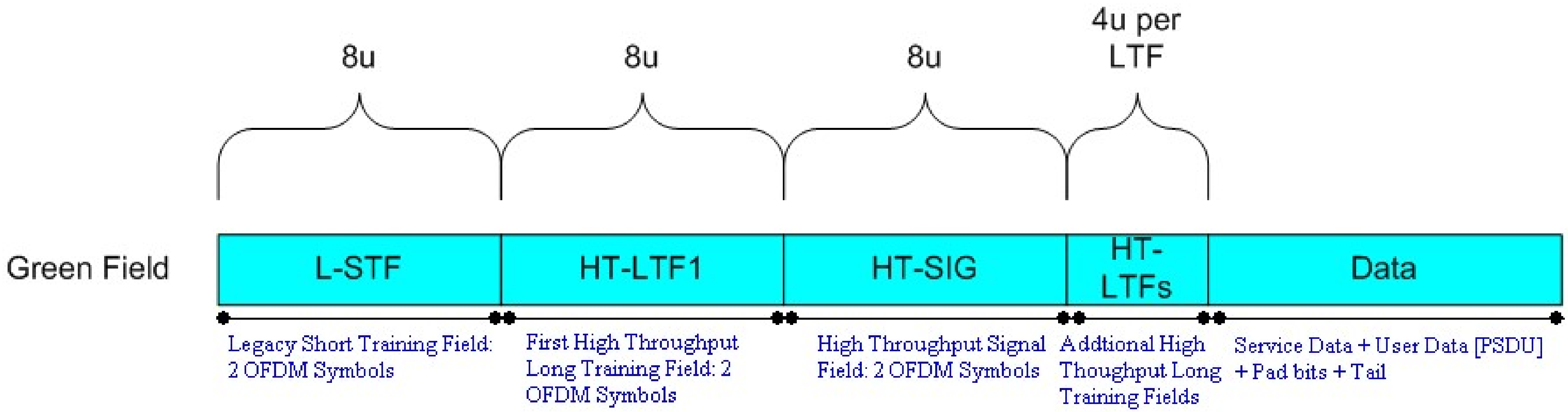
PLC – PHY Layve Convergence protocol

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

Interoperability: High Throughput (HT) Modes

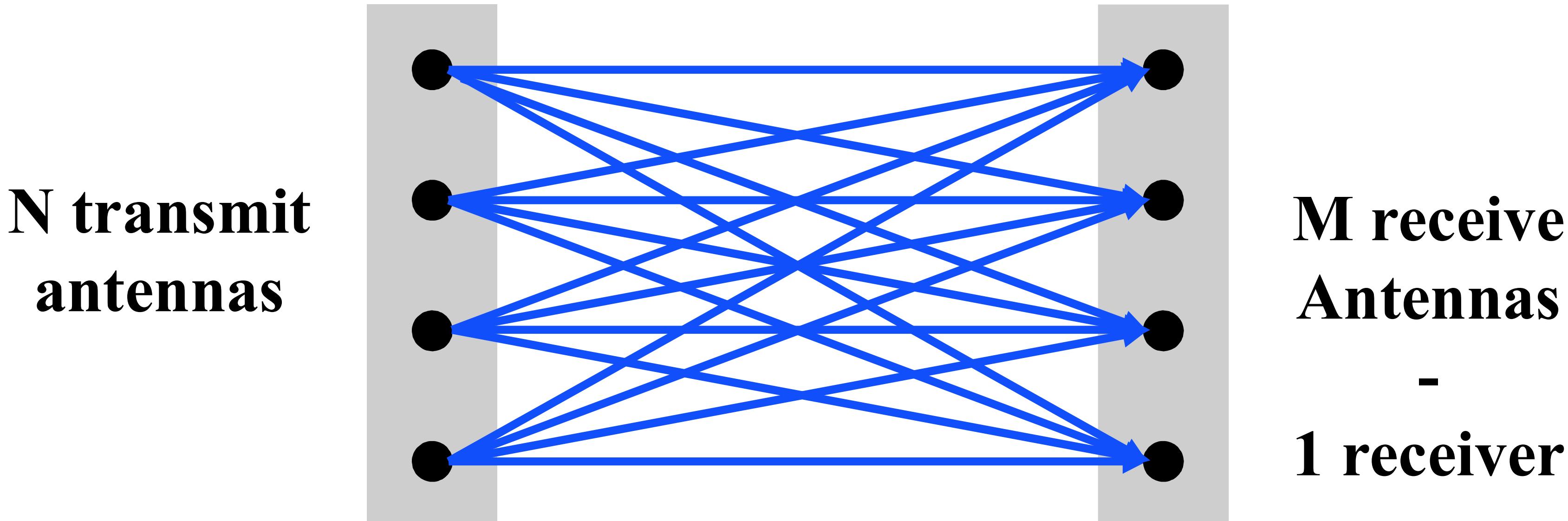


- **Green field mode: use 802.11n OFDM format**

