

Communications Research at WVU

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*West Virginia University
Morgantown, West Virginia
Fall 2009*

Presentation Outline

- The Wireless Communications Research Lab (WCRL)
- Classes related to communications research
- The relationship between information theory, communication theory, and signal processing.
- Point-point information theory
- Flow networks and the max-flow min-cut theorem
- Application to multiple access channels and relay channels
- Recent, ongoing, and future work.

The WCRL (wcrl.csee.wvu.edu or wcrlcluster.csee.wvu.edu)

- Located in the Engineering Research Building, 2nd floor.
- Serves as the hub for research activity at WVU in the area of communications.
- Supports 4 faculty (Kulathumani, Reynolds, Valenti, Woerner) and a dozen or so M.S./Ph.D. students.
- Projects have been funded by NSF, NASA, DoD, and others.
- There is always room for more good students who love challenging analytical work!

Research Interests/Topics

- (*Reynolds*) Cooperative wireless and wired communications; multiuser communications; multi-antenna communications
- (*Valenti*) Coding theory; grid computing; genetic algorithms for communications; ad hoc and wireless sensor networks; cooperative communications.
- (*Kulathumani*) Wireless sensor networks; distributed systems
- (*Woerner*) Distributed computing and communication systems; multiple-antenna communications; low-power signal processing for communications

Graduate Classes Related to Our Research I/II

- *EE 513 (Stochastic Systems Theory)* A required class that provides background on probability and statistics needed for every student researcher. **Taught every fall.**
- *EE 561 (Communication Theory)* Covers the basic elements of a digital communication system, including its performance in AWGN. **Next taught in Spring 2011.**
- *EE 562 (Wireless Communications)* Describes the unique problems and solutions associated with communicating over a wireless channel. **Next taught in Spring 2010.**
- *EE 591 (Coding Theory)* Covers techniques for error control coding, i.e., for adding controlled redundancy to a bit stream for limiting errors. **Next taught in Spring 2010.**

Graduate Classes Related to Our Research

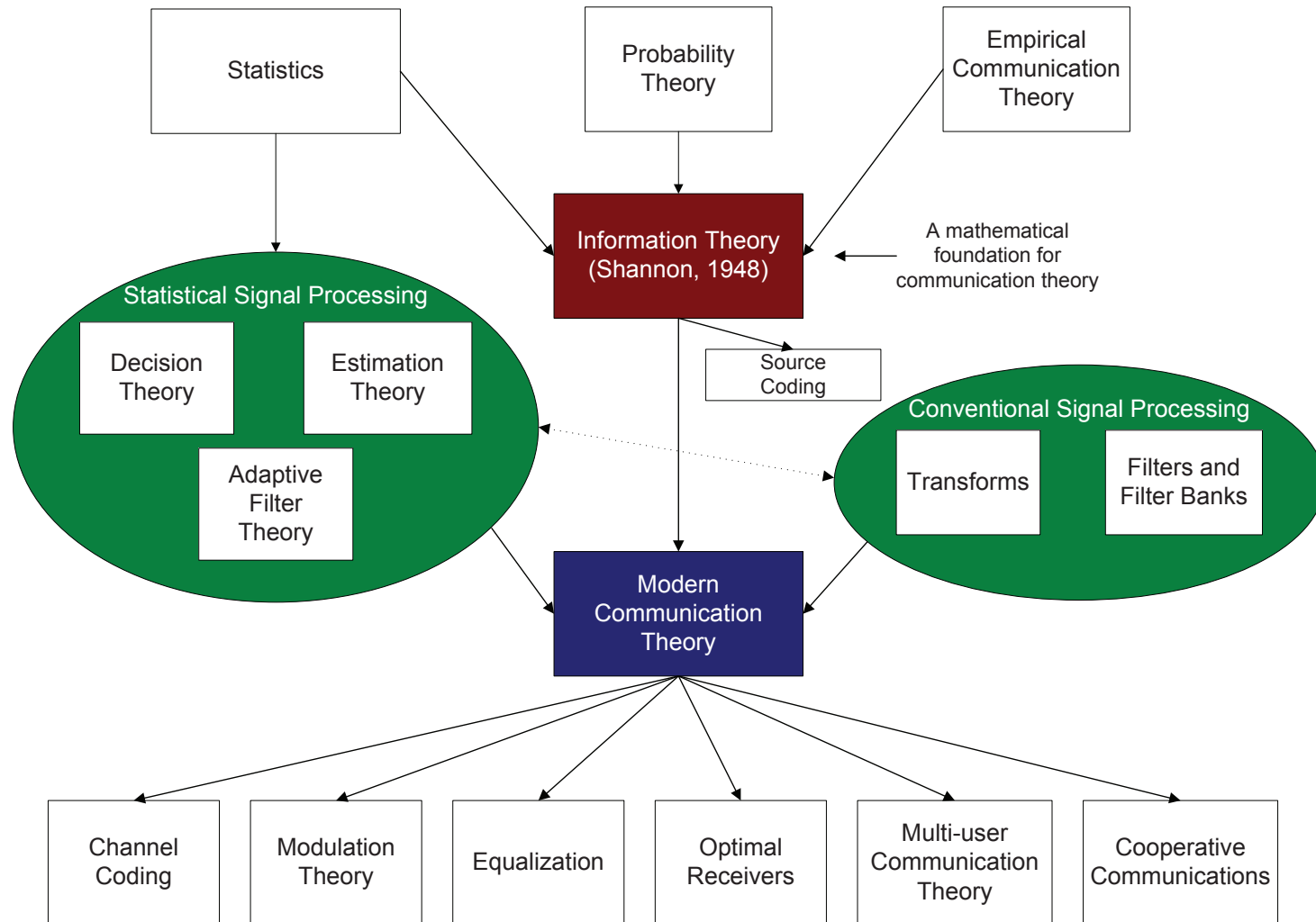
II/II

- *EE 591 (Multiterminal Networks)* A special topics class that will describe the information and communication theories of multiterminal networks. **Planned for Fall 2010.**
- *EE 591 (Introduction to Wireless Sensor Networks)* A special topics class offered in 2008 and 2009 that covers an important application of wireless communications: sensor networks. **Next taught in Fall 2010.**
- *EE 568 (Information Theory)* Covers the basics of information theory. **Next taught in Fall 2010.**

