EE360: Lecture 11 Outline
Cross-Layer Design and CR

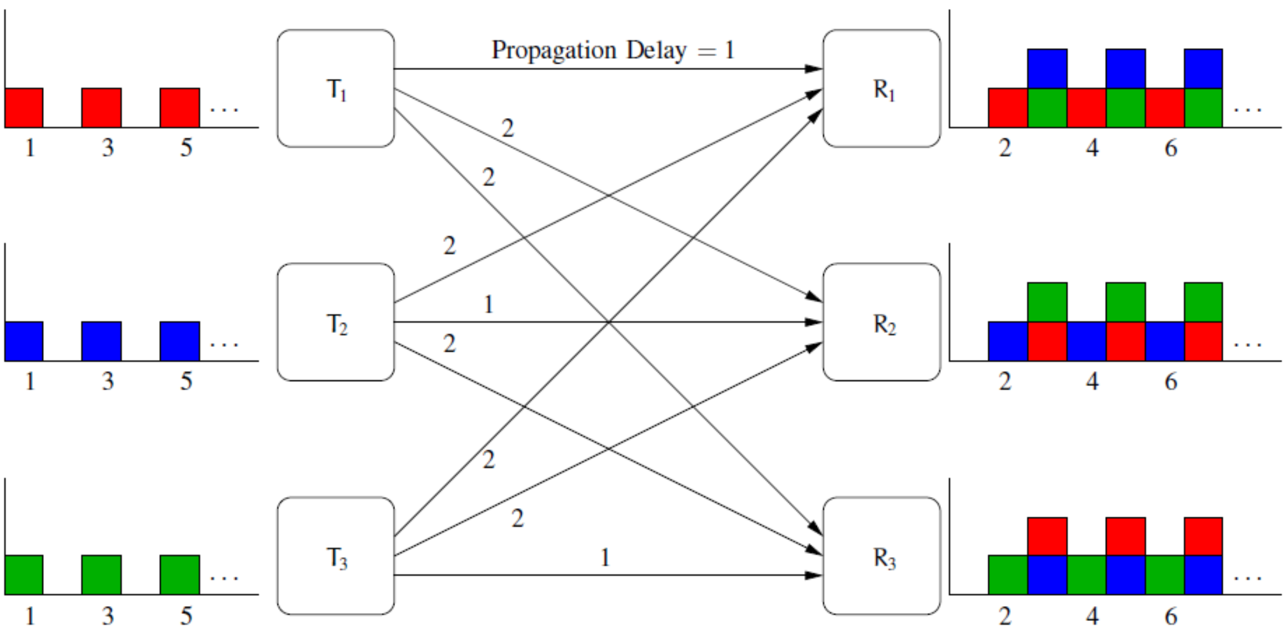
- Announcements
  - HW 1 posted, due Feb. 24 at 5pm
  - Progress reports due Feb. 29 at midnight (not Feb. 27)
- Interference alignment
- Beyond capacity: consummating unions
- Cross layer design in ad hoc networks

Interference Alignment

- Addresses the number of interference-free signaling dimensions in an interference channel
- Based on our orthogonal analysis earlier, it would appear that resources need to be divided evenly, so only 2BT/N dimensions available
- Jafar and Cadambe showed that by aligning interference, 2BT/2 dimensions are available
- Everyone gets half the cake!

Basic Premise

- For any number of TXs and RXs, each TX can transmit half the time and be received without any interference
  - Assume different delay for each transmitter-receiver pair
  - Delay odd when message from TX *i* desired by RX *j*; even otherwise.
  - Each TX transmits during odd time slots and is silent at other times.
  - All interference is aligned in even time slots.

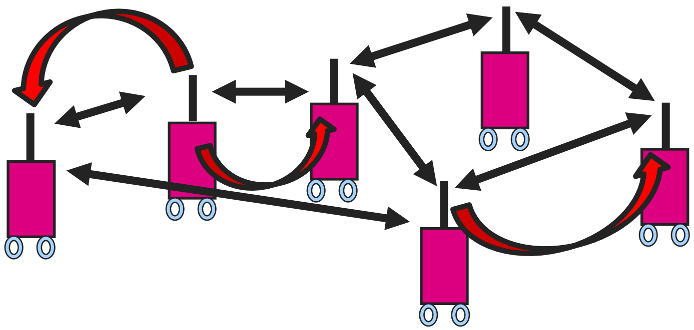


Extensions

- Multipath channels
- Fading channels
- MIMO channels
- Cellular systems
- Imperfect channel knowledge
- …

Feedback in Networks

- Feedback in ptp links
  - Does not increase capacity
  - Ensures reliable transmission
  - Reduces complexity; adds delay
  - Used to share CSI



- Types of feedback in networks
  - Output feedback
  - CSI
  - Acknowledgements
  - Network/traffic information
  - Something else

  } Noisy/Compressed (Output feedback, CSI)

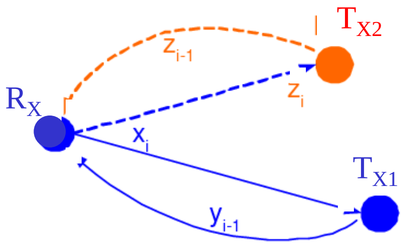
- What is the network metric to be improved by feedback?
  - Capacity, delay, …

Capacity and Feedback

- Feedback does not increase capacity of ptp memoryless channels
  - Reduces complexity of optimal transmission scheme
  - Drives error to zero faster
- Capacity of ptp channels under feedback largely unknown
  - E.g. for channels with memory; finite rate and/or noisy feedback
  - Feedback introduces a new metric: directed mutual information

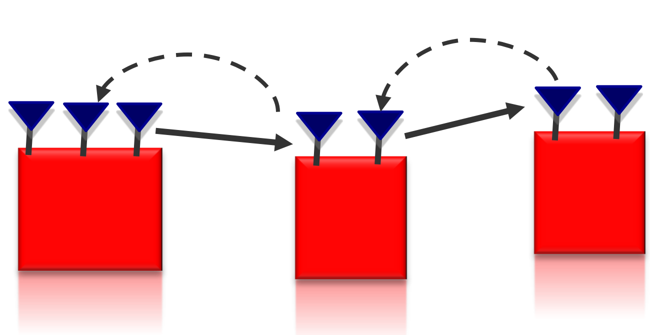
$$I\left(X^n \rightarrow Y^n \mid s_0\right) = \sum_{i=1}^{n} I\left(X^i; Y_i \mid Y^{i-1}, s_0\right)$$

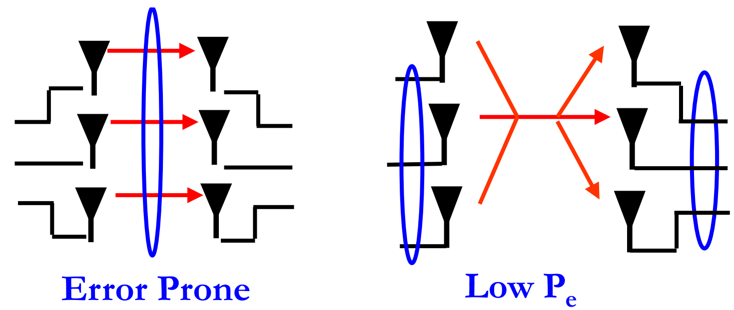
- Multiuser channel capacity with FB largely unknown
  - Feedback introduces cooperation
  - RX cooperation in the BC
  - TX cooperation in the MAC



- Capacity of multihop networks unknown with/without feedback
- But ARQ is ubiquitious in practice
  - Works well on finite-rate noisy feedback channels
  - Reduces end-to-end delay
- How to explore optimal use of feedback in networks

