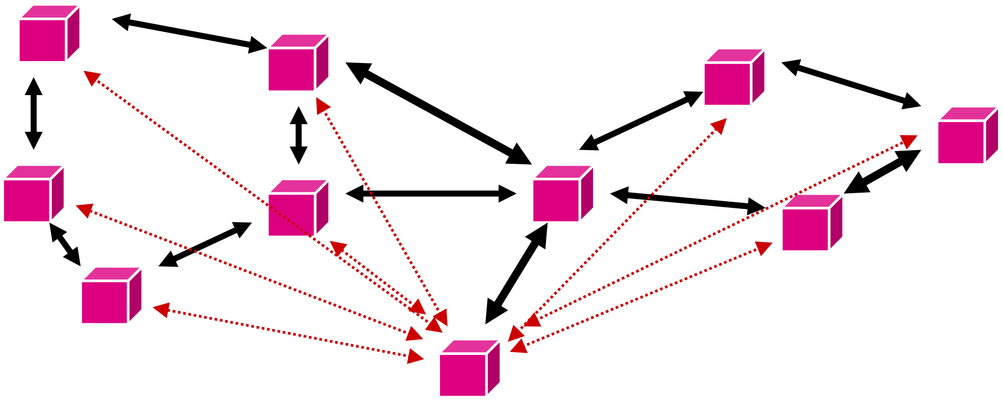
EE360: Lecture 8 Outline
Intro to Ad Hoc Networks

- Announcements
  - Proposal feedback by Wed, revision due following Mon
  - HW 1 posted this week, due Feb. 22
- Overview of Ad-hoc Networks
- Design Issues
- MAC Protocols
- Routing
- Relay Techniques
- Generalized cooperation
- Feedback in Ad-Hoc Networks

Ad-Hoc Networks



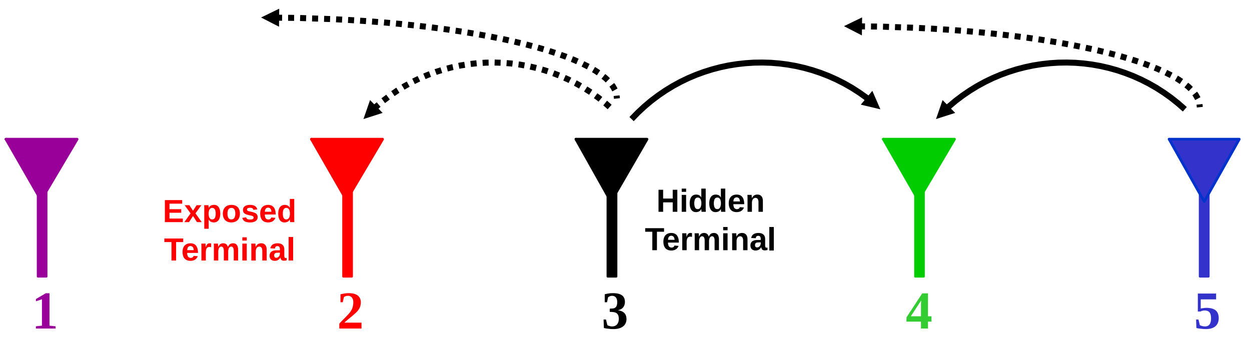
- Peer-to-peer communications
  - No backbone infrastructure or centralized control
- Routing can be multihop.
- Topology is dynamic.
- Fully connected with different link SINRs
- Open questions
  - Fundamental capacity
  - Optimal routing
  - Resource allocation (power, rate, spectrum, etc.) to meet QoS

Ad-Hoc Network Design Issues

- Ad-hoc networks provide a flexible network infrastructure for many emerging applications.
- The capacity of such networks is generally unknown.
- Transmission, access, and routing strategies for ad-hoc networks are generally ad-hoc.
- Crosslayer design critical and very challenging.
- Energy constraints impose interesting design tradeoffs for communication and networking.

Medium Access Control

- Nodes need a decentralized channel access method
  - Minimize packet collisions and insure channel not wasted
  - Collisions entail significant delay
- Aloha w/ CSMA/CD have hidden/exposed terminals



- 802.11 uses four-way handshake
  - Creates inefficiencies, especially in multihop setting

Frequency Reuse

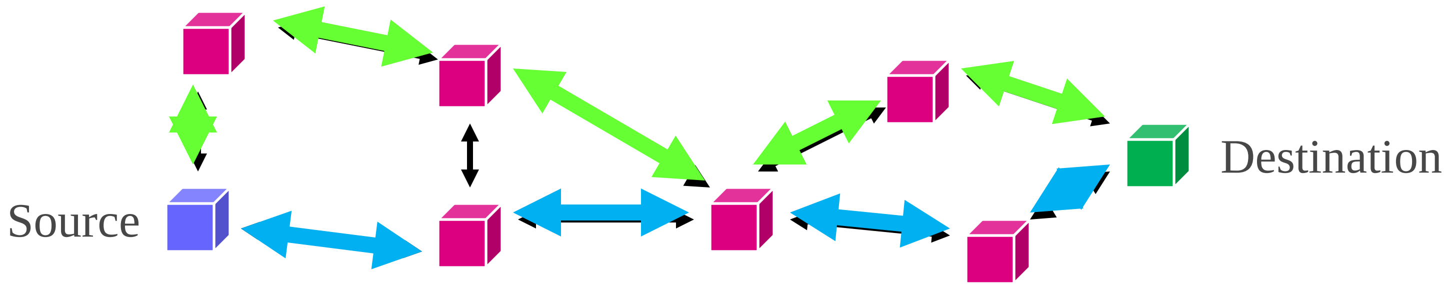
- More bandwidth-efficient
- Distributed methods needed.
- Dynamic channel allocation hard for packet data.
- Mostly an unsolved problem
  - CDMA or hand-tuning of access points.

DS Spread Spectrum: Code Assignment

- Common spreading code for all nodes
  - Collisions occur whenever receiver can "hear" two or more transmissions.
  - Near-far effect improves capture.
  - Broadcasting easy
- Receiver-oriented
  - Each receiver assigned a spreading sequence.
  - All transmissions to that receiver use the sequence.
  - Collisions occur if 2 signals destined for same receiver arrive at same time (can randomize transmission time.)
  - Little time needed to synchronize.
  - Transmitters must know code of destination receiver
    - Complicates route discovery.
    - Multiple transmissions for broadcasting.

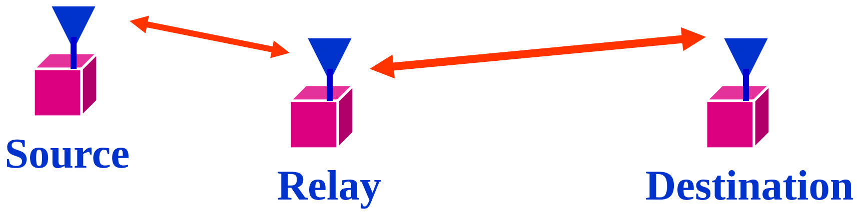
- Transmitter-oriented
  - Each transmitter uses a unique spreading sequence
  - No collisions
  - Receiver must determine sequence of incoming packet
    - Complicates route discovery.
    - Good broadcasting properties
  - Poor acquisition performance
- Preamble vs. Data assignment
  - Preamble may use common code that contains information about data code
  - Data may use specific code
  - Advantages of common and specific codes:
    - Easy acquisition of preamble
    - Few collisions on short preamble
    - New transmissions don't interfere with the data block

Introduction to Routing



- Routing establishes the mechanism by which a packet traverses the network
- A "route" is the sequence of relays through which a packet travels from its source to its destination
- Many factors dictate the "best" route
- Typically uses "store-and-forward" relaying
  - Network coding breaks this paradigm