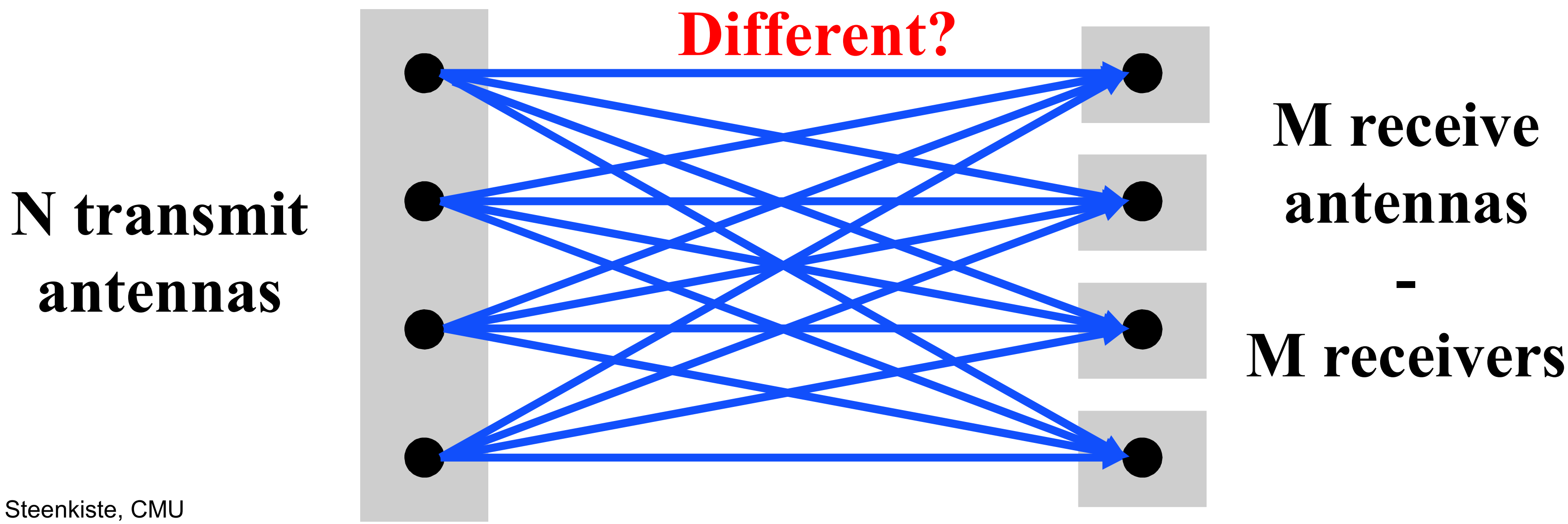


 http://rfmw.em.keysight.com/wireless/helpfiles/n7617a/mimo_ofdm_signal_structure.htm

MIMO in a Network Context

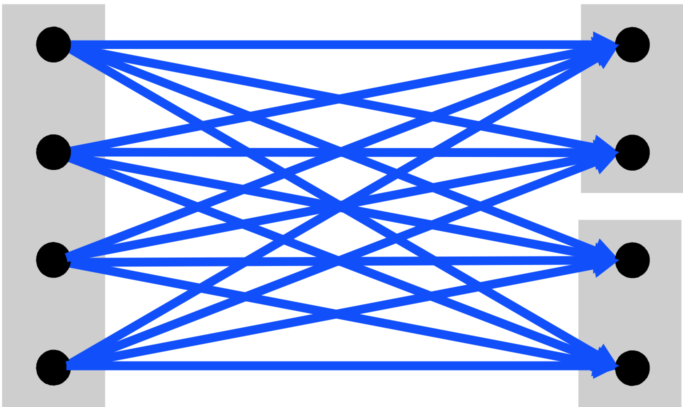


How is this Different?