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

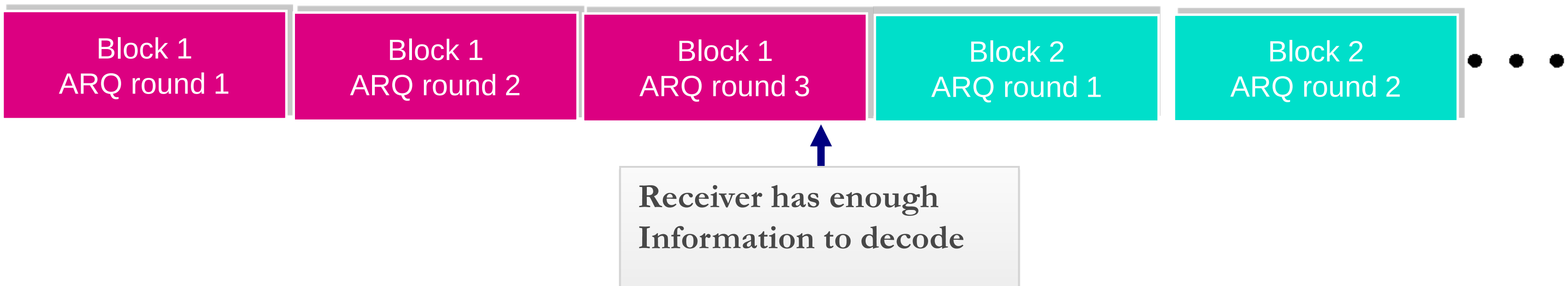




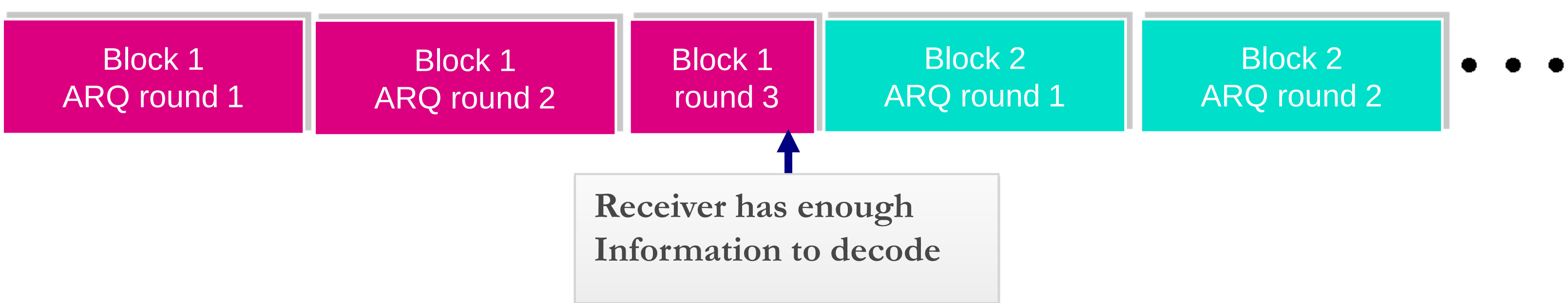
- MIMO used to increase data rate or robustness
- Multihop relays used for coverage extension
- ARQ protocol:
  - Can be viewed as 1 bit feedback, or time diversity,
  - Retransmission causes delay (can design ARQ to control delay)
- Diversity multiplexing (delay) tradeoff - DMT/DMDT
  - Tradeoff between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

Multihop ARQ Protocols

- **Fixed ARQ: fixed window size**
  - **Maximum allowed ARQ round for ith hop** L_i **satisfies** $\sum_{i=1}^{N} L_i \leq L$
- **Adaptive ARQ: adaptive window size**
  - **Fixed Block Length (FBL) (block-based feedback, easy synchronization)**



  - **Variable Block Length (VBL) (real time feedback)**



Asymptotic DMDT: long-term static channel

- Fixed ARQ Allocation

$$d_F(r_e,\{L_i\}) = \min\left\{ f_{M_i,M_{i+1}}\left(\frac{2r_e}{L_i}\right)\right\}, \qquad \sum L_i = L$$

Performance limited by the weakest link

- Adaptive FBL

$$d_{FBL}(r_e,L) = \min_{\sum l_i = L-(N-2)} \left\{ \sum_i f_{M_i}\left(\frac{2r_e}{l_i}\right)\right\},$$

Optimal ARQ equalizes link performance

- Adaptive VBL: close form solution in some special cases

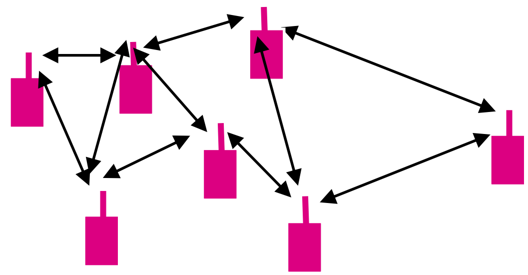
$$d_{VBL}(r_e,L) = \inf_{\{\alpha_{i,j}\}\in O} \sum_{i=1}^{N-1}\sum_{j=1}^{M_i^*}\left(1-\alpha_{i,j}\right)^+$$

$$O = \left\{ \begin{array}{l} \left(\alpha_1, \ldots \alpha_{N-1}\right) \in \Re^{M_1^*} \times \ldots \times \Re^{M_{N-1}^*} : \\ \left[\sum_{k=1}^{N-1} \frac{1}{S_k\left(\alpha_k\right)}\right]^{-1} \leq \frac{2r_e}{L}, \alpha_{i,1} \geq \ldots \geq \alpha_{i,M_i^*} \geq 0 \end{array} \right\}$$