Relay nodes in a route



- Intermediate nodes (relays) in a route help to forward the packet to its final destination.
- Decode-and-forward (store-and-forward) most common:
  - Packet decoded, then re-encoded for transmission
  - Removes noise at the expense of complexity
- Amplify-and-forward: relay just amplifies received packet
  - Also amplifies noise: works poorly for long routes; low SNR.
- Compress-and-forward: relay compresses received packet
  - Used when Source-relay link good, relay-destination link weak

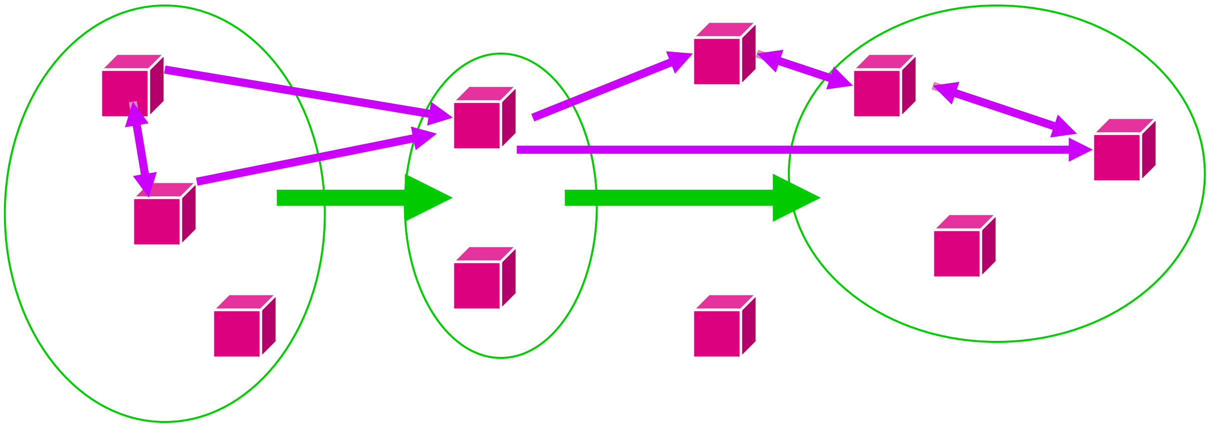
Often evaluated via capacity analysis

Routing Techniques

- Flooding
  - Broadcast packet to all neighbors
- Point-to-point routing
  - Routes follow a sequence of links
  - Connection-oriented or connectionless
- Table-driven
  - Nodes exchange information to develop routing tables
- On-Demand Routing
  - Routes formed “on-demand”

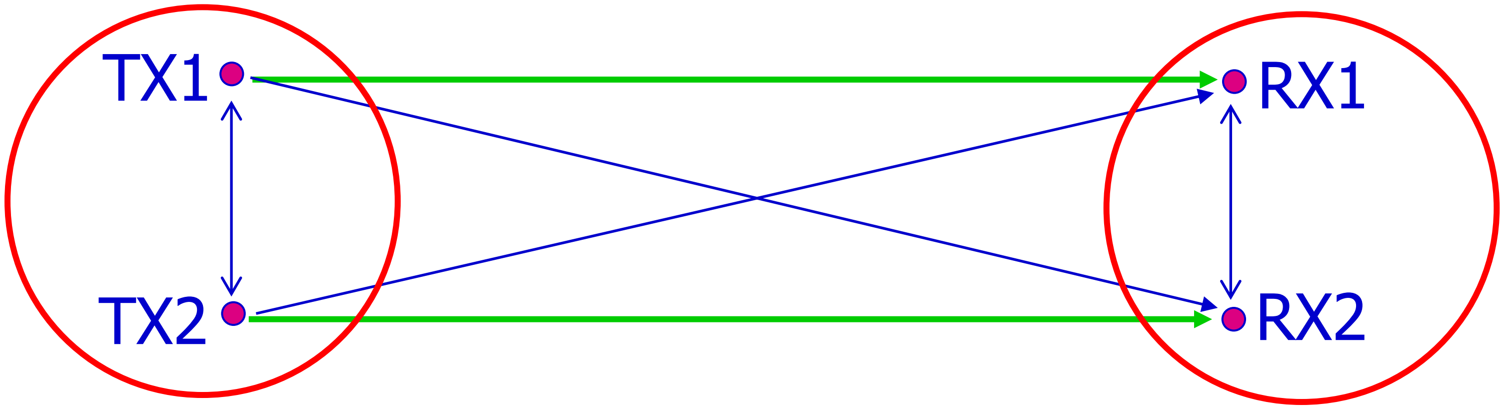
“E.M. Royer and Chai-Keong Toh, “A review of current routing protocols for ad hoc mobile wireless networks,” IEEE Personal Communications Magazine, Apr 1999.”

Cooperation in Wireless Networks



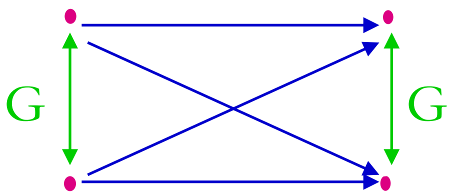
- Routing is a simple form of cooperation
- Many more complex ways to cooperate:
  - Virtual MIMO , generalized relaying, interference forwarding, and one-shot/iterative conferencing
- Many theoretical and practice issues:
  - Overhead, forming groups, dynamics, synch, …

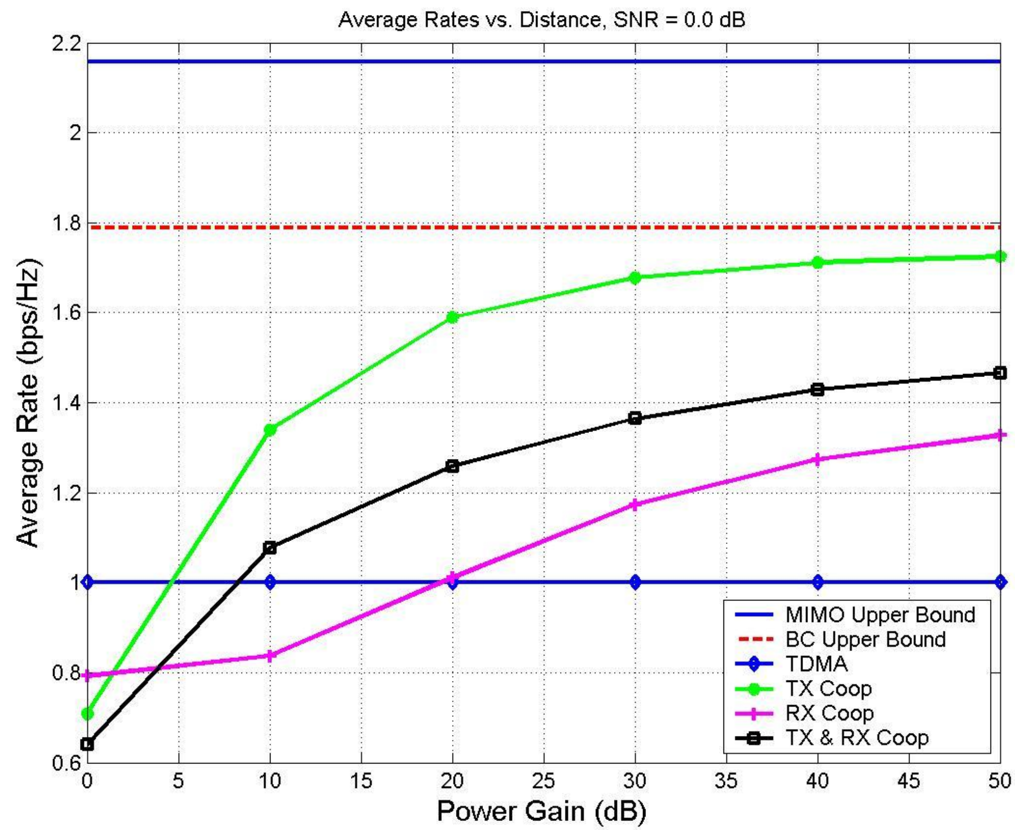
Virtual MIMO



- TX1 sends to RX1, TX2 sends to RX2
- TX1 and TX2 cooperation leads to a MIMO BC
- RX1 and RX2 cooperation leads to a MIMO MAC
- TX and RX cooperation leads to a MIMO channel
- Power and bandwidth spent for cooperation

