18-452/18-750
Wireless Networks and Applications
Lecture 7: MIMO

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Spring Semester 2024

http://www.cs.cmu.edu/~prs/wirelessS24/

Announcements

- **Gradescope questionaires**
  - » Status P1 laptop set up and background/interests
- **P1 project: status so far**
  - » Problems limited to Windows on older devices?
  - » If you are in this situation you have some options
    - – Borrow a laptop from someone
    - – I have a (very old!) loaner
    - – I ordered a USB WiFi device that should work
  - » There is no time pressure for P1
- **HW 1 will be released early next week**
- **Please refresh the course web page regularly**
  - » Ensure you get the up-to-date version of handouts

Outline

- RF introduction
- Modulation and multiplexing
- Channel capacity
- Antennas and signal propagation
- Modulation
- Diversity and coding
  - » Space, time and frequency diversity
  - » Spread spectrum
- OFDM and MIMO

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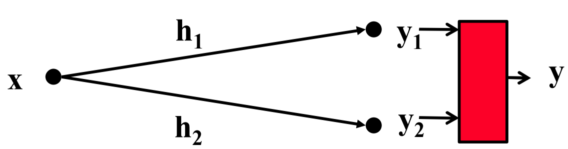
Reminder: Spatial Diversity

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



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

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

- 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)

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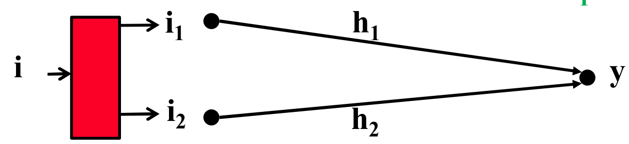
Other Diversity Options

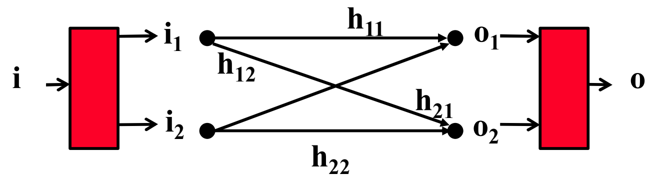
- **Transmit diversity:**

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



- **Combined:**

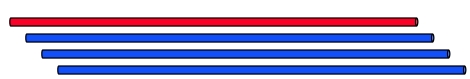
$i \times \vec{P}_T \times H \times \vec{P}_R = o$



How Do We Increase Throughput in Wireless?

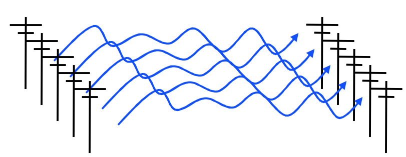
- **Wired world:**

Pull more wires



- **Wireless world:**

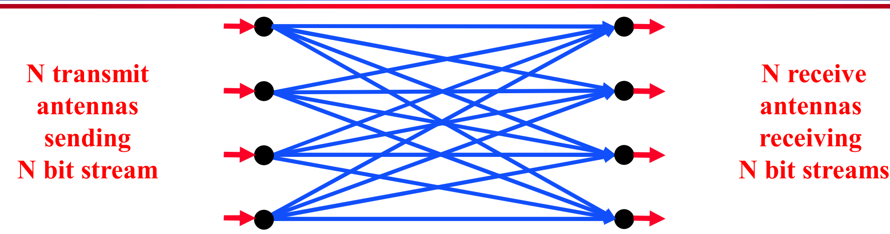
More spectrum bands



- **But spectrum is expensive!**

How about if we could send parallel data streams in the same spectrum band!