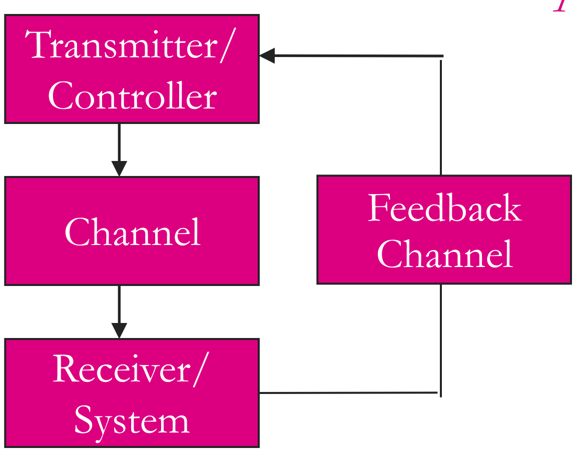
$$M_i^* = \min\{M_i, M_{i+1}\}$$

Adaptive ARQ: this equalizing optimization is done automatically

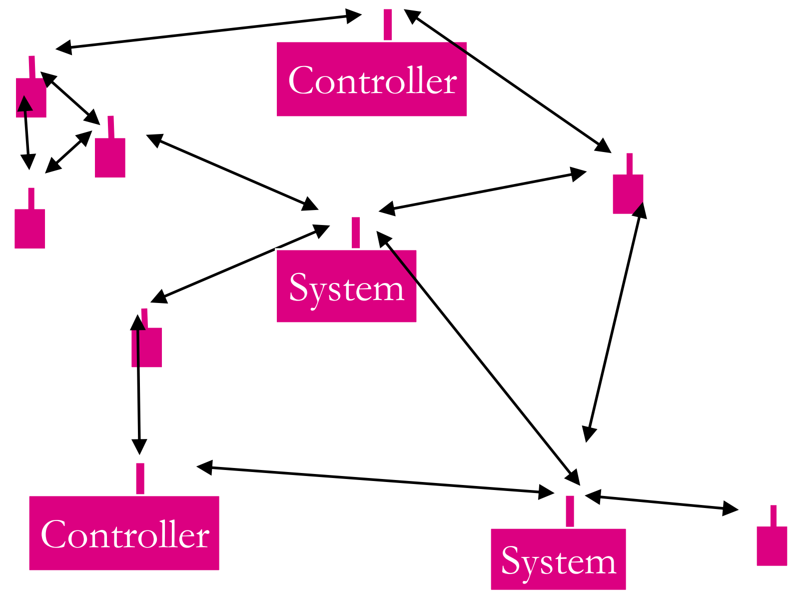
Connections



Multihop networks with imperfect feedback



Feedback channels and stochastic control

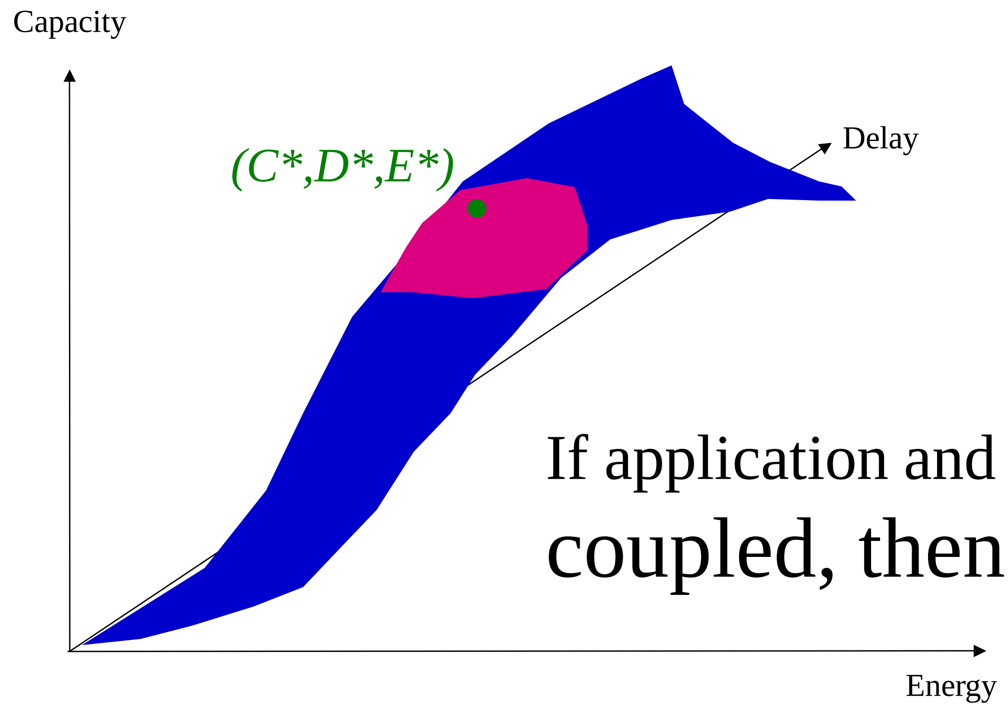


Distributed Control with imperfect feedback

Is a capacity region all we need to design networks?

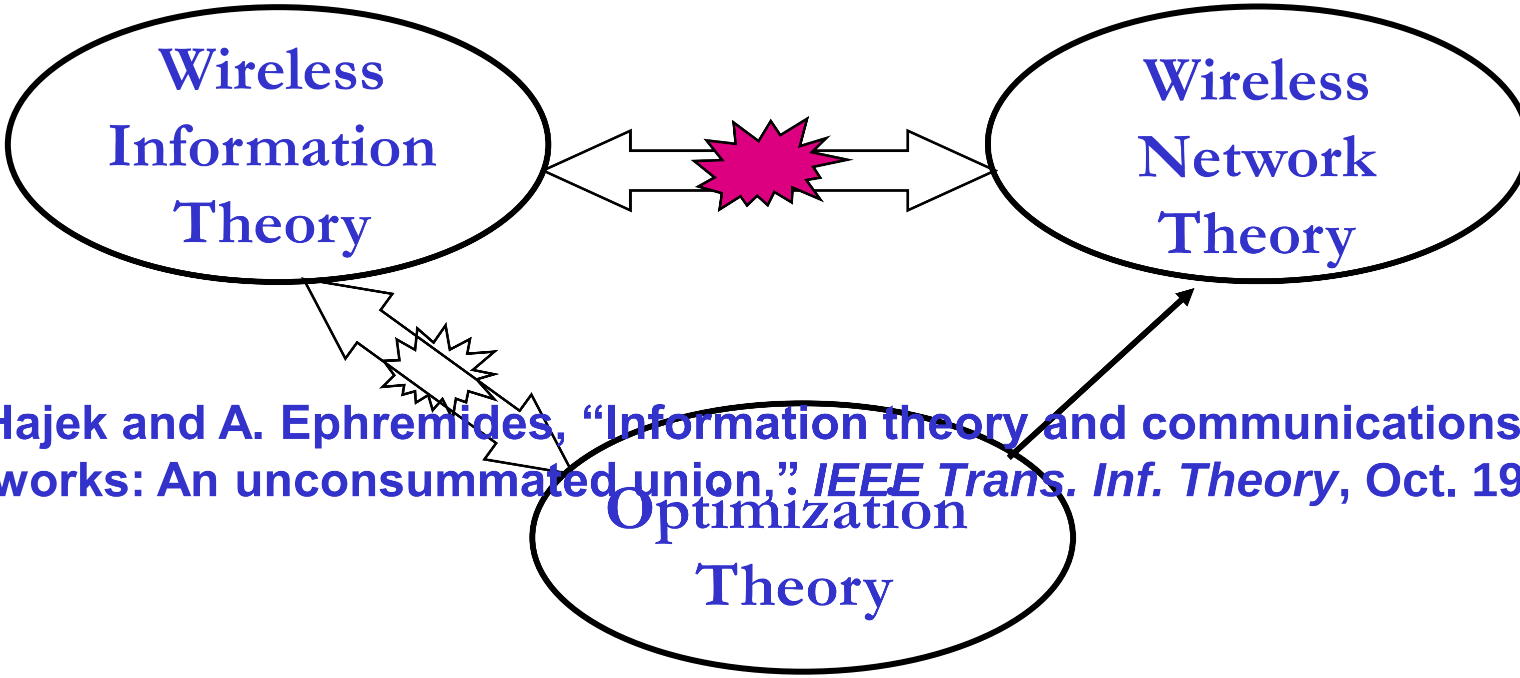
Yes, if the application and network design can be decoupled

Application metric: *f(C,D,E)*: *(C*,D*,E*)=arg max f(C,D,E)*



If application and network design are coupled, then cross-layer design

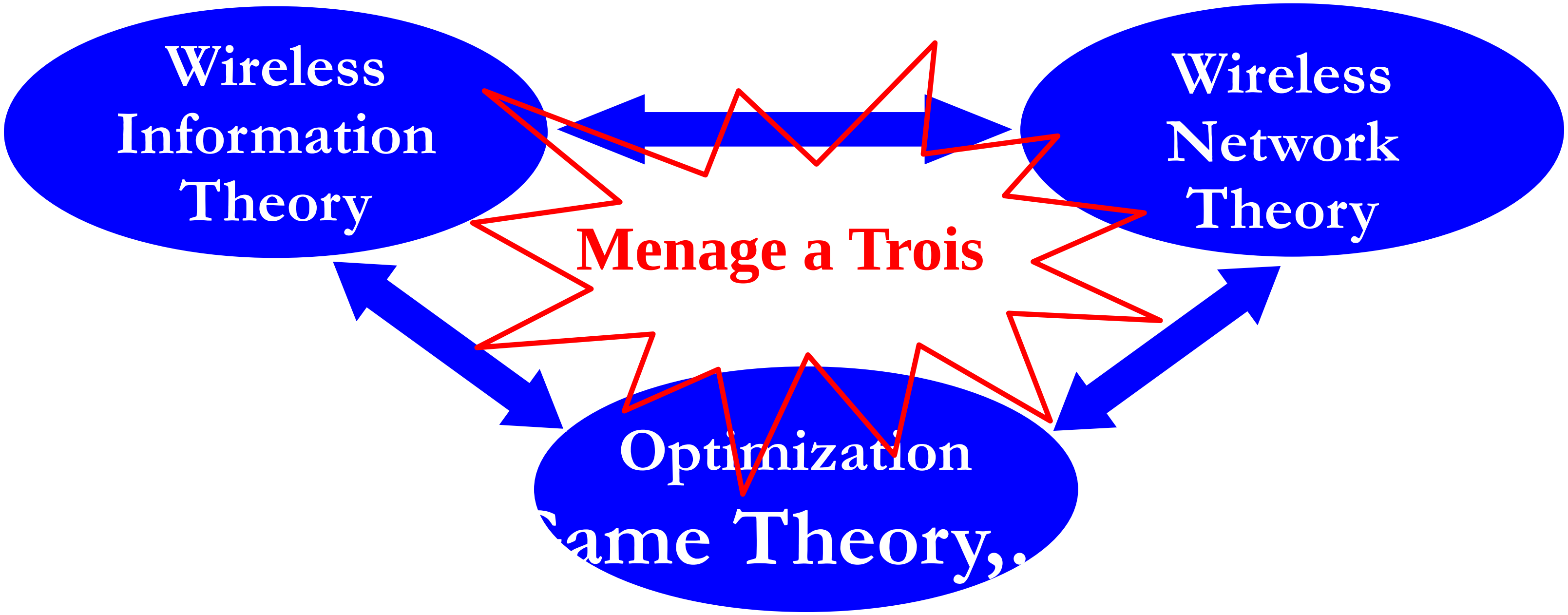
Limitations in theory of ad hoc networks today