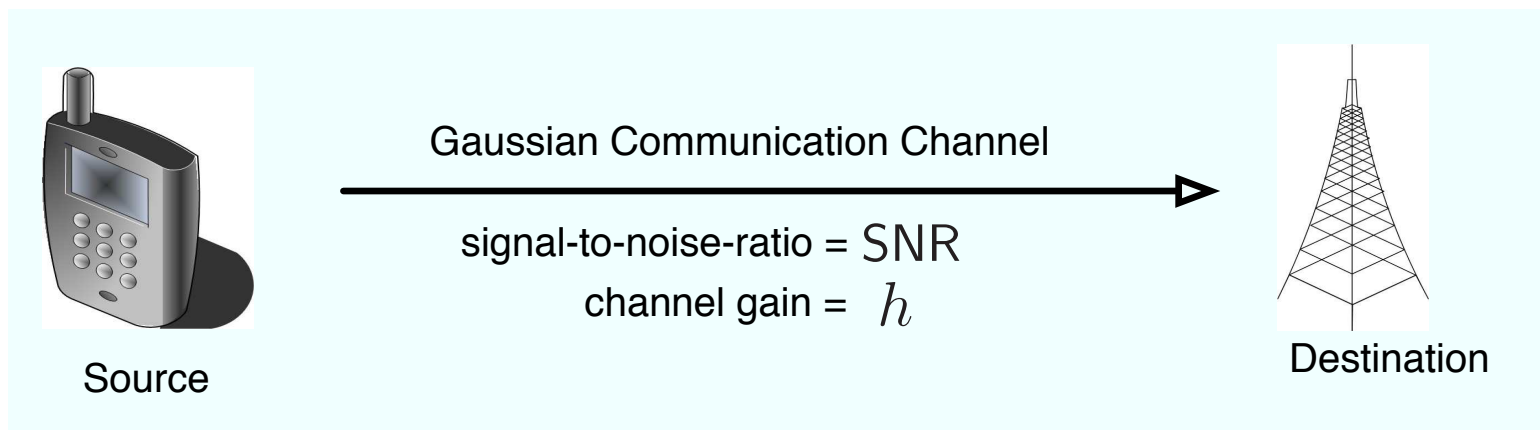
Information Theory, Communication Theory, and Signal Processing

- *Information Theory*: Provides a mathematical and statistical framework for finding fundamental limits for communication, compression/distortion, coding.
- *Communication Theory*: Designs and analyzes codes, modulations, and protocols in an attempt to achieve the limits provided by information theory.
- *Signal Processing for Communications*: Designs and analyzes practical algorithmic structures for manipulating signals to implement communication protocols.

Information Theory, Communication Theory, and Signal Processing

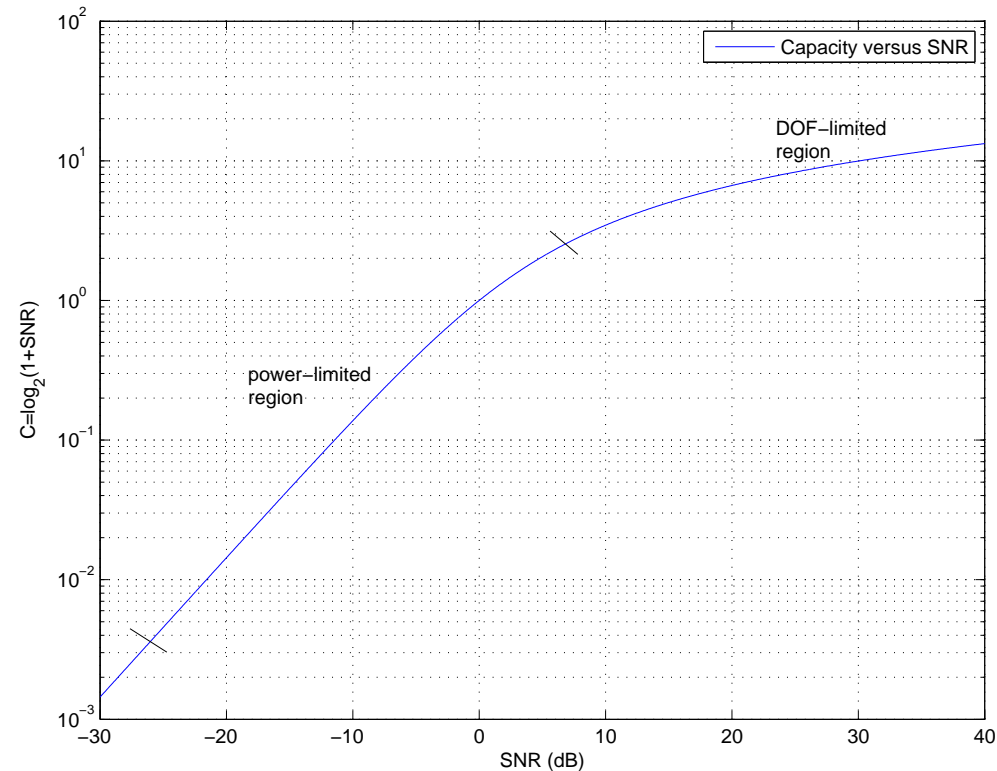


Point-Point Information Theory I/VI



- Assume a channel corrupted by AWGN, i.e., $r(t) = h \cdot s(t) + n(t)$.
- *Capacity* (C) is the highest data rate achievable with low error probability.
- $C = \log_2(1 + |h|^2\text{SNR})$ bits/sec/Hz, provided by information theory (1940's).
- (Almost) achieved in practice with modern communications and signal processing tools.