MIMO
Multiple In Multiple Out



- N antennas on sender and receiver = N x N channels
- We use those to send N data streams in parallel
- Instantaneous fading on channels is largely independent
  - Assuming antennas are separate ½ wavelength or more
- Challenge: Each receive antenna will receive weighted sum of all transmitted signals ► lots of interference!
- MIMO builds on ideas from space diversity

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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/MIMO	$NB \log_2(1 + \rho)$

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

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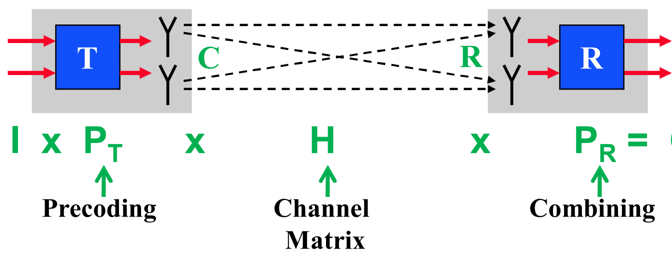
MIMO
How Does it Work?

- **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**

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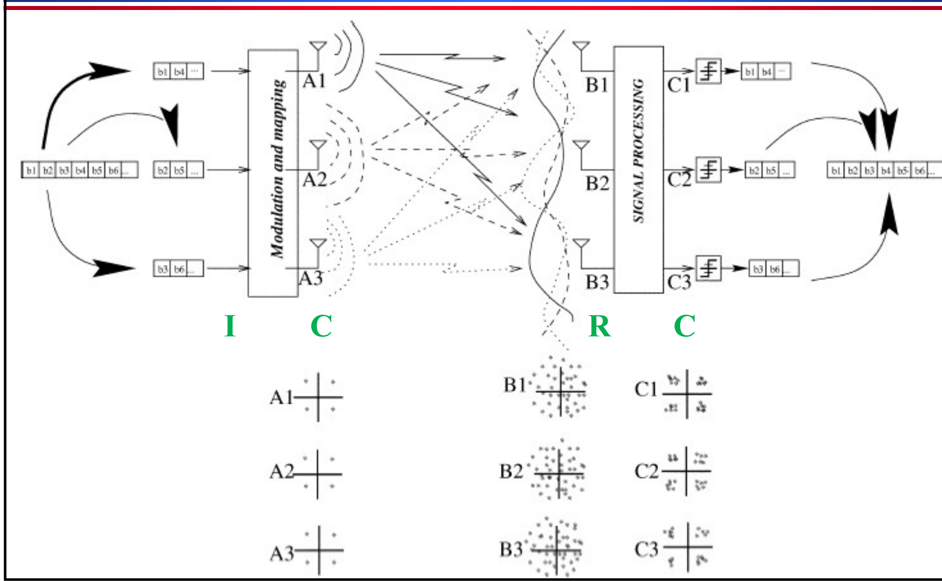
An Example of
Space Coding



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

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

Decoding: $\underset{D}{\vec{O}} = \underset{DxM}{P_R} * \underset{M}{\vec{R}}$ $\qquad \underset{N}{\vec{C}} = \underset{N}{\vec{I}}$ ← No transmit processing

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

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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

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Precoded NxM MIMO

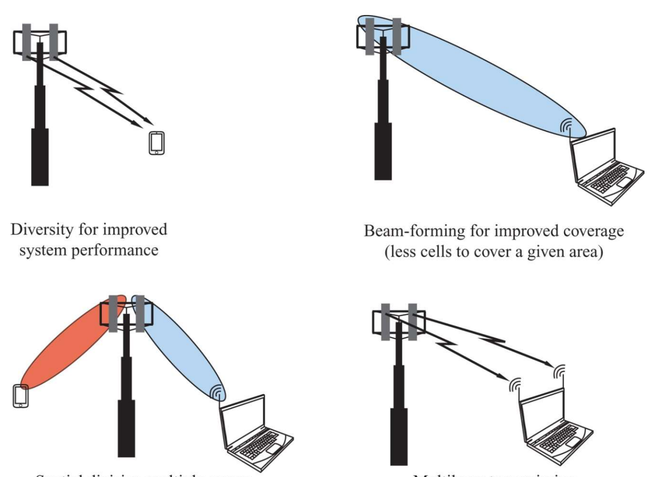
Effect of transmission: $\underset{M}{\vec{R}} = \underset{MxN}{H} * \underset{N}{\vec{C}} + \underset{M}{\vec{N}}$

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

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



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 recent WiFi /cellular 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?

