Communications Research at WVU

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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, 2\textsuperscript{nd} 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.
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.
• **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**:

$$P_{\text{out}}(R, \text{SNR}) = \text{Prob}\{C < R\}$$

$$= 1 - e^{-\frac{2^R - 1}{\text{SNR}}}$$

$$\approx \frac{2^R - 1}{\text{SNR}} \text{ at high SNR.}$$

- Serves as a bound for the error performance of practically coded systems operating at rate (spectral efficiency) $R$. 
Point-Point Information Theory IV/VI

SNR (dB) vs. Prob(C<R=1)

- Information Outage Probability
- high-SNR approximation

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

• Capacities add:

\[
C' = B_{wl} \log_2 (1 + |h_{wl}|^2 \text{SNR}_{wl}) + B_w \log_2 (1 + |h_w|^2 \text{SNR}_w) \text{ bits/sec} \\
= \left( \frac{B_w}{B_{wl}} \right) C_{wl} + \frac{B_w}{B_{wl}} C_w \text{ bits/sec/wireless Hz.}
\]
Point-Point Information Theory VI/VI

- $C_{wl}$ is random, but $C_w$ is not.

- **Information outage probability:**

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

- 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 its 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.
• 2 cuts:

\[ C < \text{capacity from source and relay to destination} \]
\[ C < \text{capacity from source to relay and destination.} \]

• Not achievable in general. Need more achievable rates!
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?
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.

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• Thanks for listening!