Point-Point Information Theory II/VI



- *Power-limited region*: Increasing SNR improves C more than increasing bandwidth or time
- *DOF-limited region*: SNR saturates so increasing time and/or bandwidth increases C

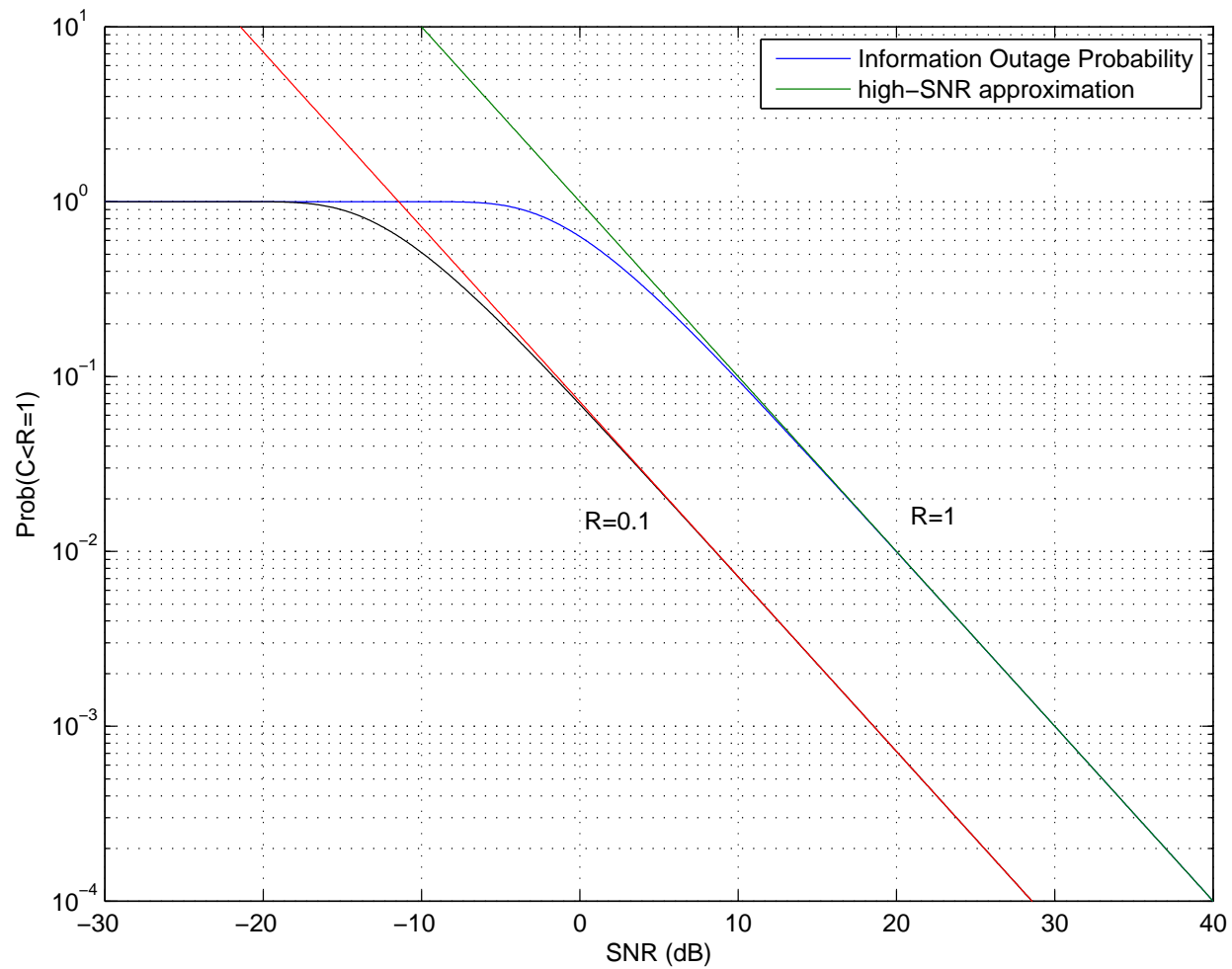
Point-Point Information Theory III/VI

- *Wireless channels*: h is random, so C is random \Rightarrow no guaranteed rate at any particular time!
- *Information outage probability for slow fading*:

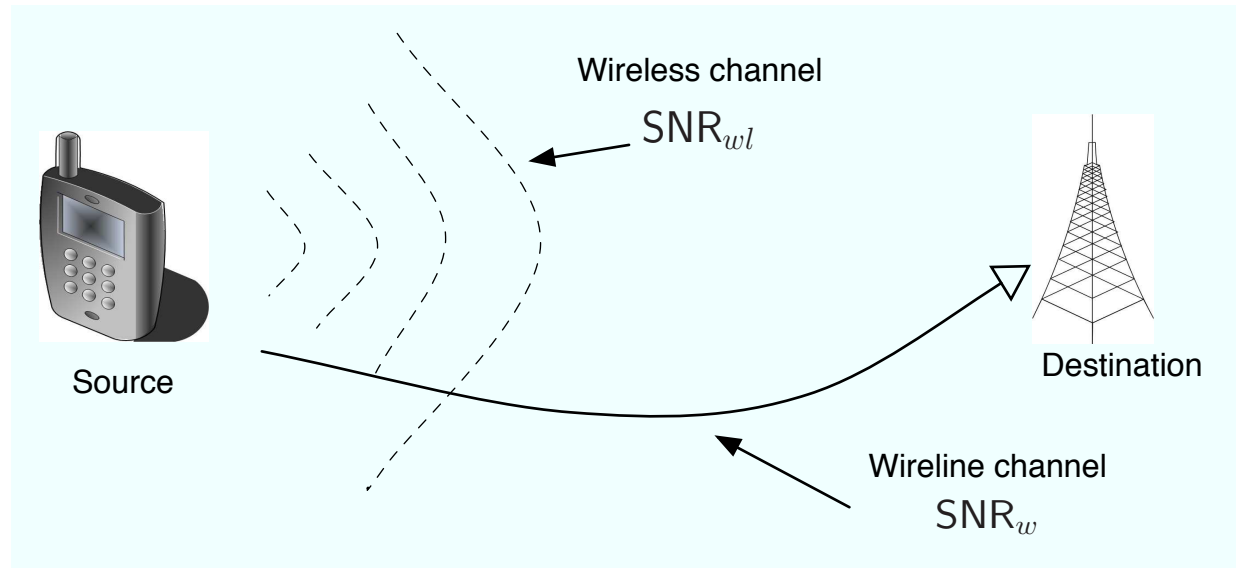
$$\begin{aligned} P_{\text{out}}(R, \text{SNR}) &= \text{Prob}\{C < R\} \\ &= 1 - e^{-\frac{2^R - 1}{\text{SNR}}} \\ &\approx \frac{2^R - 1}{\text{SNR}} \quad \text{at high SNR.} \end{aligned}$$

- Serves as a bound for the error performance of practically coded systems operating at rate (spectral efficiency) R .