B. Hajek and A. Ephremides, "Information theory and communications networks: An unconsummated union," *IEEE Trans. Inf. Theory*, Oct. 1998.

- Shannon capacity pessimistic for wireless channels and intractable for large networks
  - Large body of wireless (and wired) network theory that is ad-hoc, lacks a basis in fundamentals, and lacks an objective success criteria.
  - Little cross-disciplinary work spanning these fields
  - Optimization techniques applied to given network models, which rarely take into account fundamental network capacity or dynamics

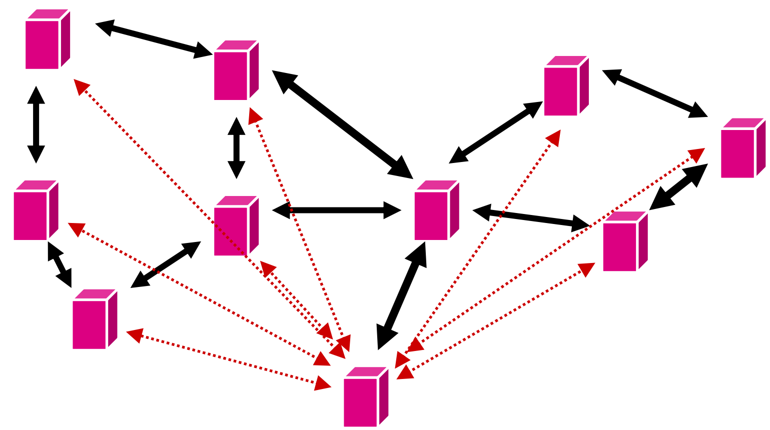
Consummating Unions



- When capacity is not the only metric, a new theory is needed to deal with nonasymptopia (i.e. delay, random traffic) and application requirements
  - Shannon theory generally breaks down when delay, error, or user/traffic dynamics must be considered
- Fundamental limits are needed outside asymptotic regimes
- Optimization, game theory, and other techniques provide the missing link

Crosslayer Design in Ad-Hoc Wireless Networks

- Application
- Network
- Access
- Link
- Hardware

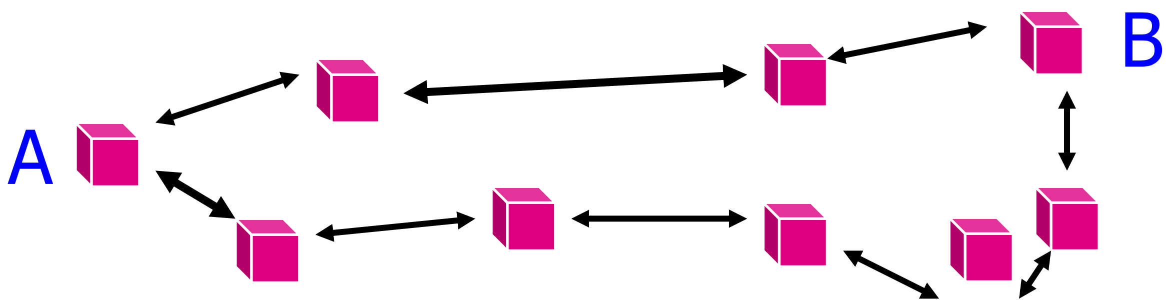


Substantial gains in throughput, efficiency, and end-to-end performance from cross-layer design

Why a crosslayer design?

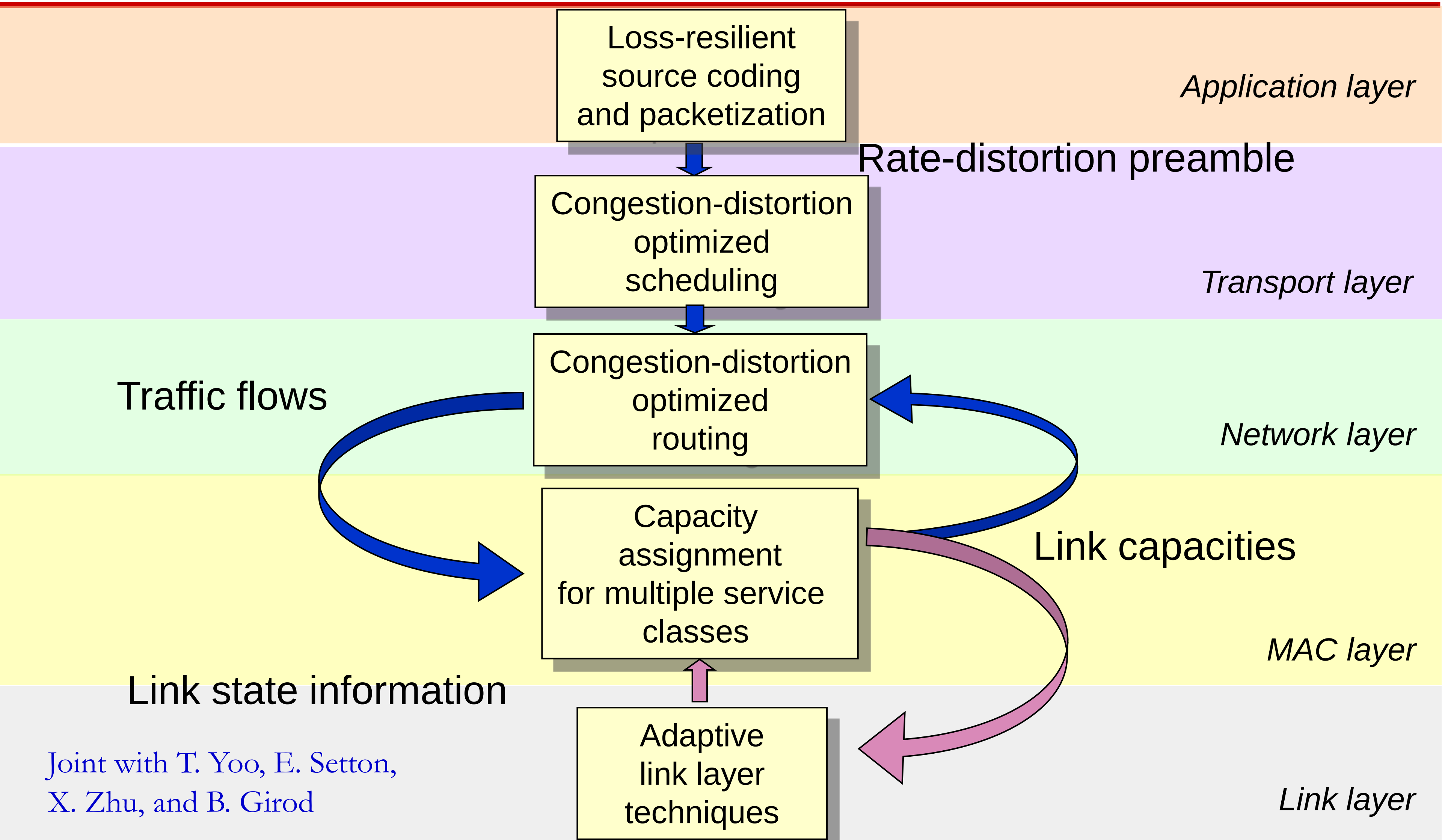
- The technical challenges of future mobile networks cannot be met with a layered design approach.
- QoS cannot be provided unless it is supported across all layers of the network.
  - The application must adapt to the underlying channel and network characteristics.
  - The network and link must adapt to the application requirements
- Interactions across network layers must be understood and exploited.