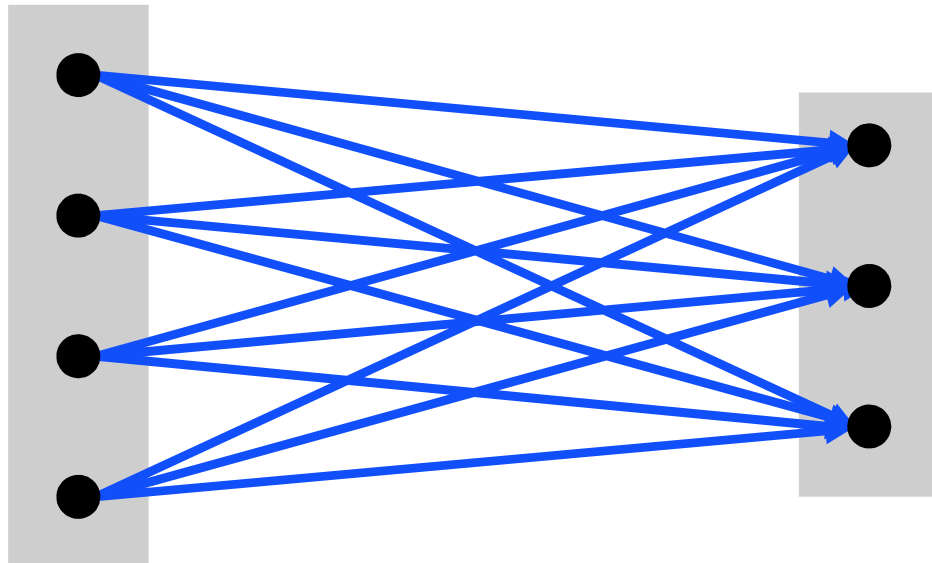
Multi-User MIMO Discussion

- 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
  - » Cannot cancel interference – limits ability to extract useful data
  - » Can only do transmit-side preprocessing
- 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



How about This?

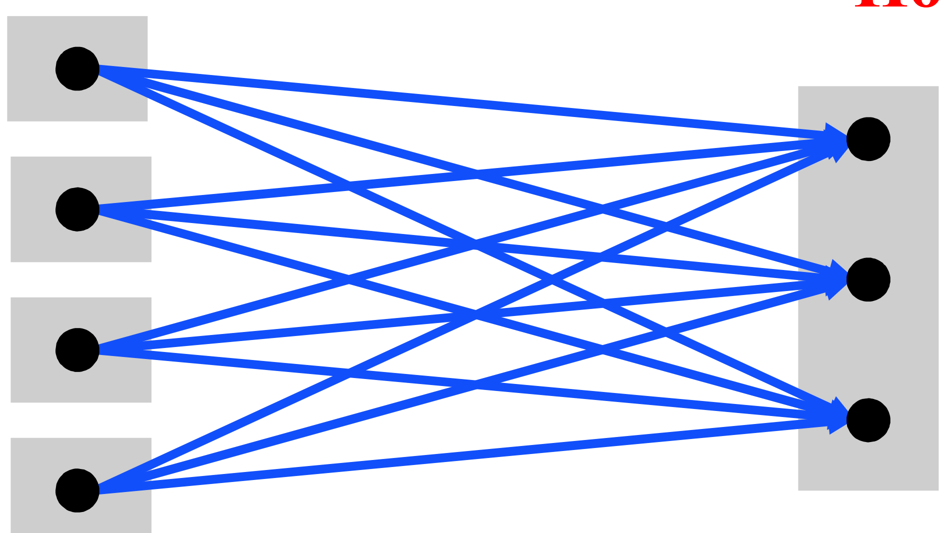
N transmit antennas



M receive Antennas
-
1 receiver

How is this Different?

N transmit antennas



M receive antennas
-
M receivers

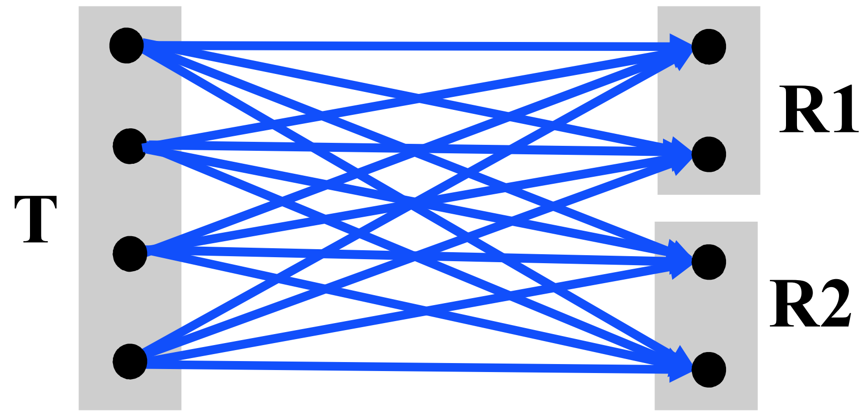
Multi-User MIMO
Up versus Down Link

- 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!
  - » Tricky for traditional CSMA-CA protocols