Point-Point Information Theory IV/VI



Point-Point Information Theory V/VI



- *Parallel Channels*: Two non-interfering data paths from source to destination, e.g., wire + wireless
- Capacities add:

$$\begin{aligned}
 C &= B_{wl} \log_2(1 + |h_{wl}|^2 \text{SNR}_{wl}) + B_w \log_2(1 + |h_w|^2 \text{SNR}_w) \text{ bits/sec} \\
 &= \underbrace{\log_2(1 + |h_{wl}|^2 \text{SNR}_{wl})}_{C_{wl}} + \underbrace{\frac{B_w}{B_{wl}} \log_2(1 + |h_w|^2 \text{SNR}_w)}_{C_w} \text{ bits/sec/wireless Hz.}
 \end{aligned}$$

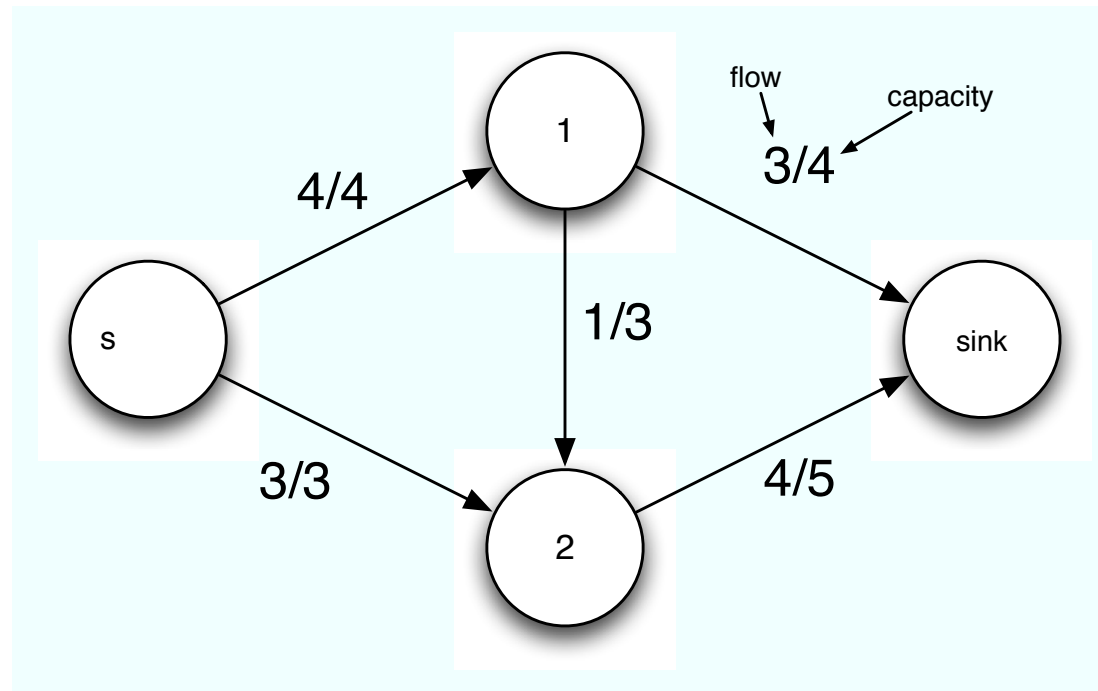
Point-Point Information Theory VI/VI

- C_{wl} is random, but C_w is not.
- *Information outage probability:*

$$\begin{aligned} P_{\text{out}}(R, \text{SNR}) &= \text{Prob}\{C < R\} \\ &= \text{Prob}\{C_{wl} < R - C_w\} \\ &\approx \frac{2^{R-C_w} - 1}{\text{SNR}} \quad \text{at high SNR.} \end{aligned}$$

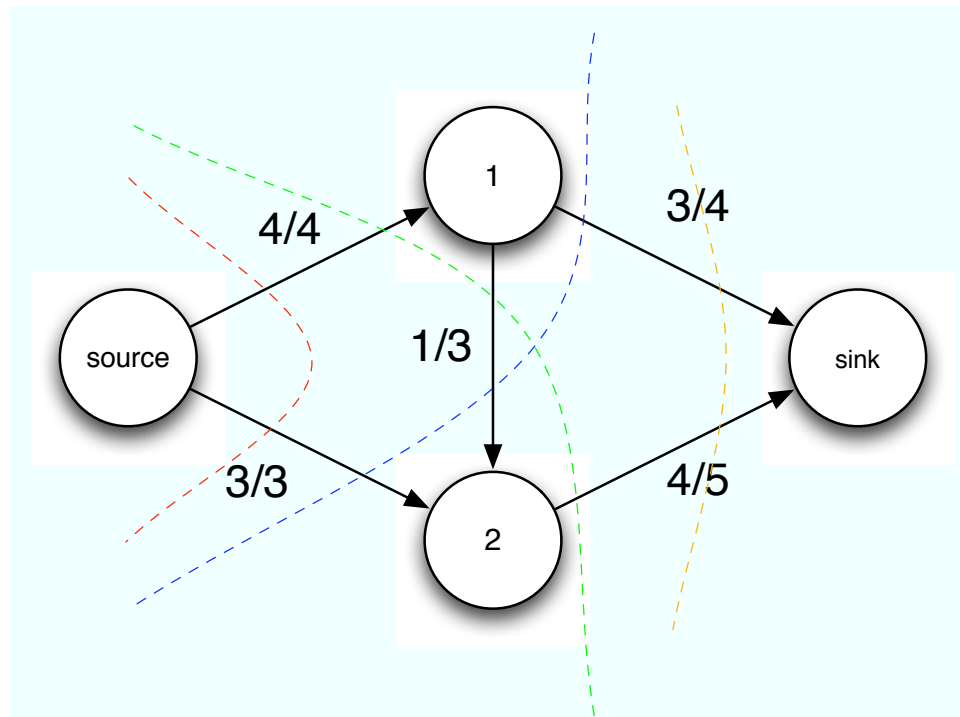
- In a point-point link, the addition of the wire serves to reduce the average rate burden on the wireless channel, improving performance.
- Adding wires in a point-point system is straightforward. What about more than 2 terminals?