Delay/Throughput/Robustness across Multiple Layers



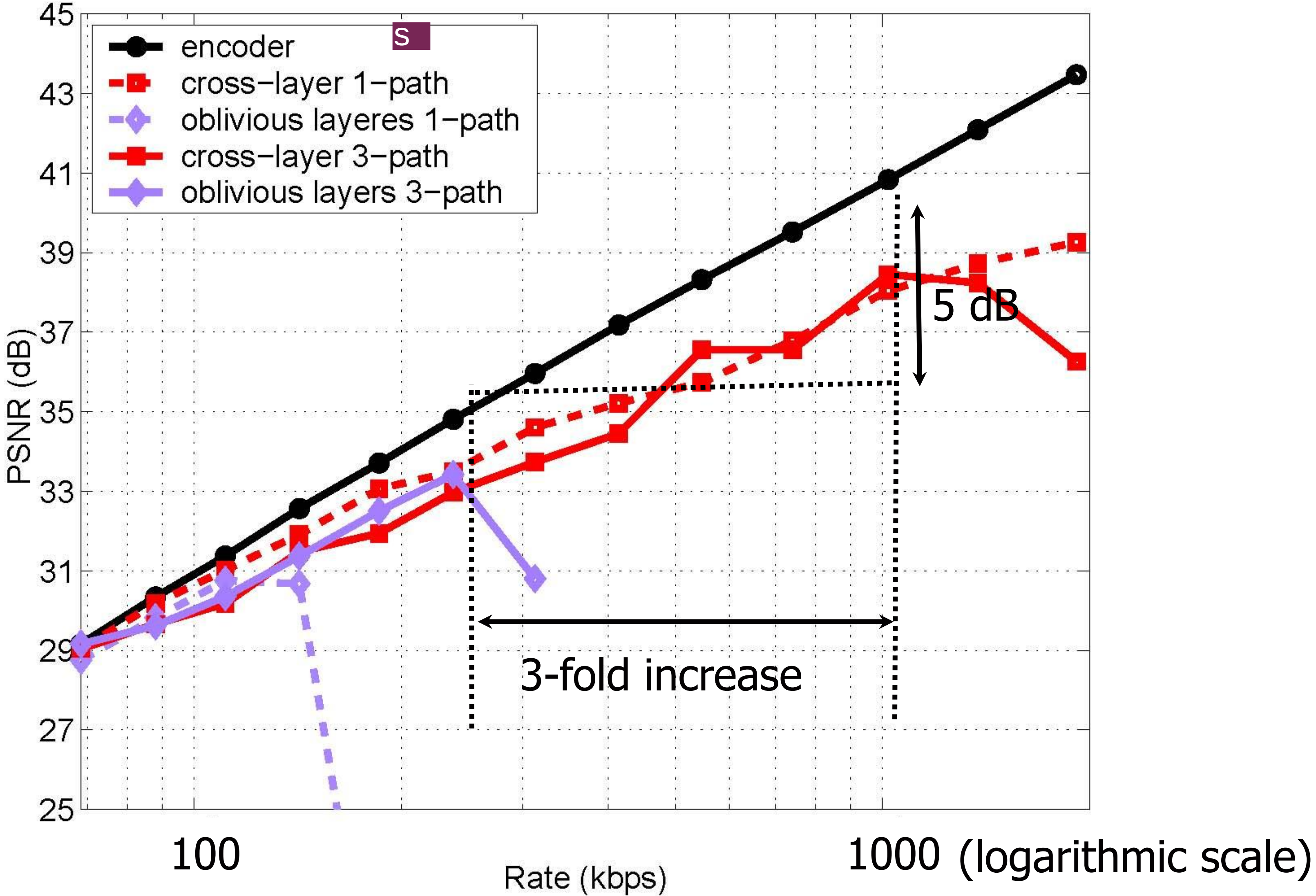
- Multiple routes through the network can be used for multiplexing or reduced delay/loss
- Application can use single-description or multiple description codes
- Can optimize optimal operating point for these tradeoffs to minimize distortion

Cross-layer protocol design for real-time media

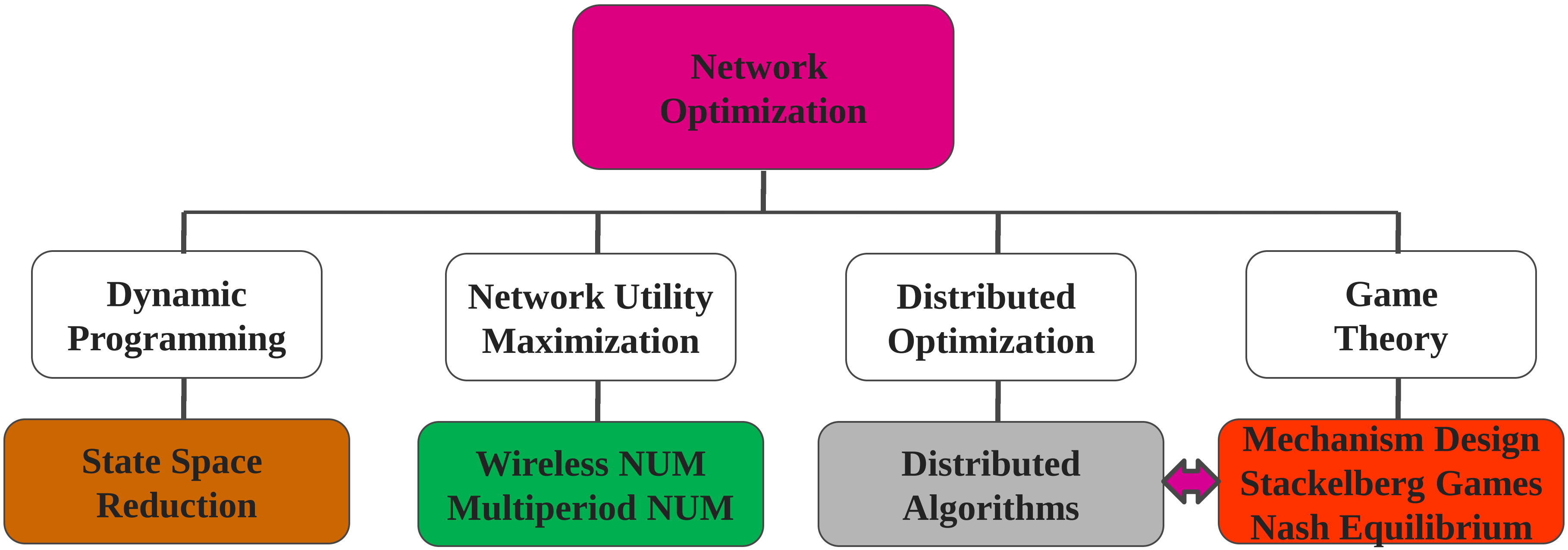


Joint with T. Yoo, E. Setton, X. Zhu, and B. Girod

Video streaming performance



Approaches to Cross-Layer Resource Allocation*



*Much prior work is for wired/static networks

Network Utility Maximization

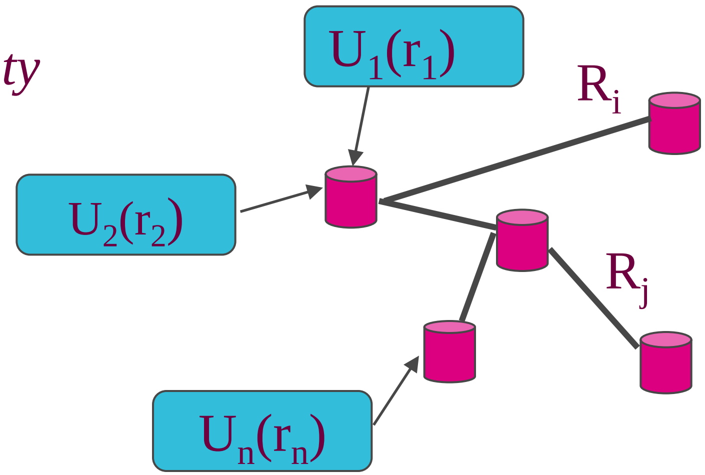
- **Maximizes a network utility function**