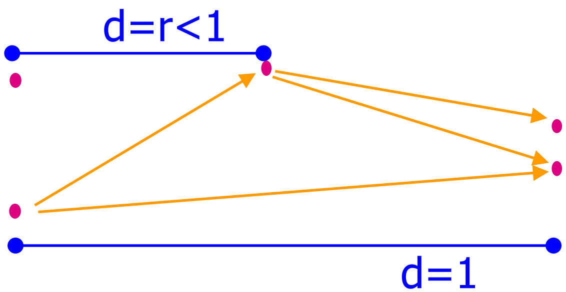
Capacity Gain with Cooperation (2x2)

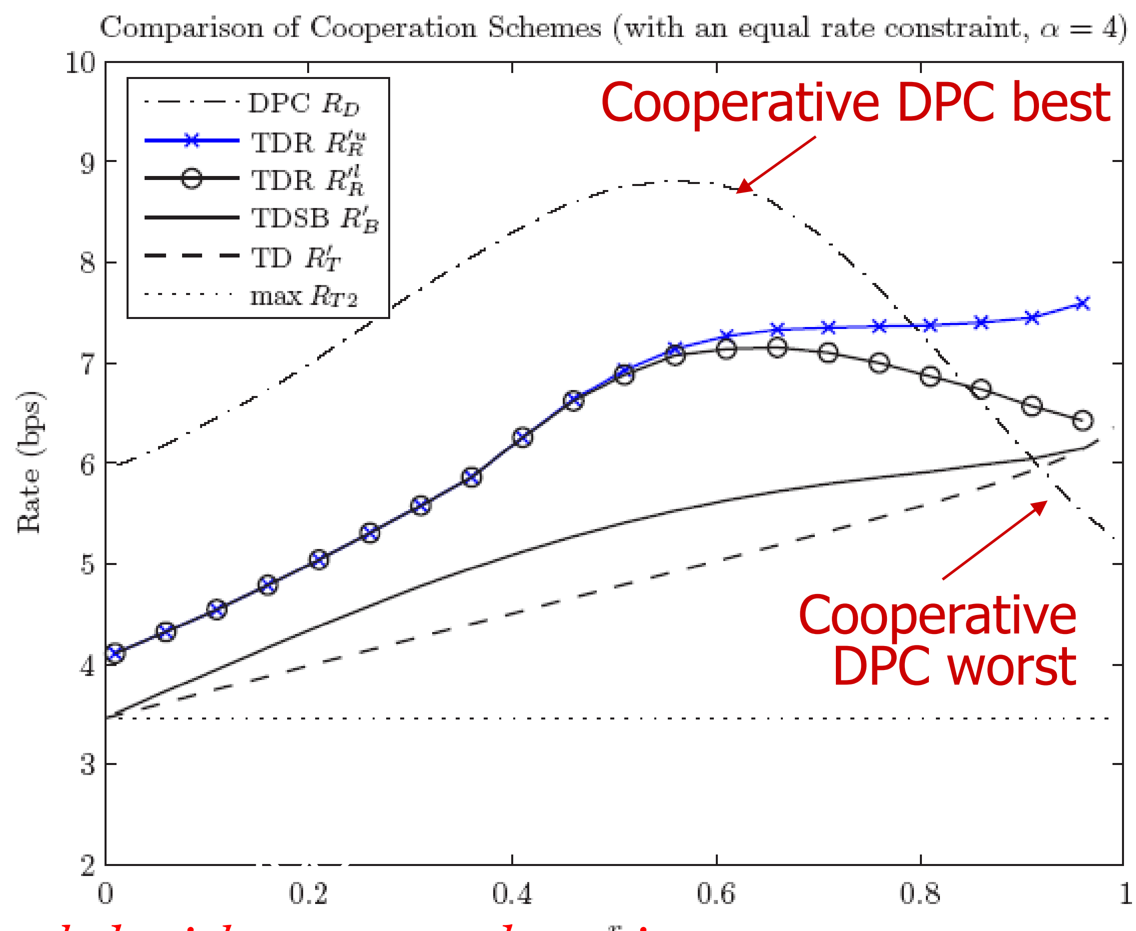




- **TX cooperation needs large cooperative channel gain to approach broadcast channel bound**
- **MIMO bound unapproachable**