Flow Networks



- Directed graph where each edge has a capacity and a flow, often called a generalized network with “nodes” and “arcs” / “edges”.
- Max-flow min-cut theorem: *The maximum value of the flow from source to sink is equal to the minimum capacity of the source-sink cuts.*

Max-flow min-cut



- *Source-sink cut*: partition of the graph into disjoint subsets with the source and sink in different sets.
- Four cuts here, so

$$C = \min\{7, 9, 10, 9\} = 7.$$

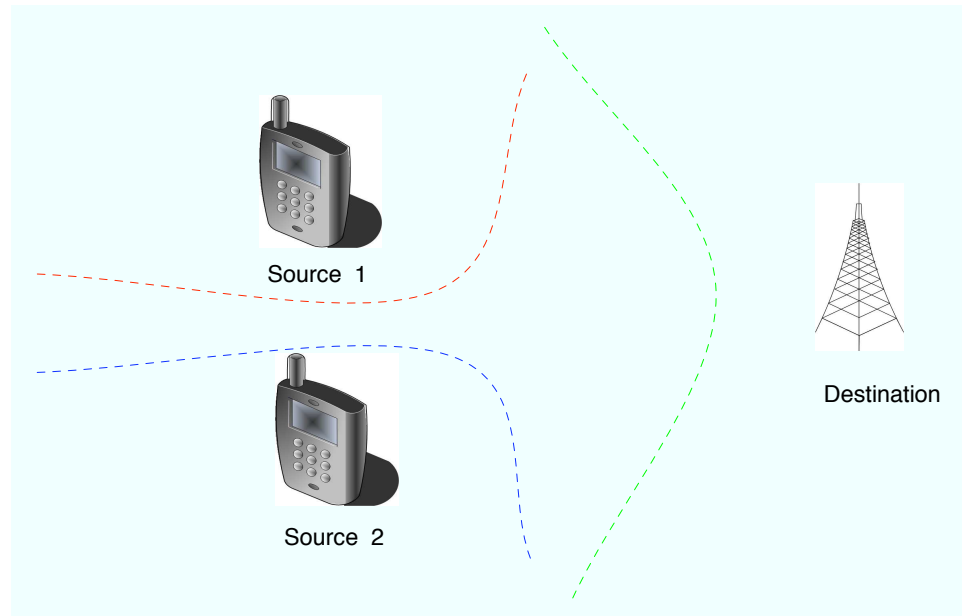
This network is operating at capacity.

What about wireless networks?

- It's easy to calculate the capacity of flow networks. Will this work for wireless networks?
- The bad news: The answer is no.
- Why not?
 - Wireless networks cannot be well defined by a set of point-point links with capacities.
 - Data is fundamentally different from other types of flows, e.g., water or electricity.
- Good news: it works for some cases and provides bounds for most other cases, i.e,

$$C \leq \text{capacity of every cut}$$

Multiple Access Channel (MAC)



- 3 Cuts:

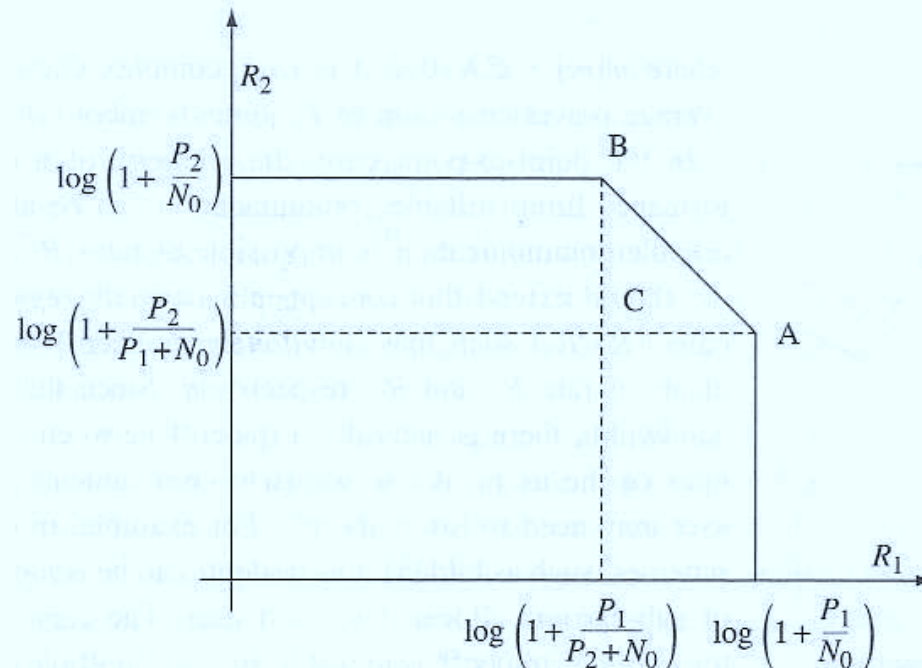
$$R_1 < \log_2 \left(1 + \frac{P_1}{N_0} \right)$$

$$R_2 < \log_2 \left(1 + \frac{P_2}{N_0} \right)$$

$$R_1 + R_2 < \log_2 \left(1 + \frac{P_1 + P_2}{N_0} \right), \text{ NOT } \log_2 \left(1 + \frac{P_1}{N_0} \right) + \log_2 \left(1 + \frac{P_2}{N_0} \right)$$