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Increase Useful <u>Aggregate</u> 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

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Outline

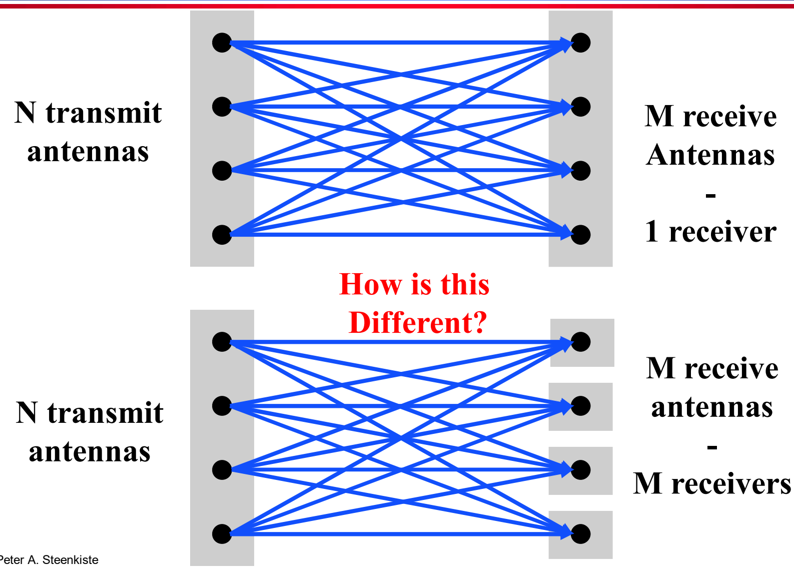
- How do further increase bit rates?
- How about short data short transfers?
  - » Multi-user MIMO
  - » OFDMA
- 802.11n through ax
- WiFi deployments
  - » Planning
  - » Channel selection
  - » Rate adaptation

Not specific to WiFi!

MIMO Limitations

- MIMO makes it possible to achieve very high data rates between two devices
  - » Send multiple data streams in parallel using multiple antennas and radios on the sender and receiver
- Practical scenario: 1 AP with many clients
  - » Common traffic patterns consist of relative small data transfers – Gbps is overkill
  - » MIMO throughput is limited by the device with the fewest antennas - client devices typically have fewer antennas than APs
- Solution: MU-MIMO – AP sends parallel data streams to multiple clients
  - » Or received parallel data streams from multiple clients

MIMO versus MU-MIMO



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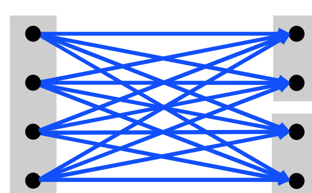
Multi-User MIMO Discussion

- **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**



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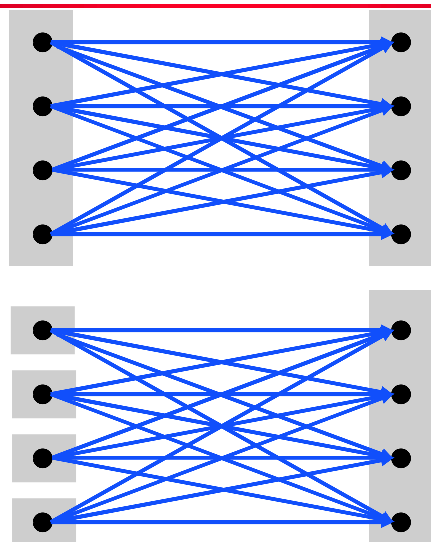
MIMO Upstream



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