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

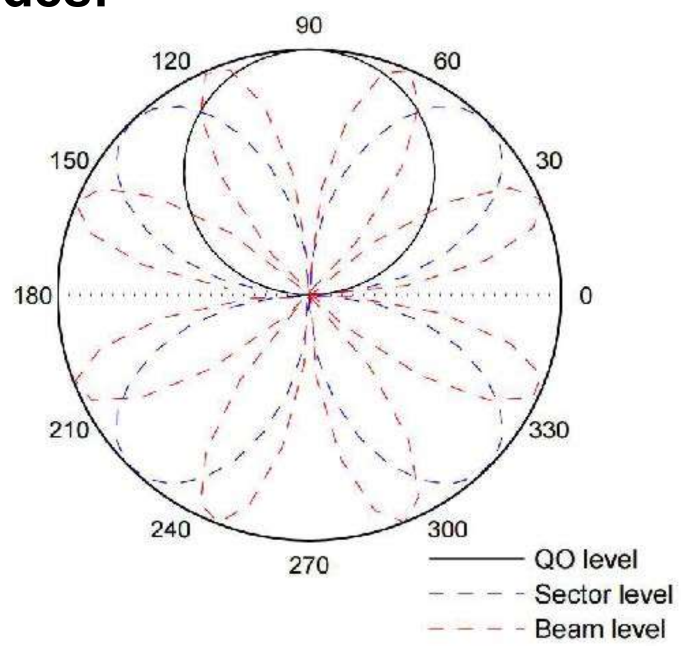
- Becomes a scheduling problem: for each "packet" transmission, identify the destinations that have traffic waiting and that are "the most" orthogonal

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 (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



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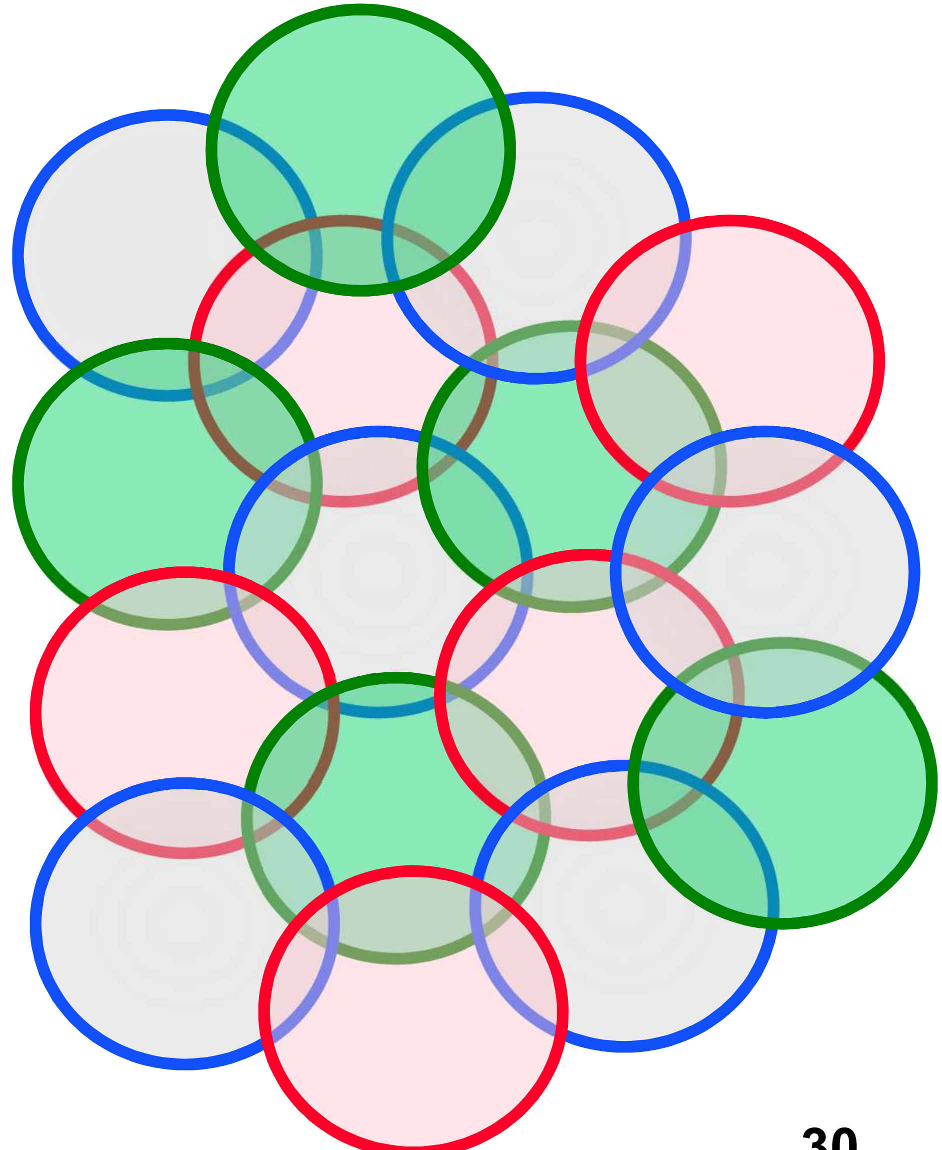
  - Refresher: spatial diversity
  - MIMO basics
  - Single user MIMO: 802.11n
  - Multi-user MIMO: 802.11ac
  - Millimeter wave: 802.11ad
- WiFi deployments
  - Planning
  - Channel selection
  - Rate adaptation