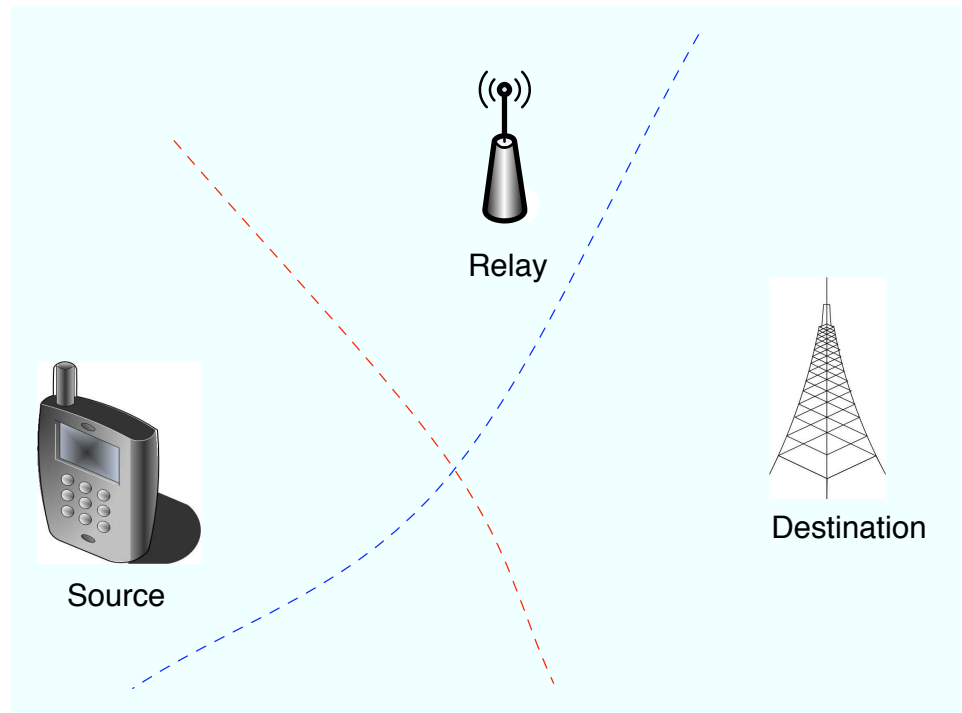
- These rates are achievable!

Implications for Practical MAC Systems



- Points A,B: One user can achieve it's single user rate, while the other use can achieve a non-zero rate!!
- Orthogonal schemes (TDMA/FDMA) cannot do this, but it's possible with CDMA. For point A: receiver considers user 1 as noise, decodes user 2, then subtracts to decode user 1.
- This is an example of the intersection of information theory and communication theory/signal processing.

Single Relay Channel



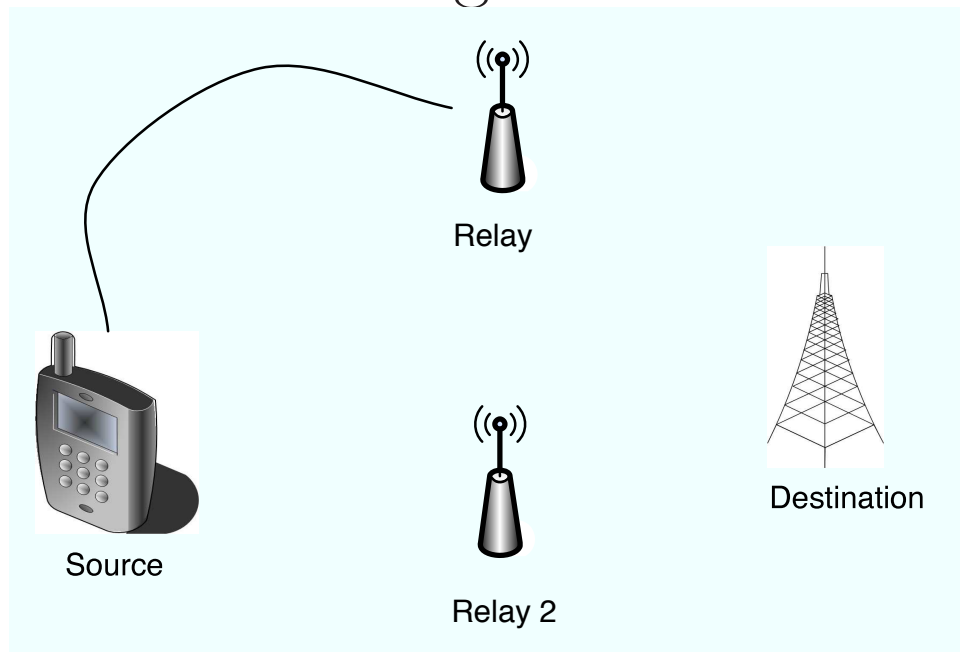
- 2 cuts:

$C <$ capacity from source and relay to destination

$C <$ capacity from source to relay and destination.