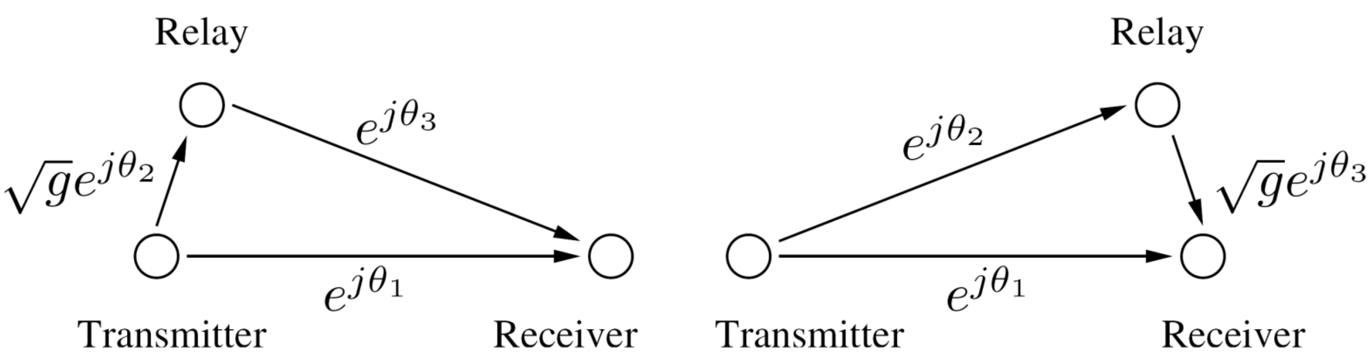
Capacity Gain vs Network Topology





Optimal cooperation coupled with access and routing

Relative Benefits of TX and RX Cooperation



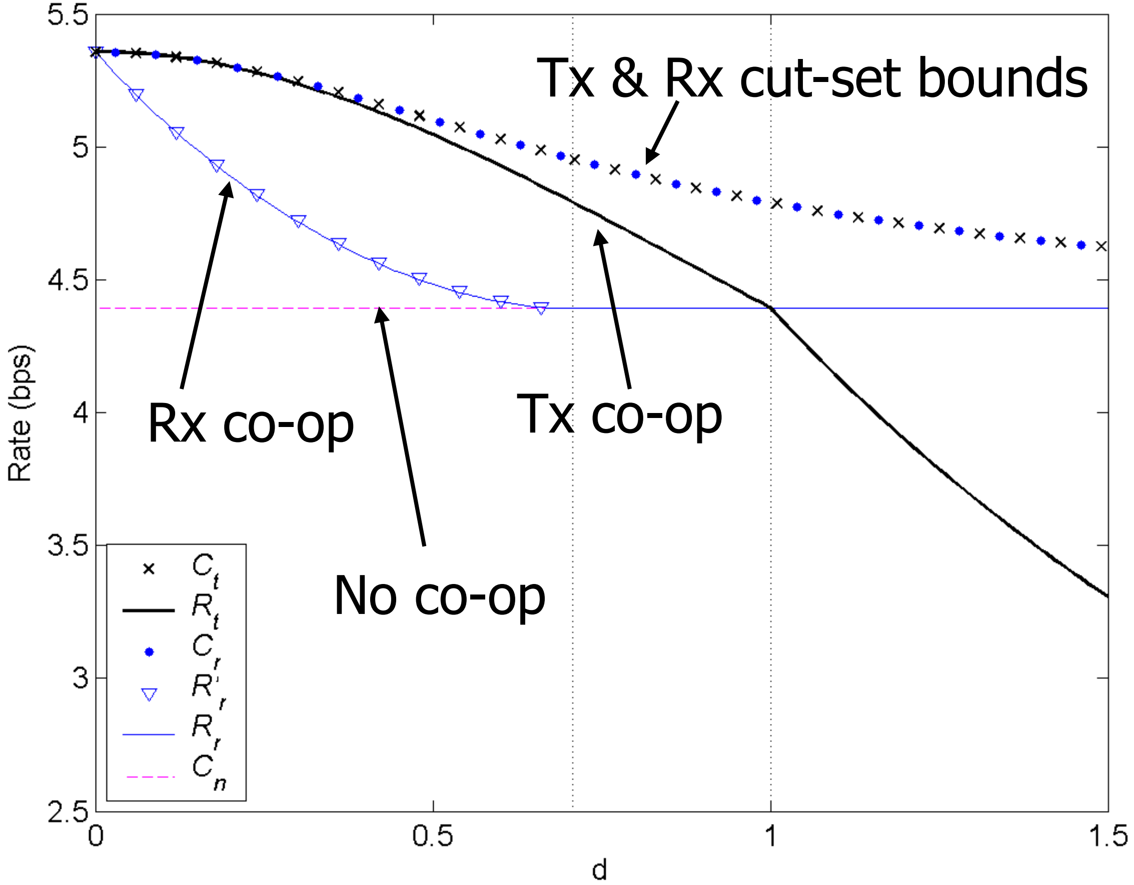
(a) Transmitter cooperation (b) Receiver cooperation

- **Two possible CSI models:**
  - **Each node has full CSI (synchronization between Tx and relay).**
  - **Receiver phase CSI only (no TX-relay synchronization).**
- **Two possible power allocation models:**
  - **Optimal power allocation: Tx has power constraint *aP*, and relay (1-*a*)*P*; 0≤*a*≤1 needs to be optimized.**
  - **Equal power allocation (*a* = ½).**

Joint work with C. Ng

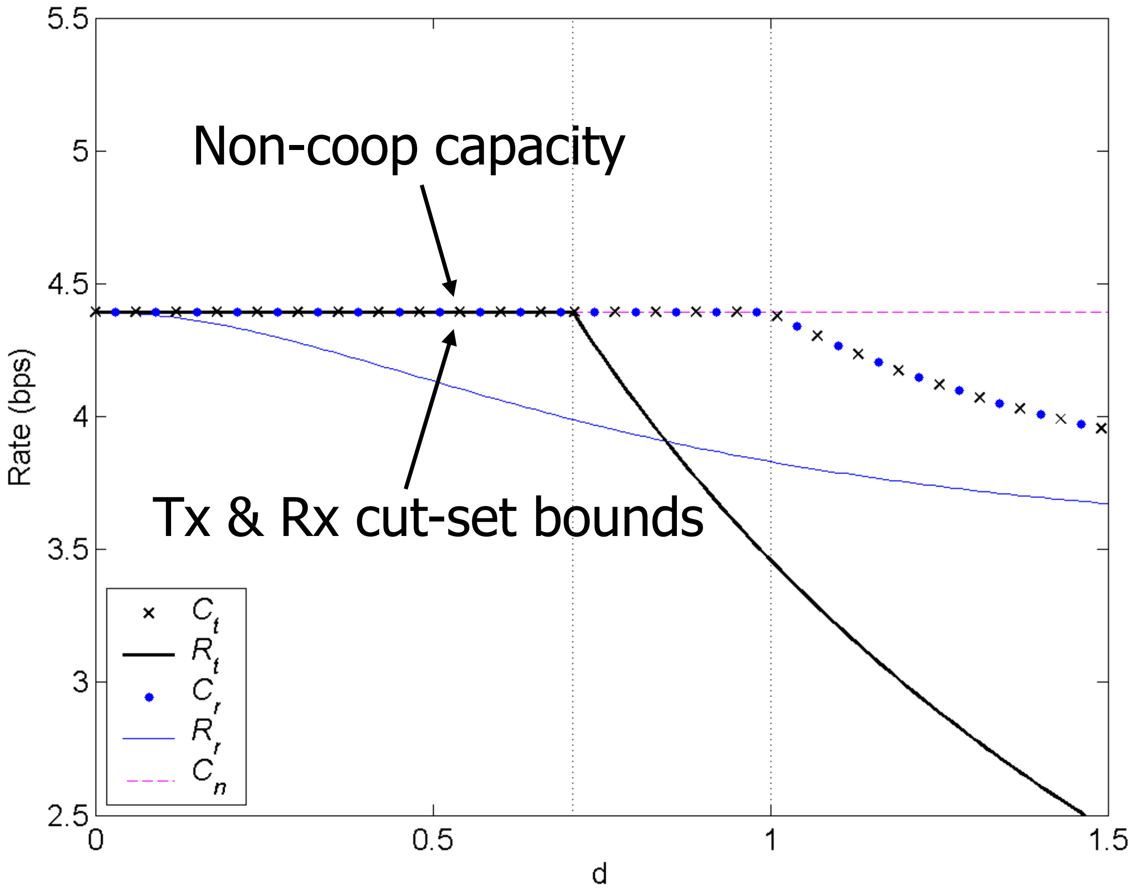
Example 1: Optimal power allocation with full CSI

- Cut-set bounds are equal.
- Tx co-op rate is close to the bounds.
- Transmitter cooperation is preferable.



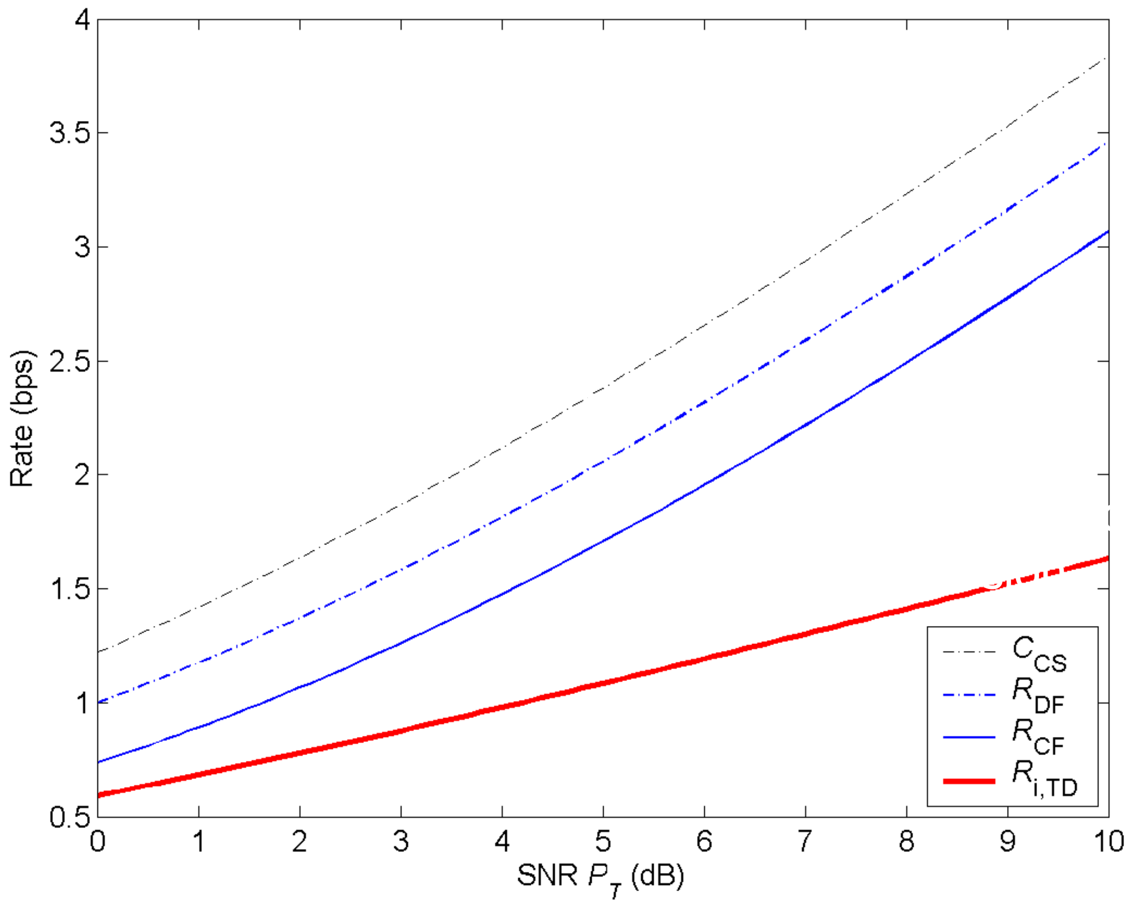
Example 2: Equal power allocation with RX phase CSI