flow k

$$\max \quad \sum U_k(r_k)$$
$$s.t. \quad Ar \le R$$

routing *Fixed link capacity*

- **Assumes**
  - Steady state
  - Reliable links
  - Fixed link capacities



- **Dynamics are only in the queues**

Wireless NUM

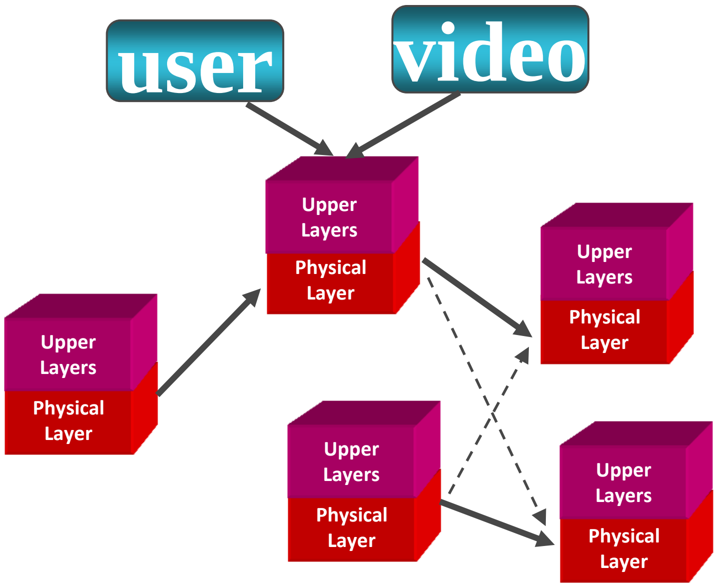
- Extends NUM to random environments
- Network operation as stochastic optimization algorithm

$$\max \quad E[\sum U(r_m(G))]$$

st

$$E[r(G)] \leq E[R(S(G), G)]$$

$$E[S(G)] \leq \bar{S}$$

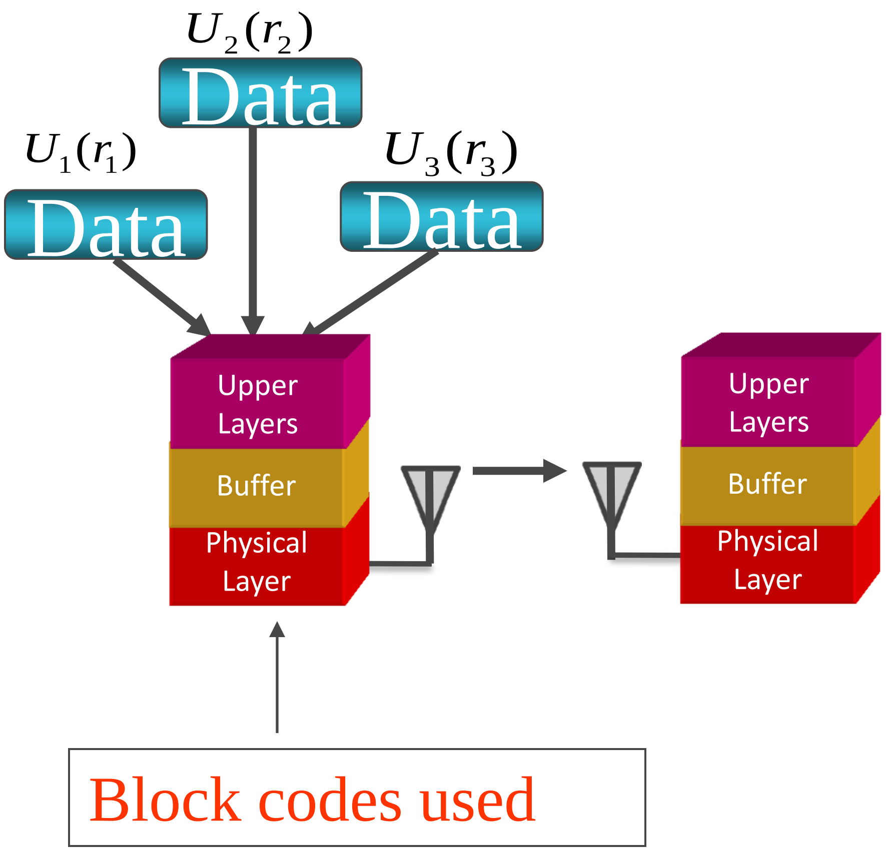


WNUM Policies

- Control network resources
- Inputs:
  - Random network channel information G^k
  - Network parameters
  - Other policies
- Outputs:
  - Control parameters
  - Optimized performance, that
  - Meet constraints
- Channel sample driven policies

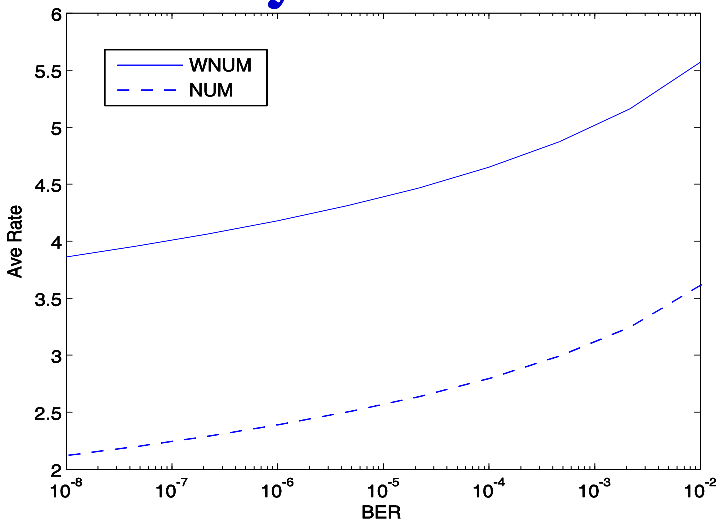
Example: NUM and Adaptive Modulation

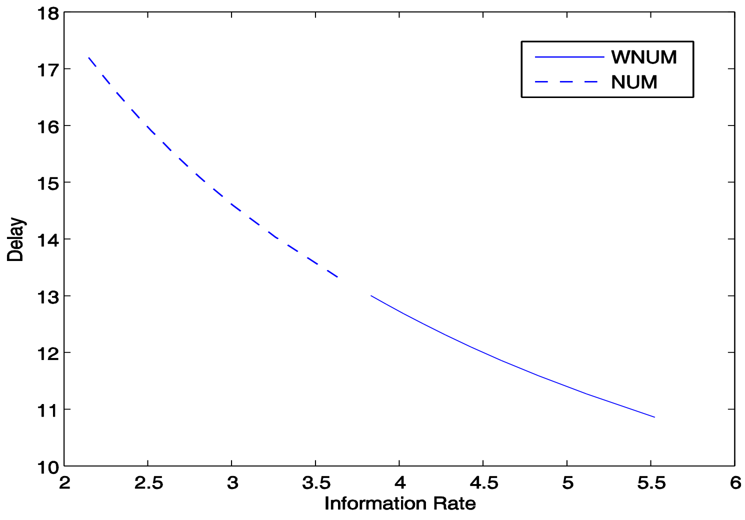
- Policies
  - Information rate
  - Tx power
  - Tx Rate
  - Tx code rate
- Policy adapts to
  - Changing channel conditions
  - Packet backlog
  - Historical power usage