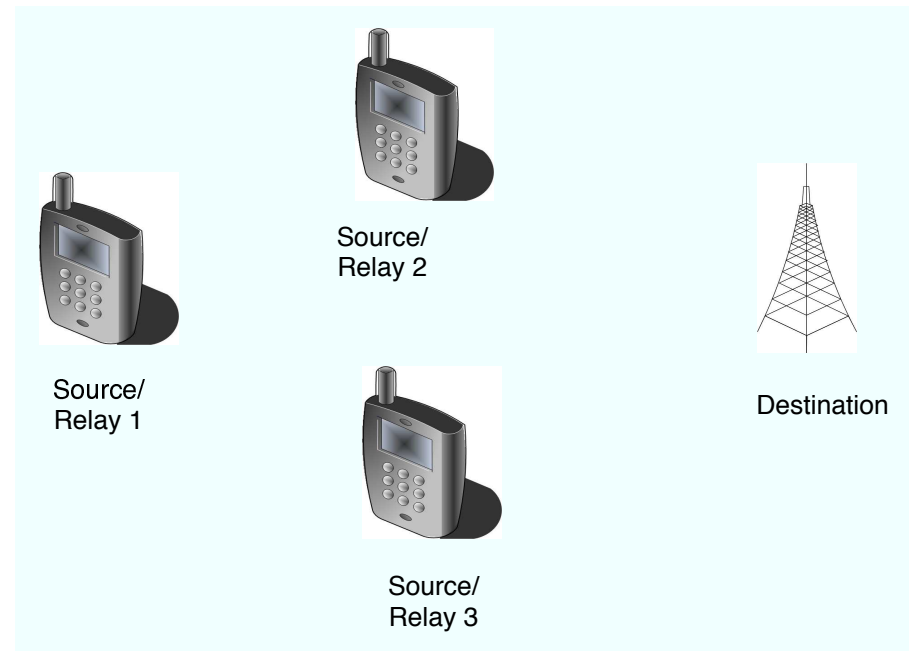
- Not achievable in general. Need more *achievable* rates!

Adding a Wire



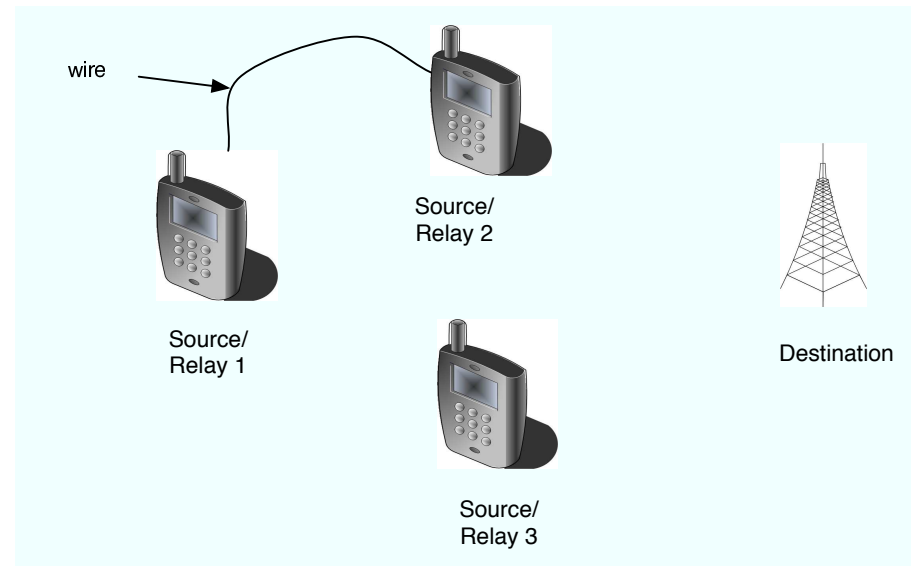
- Cut set bounds still useful, but don't provide achievable rates.
- Wire can be used to improve capacity/reduce outage at relay :)
- Adding power to the wire decreases Relay 2 performance and energy received at destination :(
- Optimal protocols not known, so lots of problems to work on.

Laneman Protocol



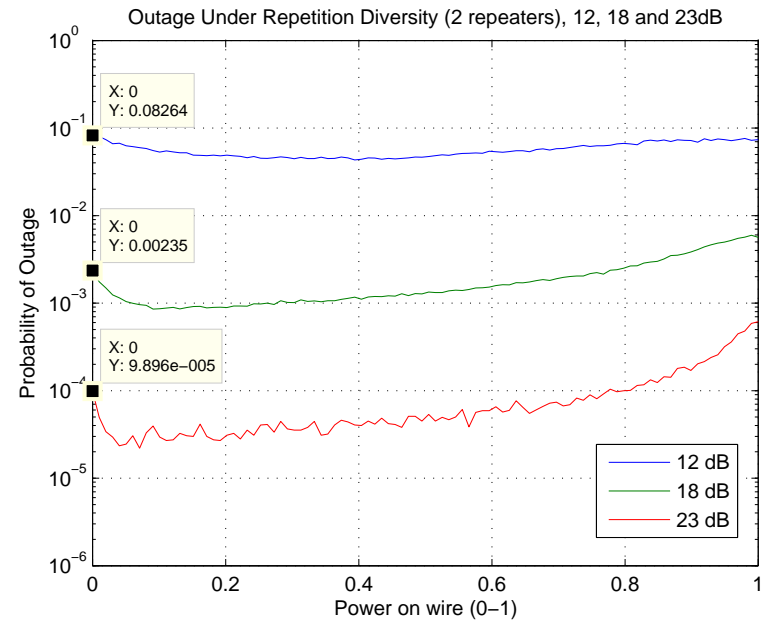
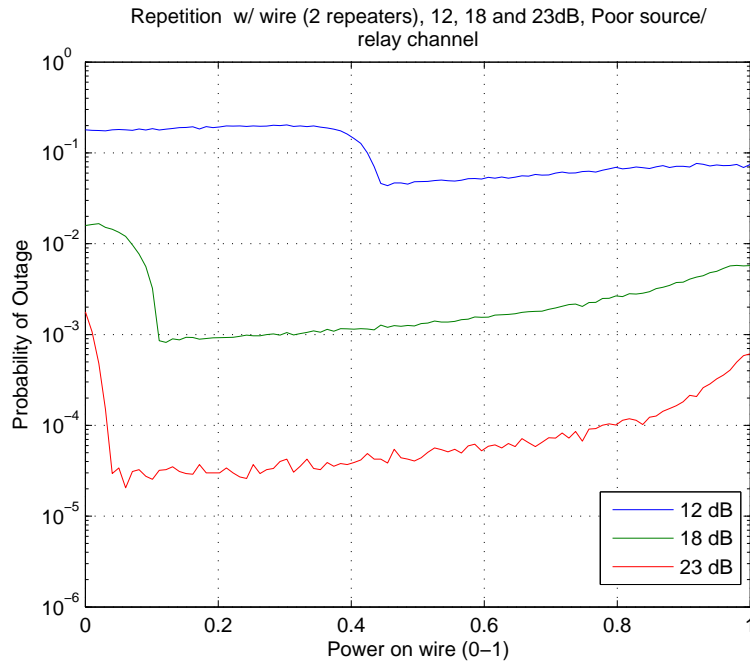
- Works with multiple sources/relays transmitting to a common destination.
- Each transmission uses two time slots: one for source signals and one for relay signals.
- Assumes use of ideal distributed “space-time codes” at the relays.
- Not optimal, but provides a good benchmark for other protocols

Laneman Protocol with Wires



- How much does the wire improve performance?
- How much power should be used on the wire?
- What kind of coding strategy is appropriate for the source?
- Where is the best place for wires?