- Non-cooperative capacity meets the cut-set bounds of Tx and Rx co-op.
- Cooperation offers no capacity gain.



Capacity: Non-orthogonal Relay Channel

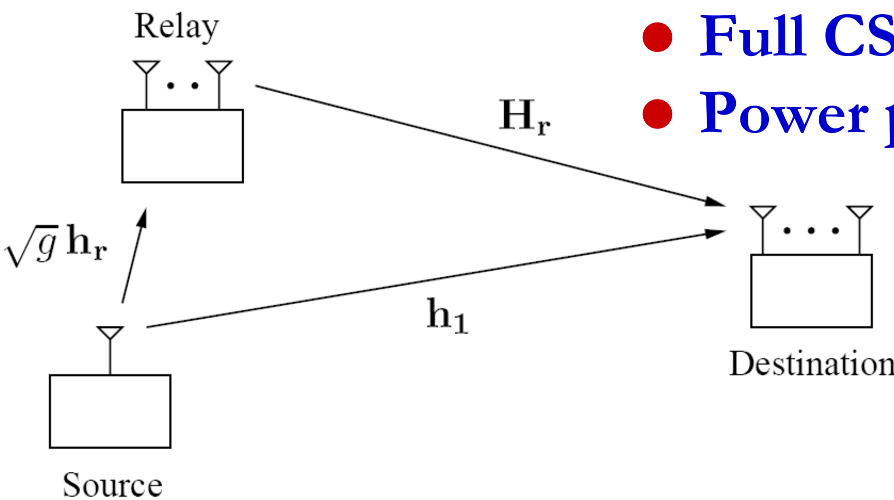
- Compare rates to a full-duplex relay channel.
- Realize conference links via time-division.
- Orthogonal scheme suffers a considerable performance loss, which is aggravated as SNR increases.



Transmitter vs. Receiver Cooperation

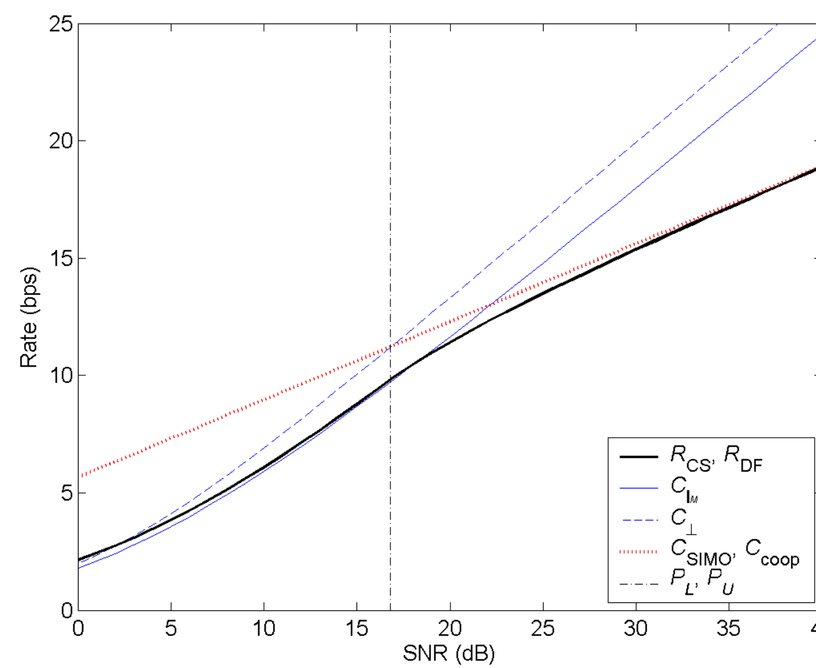
- Capacity gain only realized with the right cooperation strategy
- With full CSI, Tx co-op is superior.
- With optimal power allocation and receiver phase CSI, Rx co-op is superior.
- With equal power allocation and Rx phase CSI, cooperation offers no capacity gain.
- Similar observations in Rayleigh fading channels.

Multiple-Antenna Relay Channel



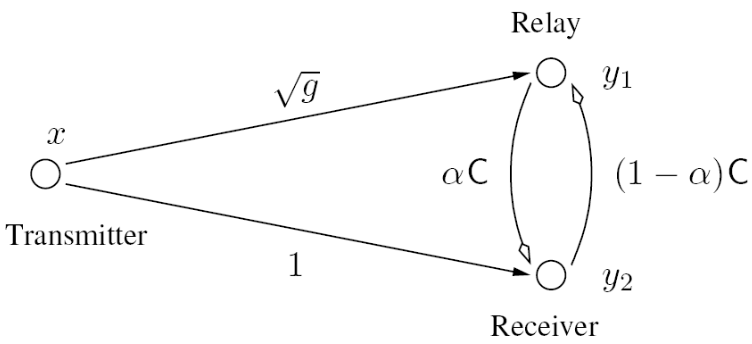
- **Full CSI**
- **Power per transmit antenna: *P/M*.**

- Single-antenna source and relay
- Two-antenna destination
  - SNR < P_L: MIMO Gain
  - SNR > P_U: No multiplexing gain; can't exceed SIMO channel capacity (Host-Madsen'05)