Rate-Delay-Reliability

- Policy Results





Game theory

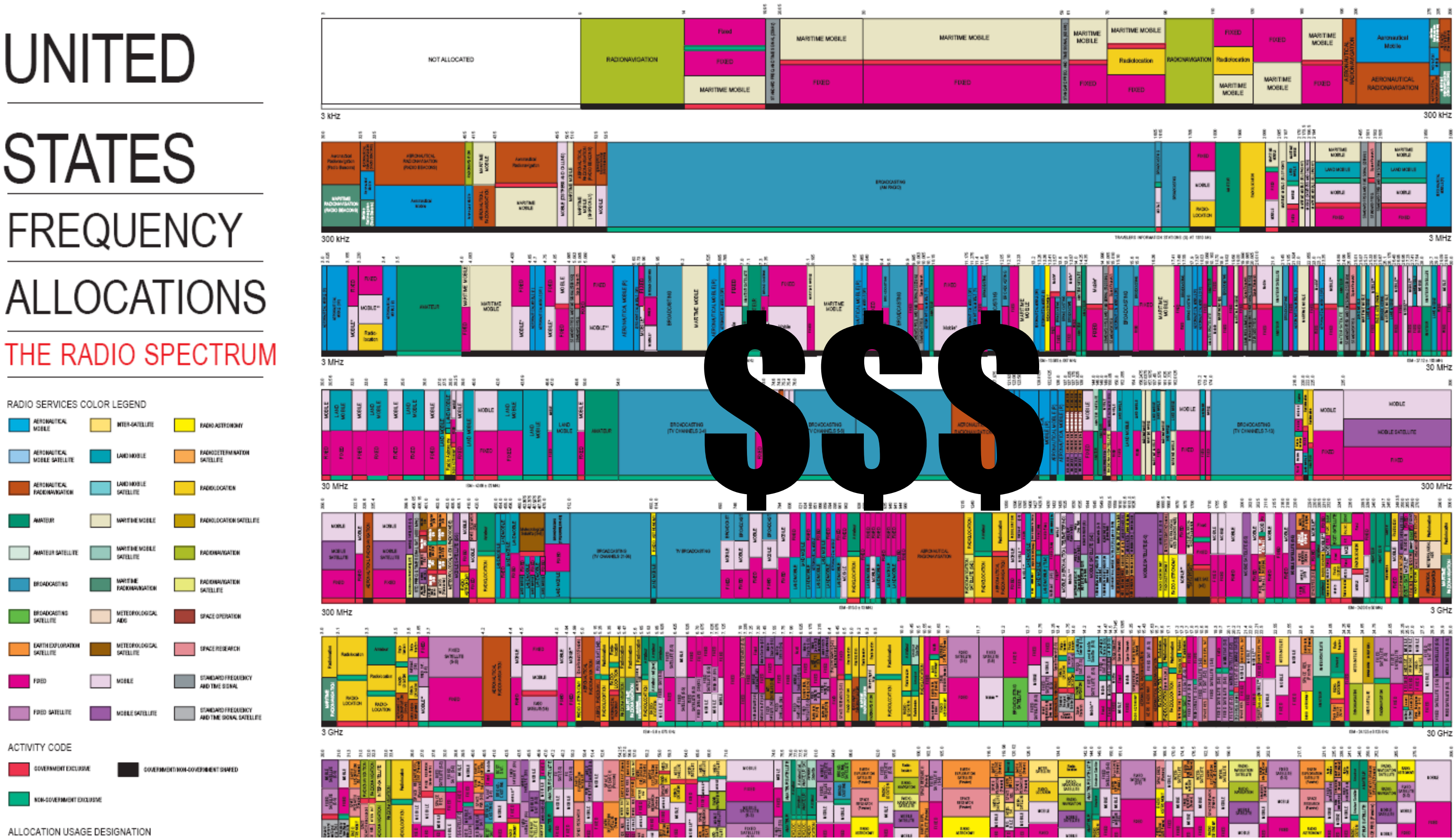
- Coordinating user actions in a large ad-hoc network can be infeasible

- Distributed control difficult to derive and computationally complex

- Game theory provides a new paradigm
  - Users act to "win" game or reach an equilibrium
  - Users heterogeneous and non-cooperative
  - Local competition can yield optimal outcomes
  - Dynamics impact equilibrium and outcome
  - Adaptation via game theory

Introduction to Cognitive Radios

Scarce Wireless Spectrum



and Expensive

Cognition Radio Motivation

- Cognitive radios can support new wireless users in existing crowded spectrum
  - <u>Without degrading performance of existing users</u>
- Utilize advanced communication and signal processing techniques
  - Coupled with novel spectrum allocation policies
- Technology could
  - Revolutionize the way spectrum is allocated worldwide
  - Provide sufficient bandwidth to support higher quality and higher data rate products and services

What is a Cognitive Radio?

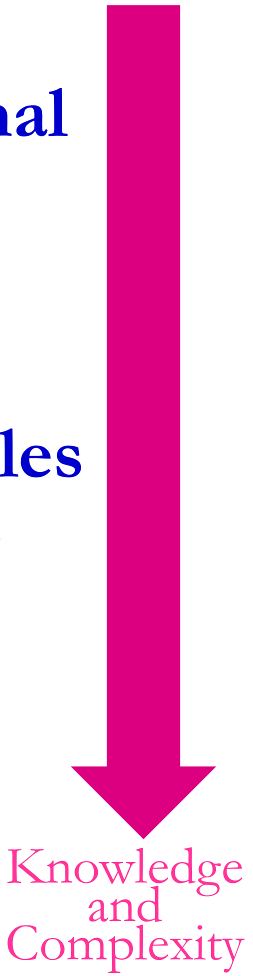
Cognitive radios (CRs) intelligently exploit available side information about the

(a) Channel conditions
(b) Activity
(c) Codebooks
(d) Messages

of other nodes with which they share the spectrum

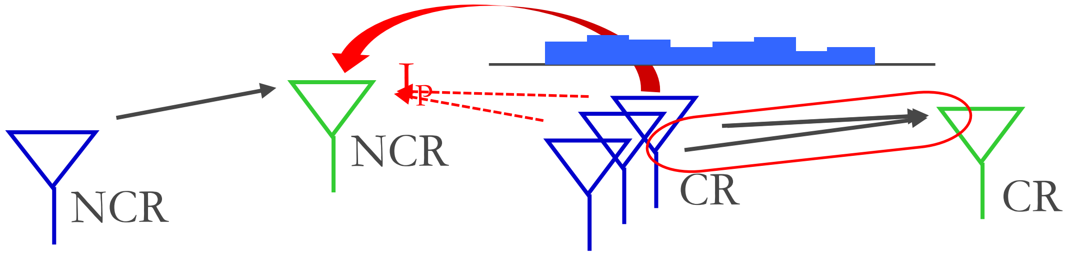
Cognitive Radio Paradigms

- Underlay
  - Cognitive radios constrained to cause minimal interference to noncognitive radios
- Interweave
  - Cognitive radios find and exploit spectral holes to avoid interfering with noncognitive radios
- Overlay
  - Cognitive radios overhear and enhance noncognitive radio transmissions



Underlay Systems

- Cognitive radios determine the interference their transmission causes to noncognitive nodes
  - Transmit if interference below a given threshold



- The interference constraint may be met
  - Via wideband signalling to maintain interference below the noise floor (spread spectrum or UWB)
  - Via multiple antennas and beamforming

Ultrawideband Radio (UWB)