Outage as a Function of Wire Power



- Performance is improved over large range of wire powers.
- “Kink” occurs because once wired relay can decode, more power is wasteful.
- Working on analytical expressions for outage and the optimal wire power.

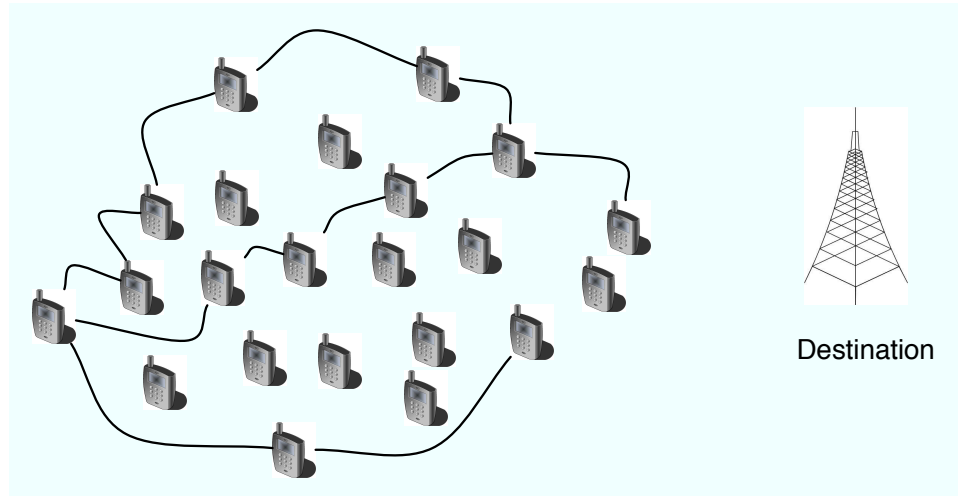
Multistage Relaying

- Similar to Laneman, but *multiple stages* are allowed.
- Increasing stages (T) increases SNR but decreases degrees of freedom (D):

$$\frac{1}{T} \log_2(1 + \text{SNR})$$

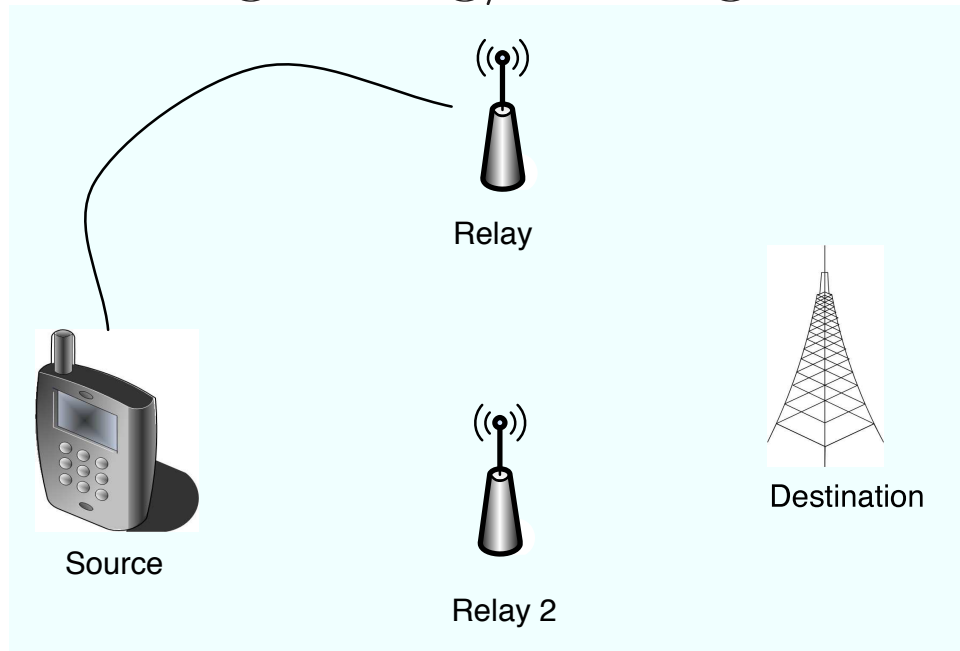
- Optimal number of stages depends: are we in DOF-limited region or SNR-limited region?
- Result: In most practical cases 3-4 stages is best. 2 is always best as $\text{SNR} \rightarrow \infty$.
- Number of stages depends upon relative locations.

Large System Analysis with Wires



- In large purely wireless networks, performance scales poorly, depending upon assumptions.
- How can wires help? How percentage of wired links is required?
- Is it best to have wires on the outside of the network or on the inside?
- What kind of wires are needed? High-bandwidth? Low-bandwidth?
- Should wires span large distances or short distances?

Practical Signalling/Coding with Wires



- What kind of modulation/coding works best with wired/wireless networks?
- Ignoring the relay aspect of the network is a bad idea.
- What kind of multiple access is best with wires, keeping in mind that wires are not broadcast?

Summary and Conclusions

- Lots of interesting funded research going in in the WCRL. Good opportunities for analytically-minded students.
- If you are interested in communications, talk to a WCRL faculty and take the right classes.
- Cooperative communications, with or without wires is a wide-open area of research with lots of interesting problems.
- Prof. Daryl Reynolds: ESB 837, daryl.reynoldsmail.wvu.edu
- Thanks for listening!