Joint work with C. Ng and N. Laneman

Conferencing Relay Channel

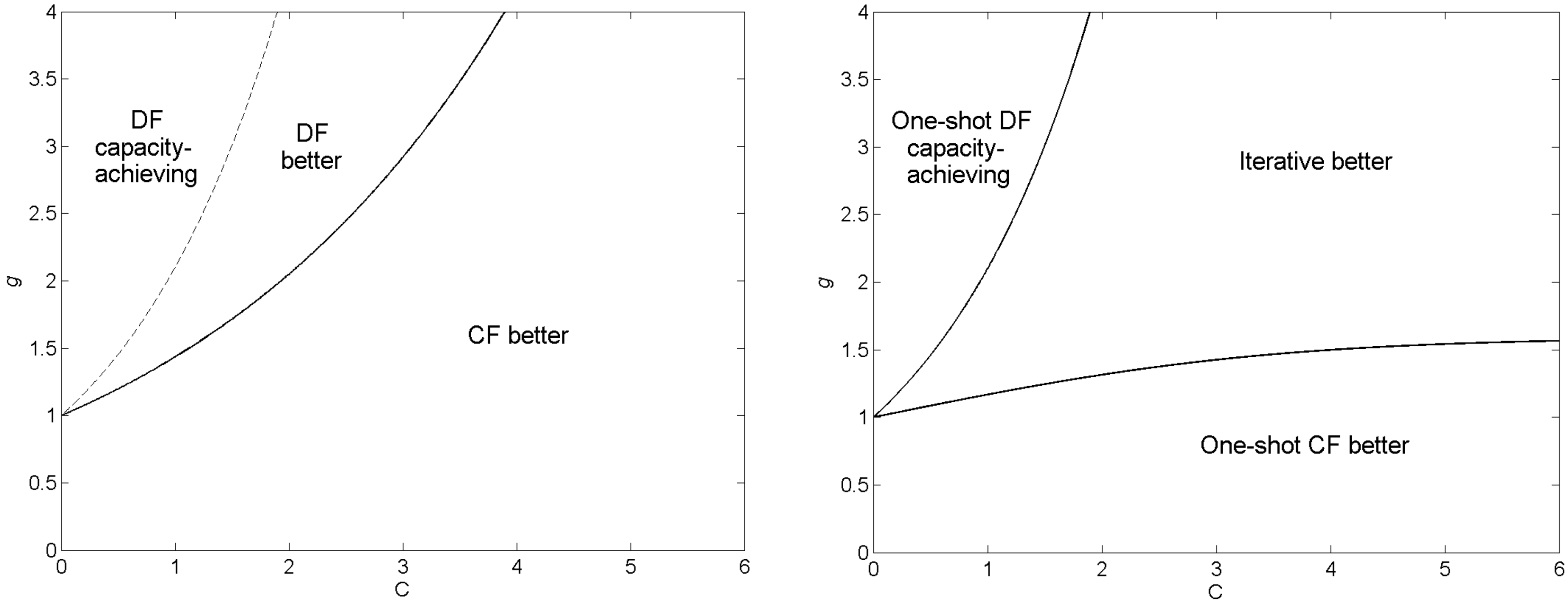


$$y_1 = \sqrt{g}\,x + n_1$$

$$y_2 = x + n_2$$

- **Willems introduced conferencing for MAC (1983)**
  - **Transmitters conference before sending message**
- **We consider a relay channel with conferencing between the relay and destination**
- **The conferencing link has total capacity C which can be allocated between the two directions**

Iterative vs. One-shot Conferencing

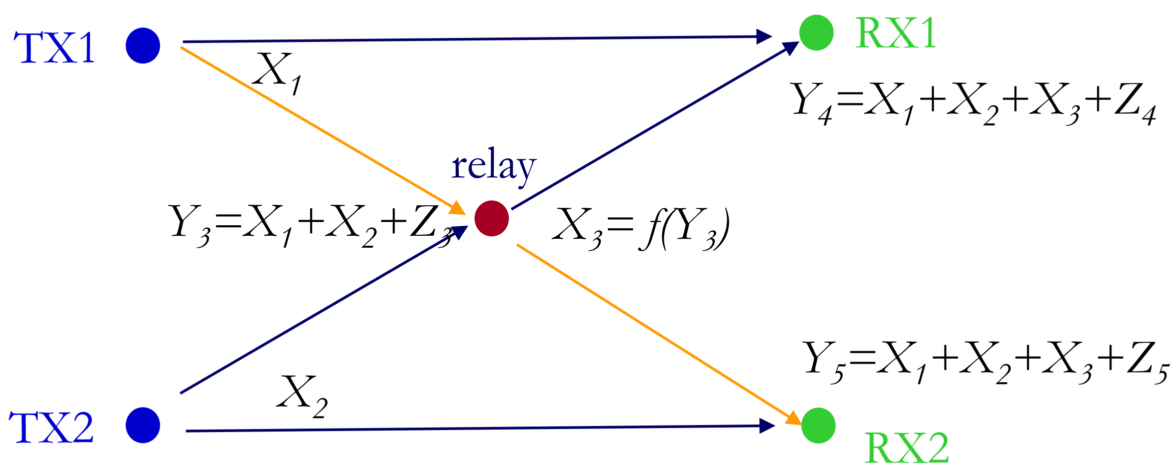


- Weak relay channel: the iterative scheme is disadvantageous.
- Strong relay channel: iterative outperforms one-shot conferencing for large C.

Lessons Learned

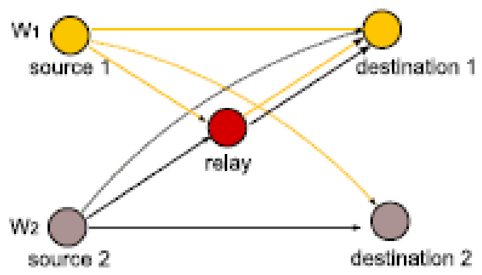
- Orthogonalization has considerable capacity loss
  - Applicable for clusters, since cooperation band can be reused spatially.
- DF vs. CF
  - DF: nearly optimal when transmitter and relay are close
  - CF: nearly optimal when transmitter and relay far
  - CF: not sensitive to compression scheme, but poor spectral efficiency as transmitter and relay do not joint-encode.
- The role of SNR
  - High SNR: rate requirement on cooperation messages increases.
  - MIMO-gain region: cooperative system performs as well as MIMO system with isotropic inputs.