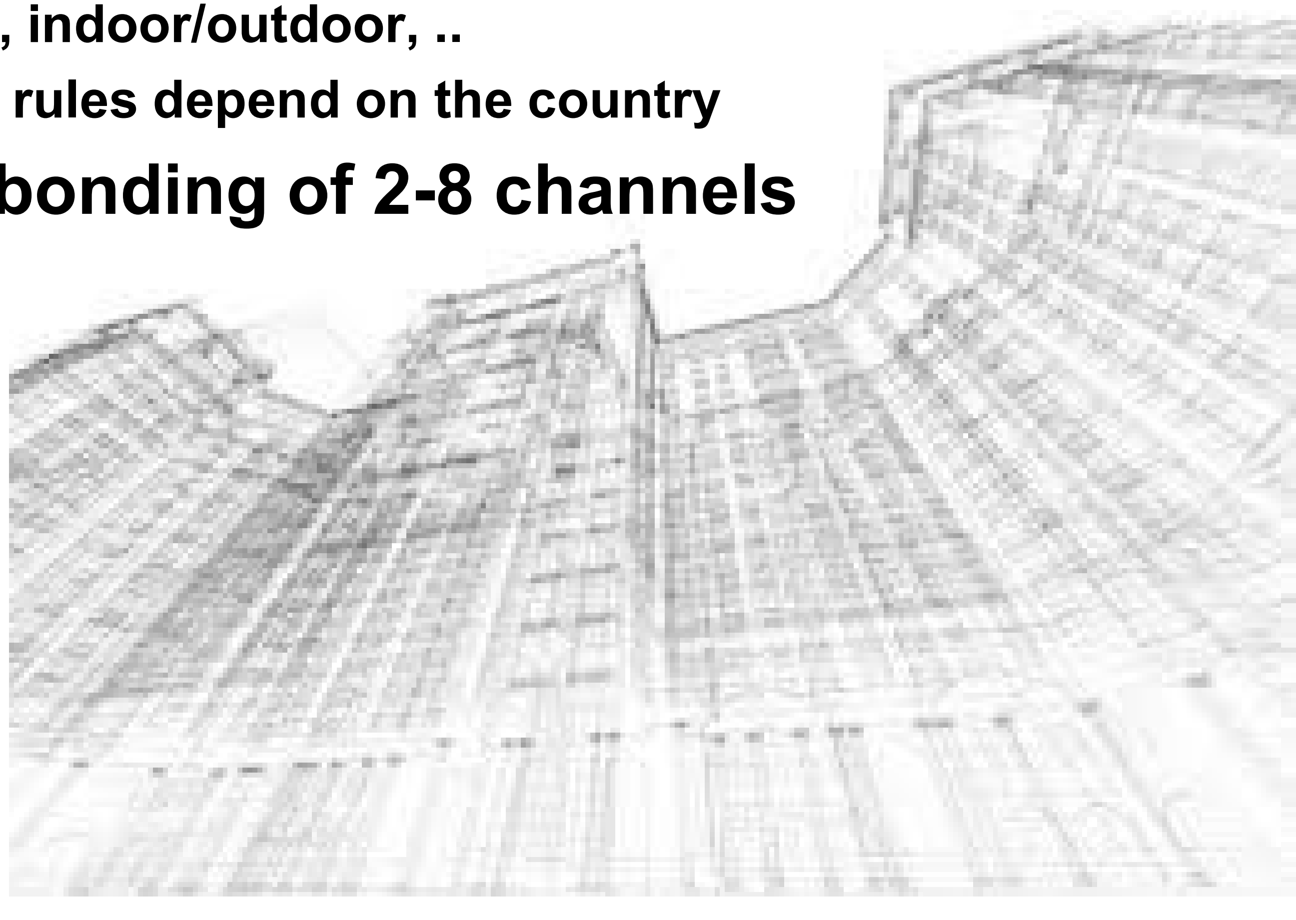
Infrastructure Deployments Frequency Reuse in Space