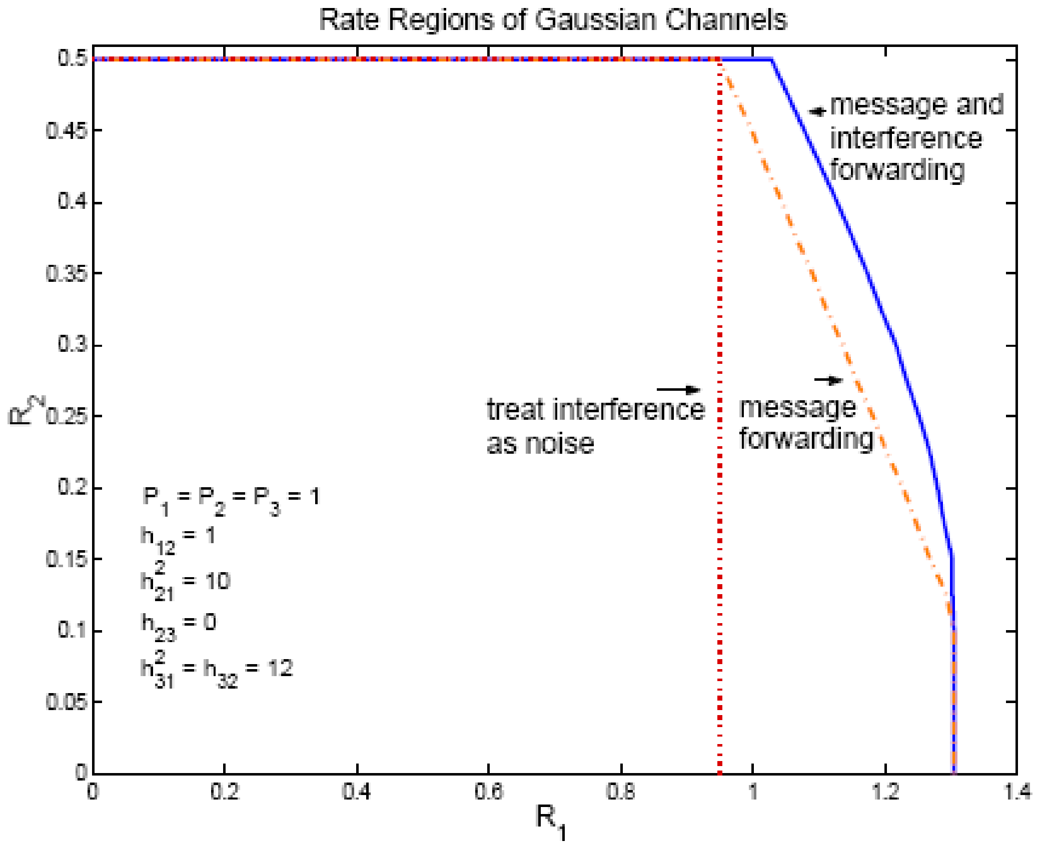
Generalized Relaying



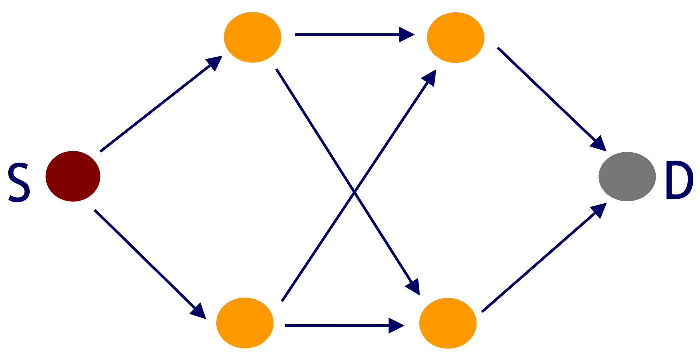
- Can forward message and/or interference
  - **Relay can forward all or part of the messages**
    - **Much room for innovation**
  - **Relay can forward interference**
    - **To help subtract it out**

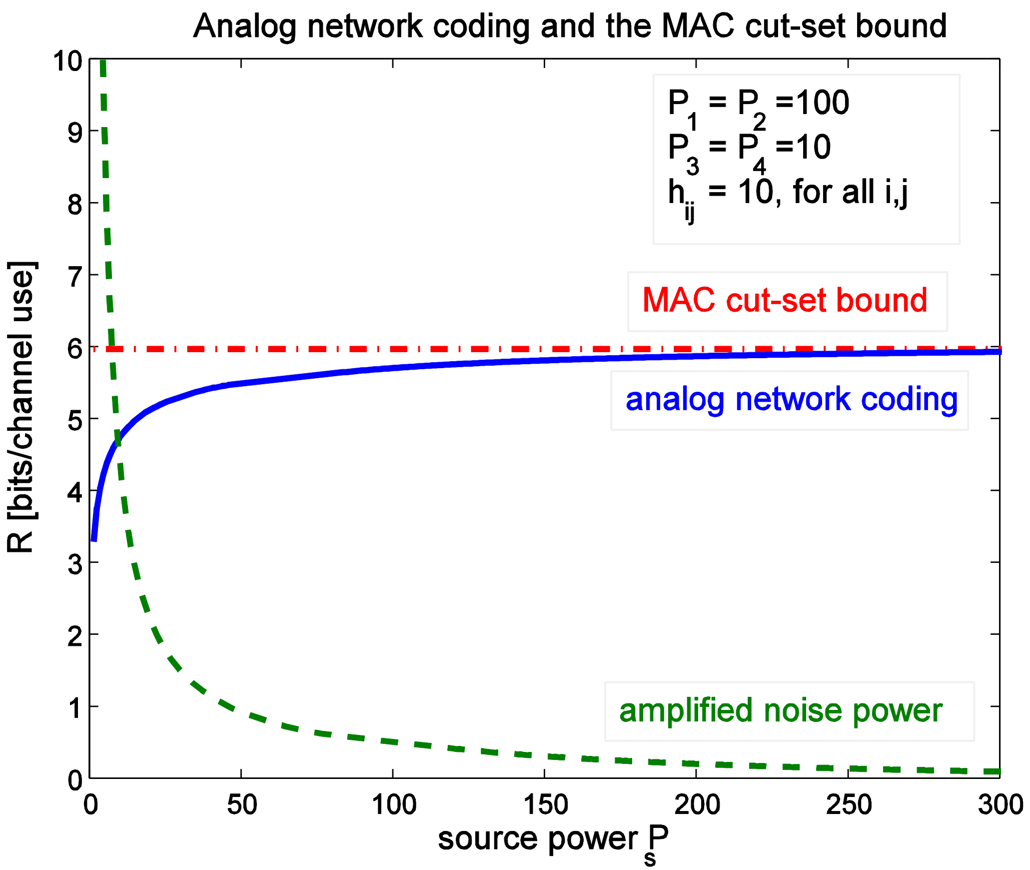
Beneficial to forward both interference and message





In fact, it can achieve capacity





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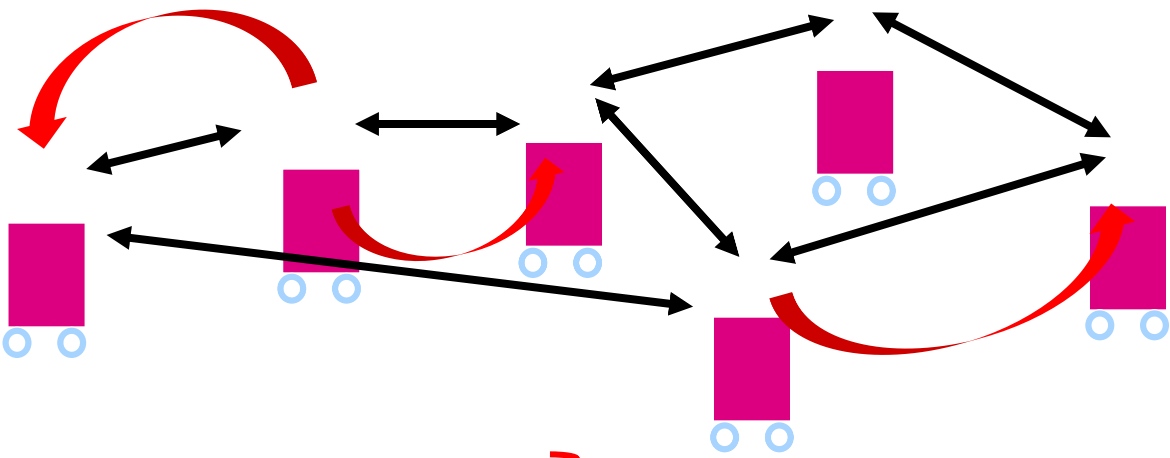
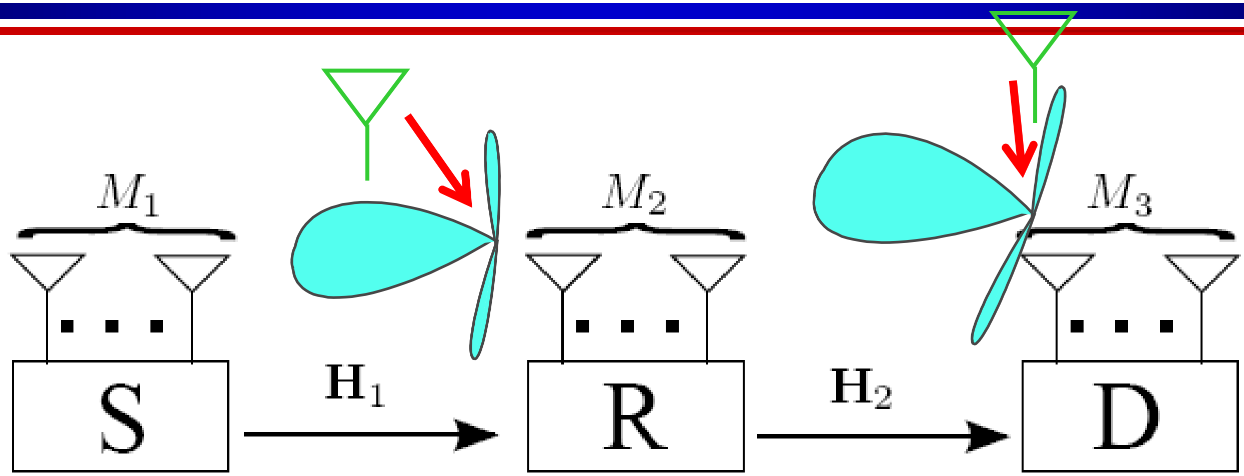
How to use Feedback in Wireless Networks