- **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!

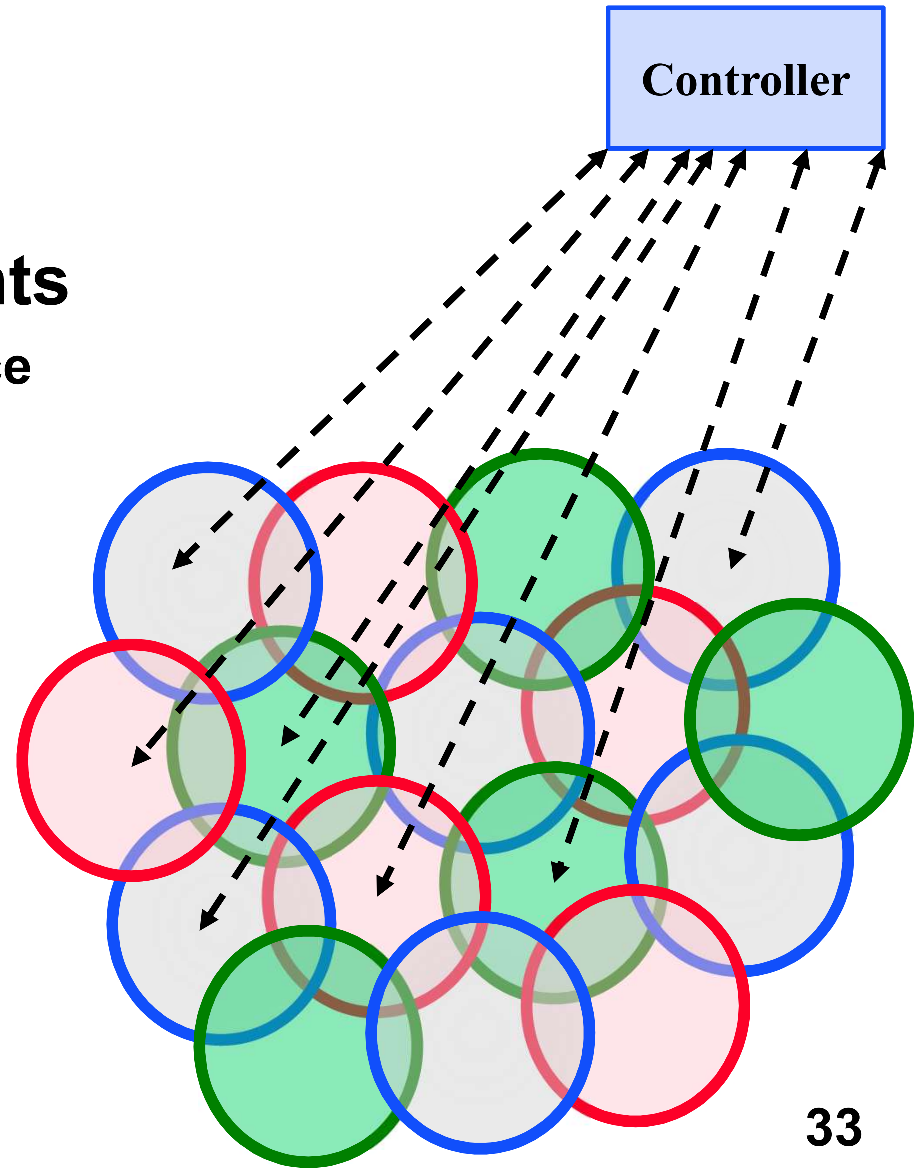


Frequency Planning

- 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 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