- Output feedback
- CSI
- Acknowledgements
- Network/traffic information
- Something else

Noisy/Compressed

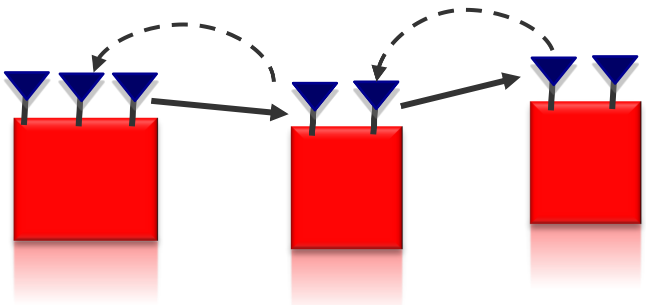
MIMO in Ad-Hoc Networks

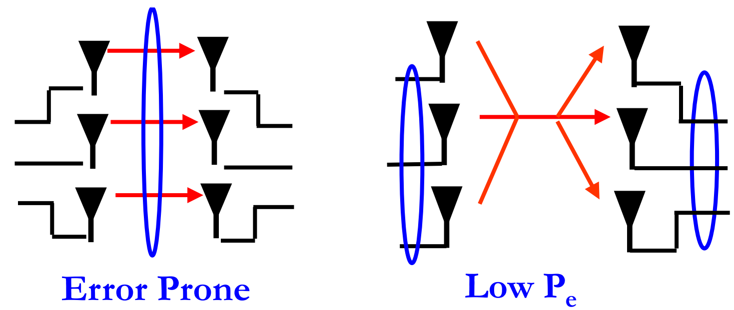


- Antennas can be used for multiplexing, diversity, or interference cancellation
  - Cancel M-1 interferers with M antennas
- What metric should be optimized?

Cross-Layer Design

Diversity-Multiplexing-Delay Tradeoffs for MIMO Multihop Networks with ARQ



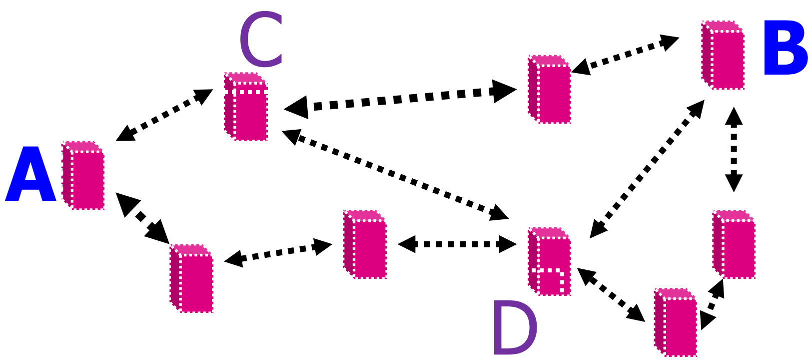


- MIMO used to increase data rate or robustness
- Multihop relays used for coverage extension
- ARQ protocol:
  - Can be viewed as 1 bit feedback, or time diversity,
  - Retransmission causes delay (can design ARQ to control delay)
- Diversity multiplexing (delay) tradeoff - DMT/DMDT
  - Tradeoff between robustness, throughput, and delay

FLoWS

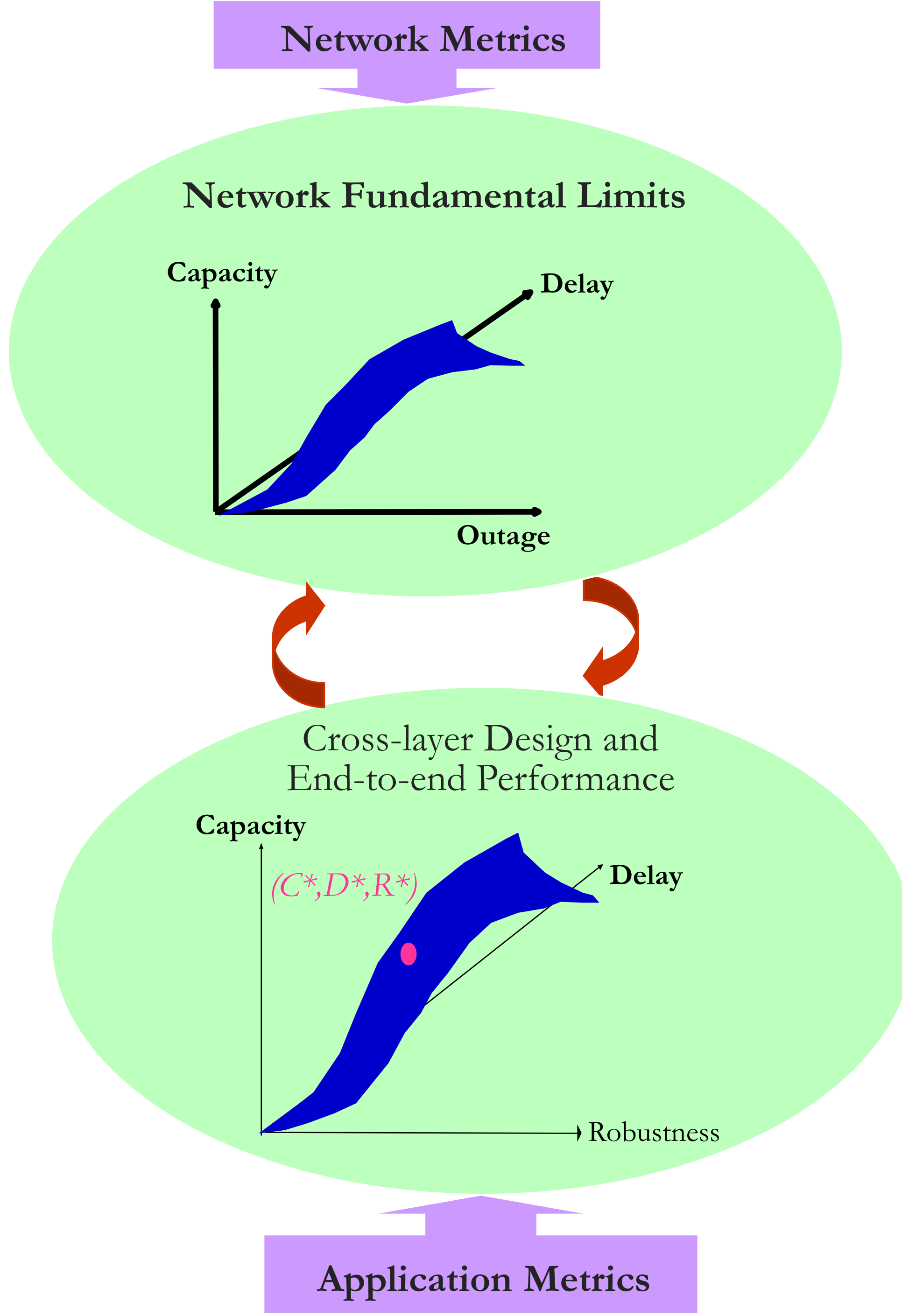
Fundamental Limits
of Wireless Systems

(DARPA Challenge Program)



Research Areas

- Fundamental performance limits and tradeoffs
- Node cooperation and cognition
- Adaptive techniques
- Layering and Cross-layer design
- Network/application interface
- End-to-end performance optimization and guarantees



Today's presentation

- *Apurva will present* "User cooperation diversity: Part I. System description", Sendonaris, A. ; Erkip, E. ; Aazhang, B. ; *IEEE Transactions on Communications*, vol. 51, pp. 1927-1938, 2003
- Required reading (forgot to post)