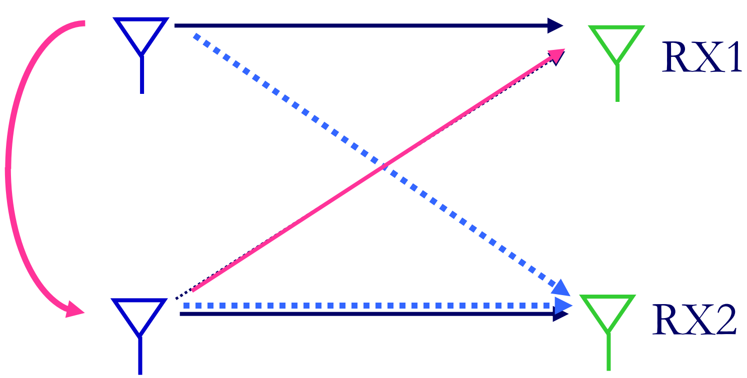
- Uses 7.5 Ghz of "free spectrum" (underlay)
- UWB is an impulse radio: sends pulses of tens of picoseconds(10^{-12}) to nanoseconds (10^{-9})
  - Duty cycle of only a fraction of a percent
- A carrier is not necessarily needed
- Uses a lot of bandwidth (GHz)
- High data rates, up to 500 Mbps
- Multipath highly resolvable: good and bad
- Limited commercial success to date

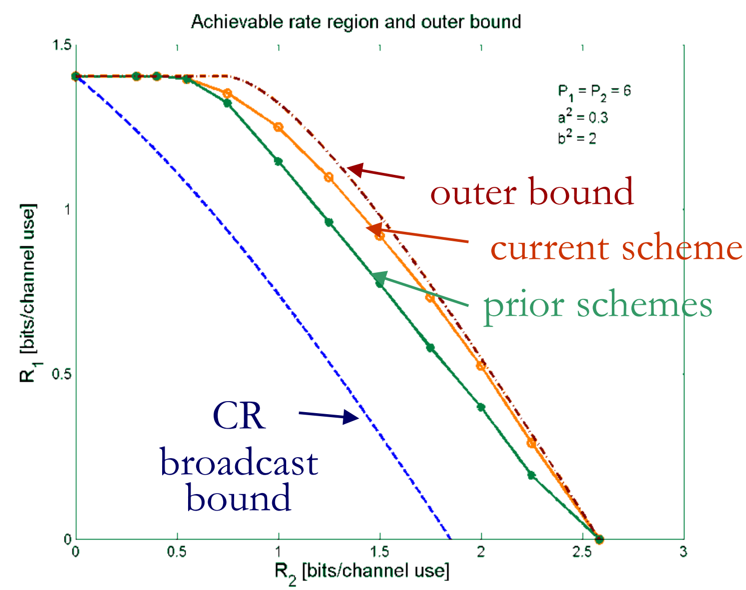
Underlay Challenges

- Measurement challenges
  - Measuring interference at NC receiver
  - Measuring direction of NC node for beamsteering
  - Both easy if NC receiver also transmits, else hard
- Policy challenges
  - Underlays typically coexist with licensed users
  - Licensed users paid $$$ for their spectrum
    - Licensed users don't want underlays
    - Insist on very stringent interference constraints
    - Severely limits underlay capabilities and applications

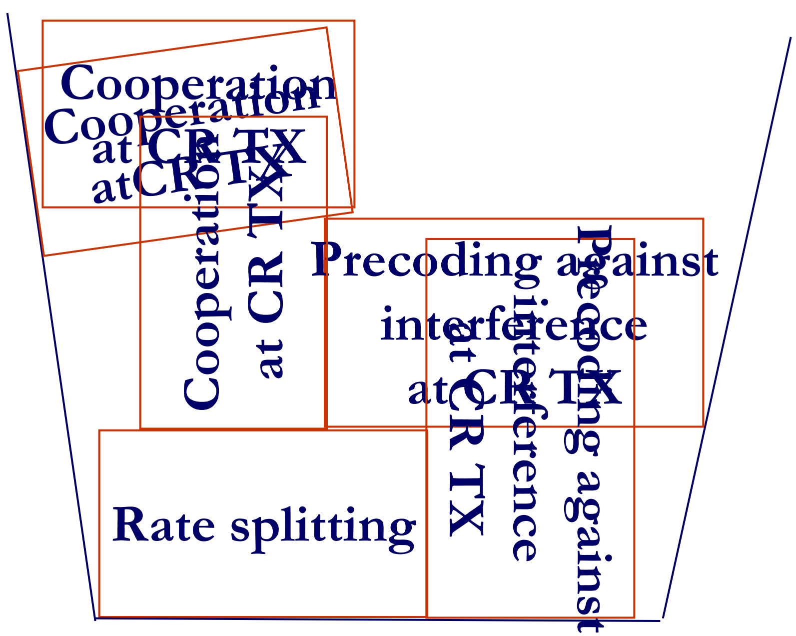
Overlay Cognitive Systems

- Cognitive user has knowledge of other user's message and/or encoding strategy
  - Used to help noncognitive transmission
  - Used to presubtract noncognitive interference





Transmission Strategy "Pieces"



To allow each receiver to decode part of the other node's message
⇨ reduces interference

Removes the NCR interference at the CR RX

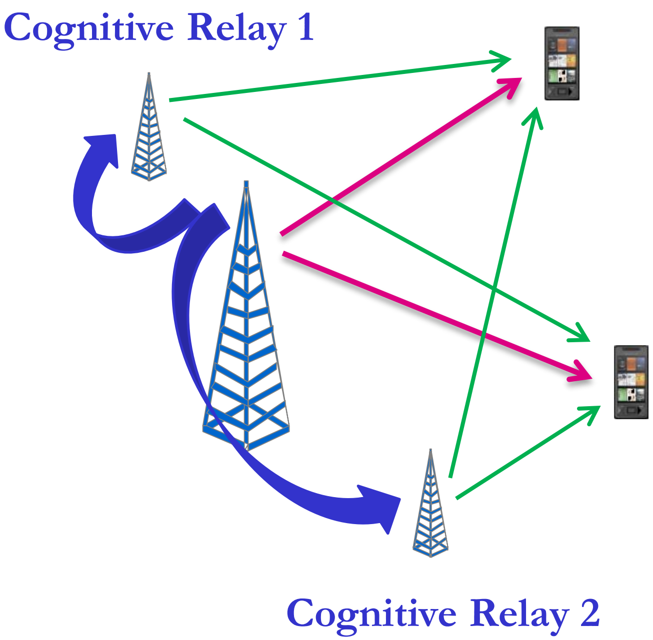
To help in sending NCR's message to its RX

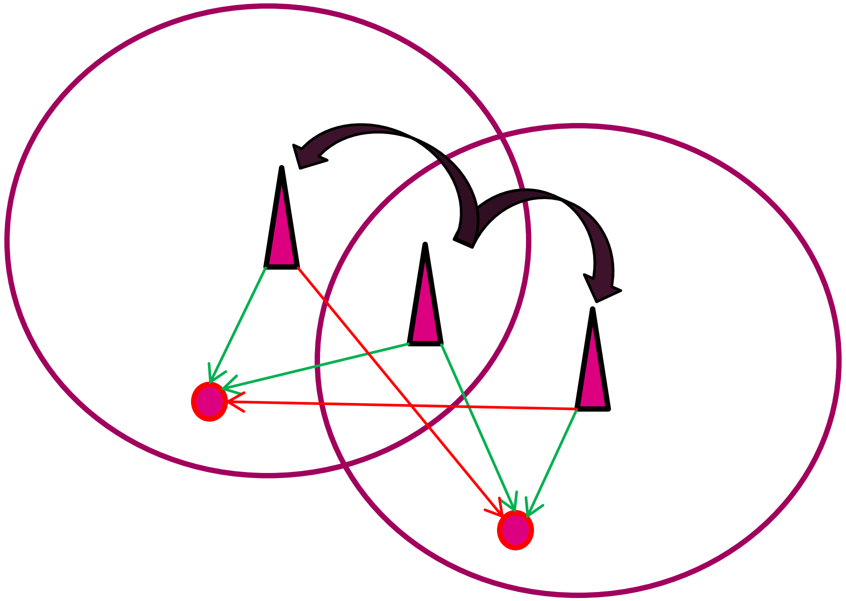
Must optimally combine these approaches

MIMO adds another degree of freedom to the design

Other Overlay Systems

- Cognitive relays
- Cognitive BSs



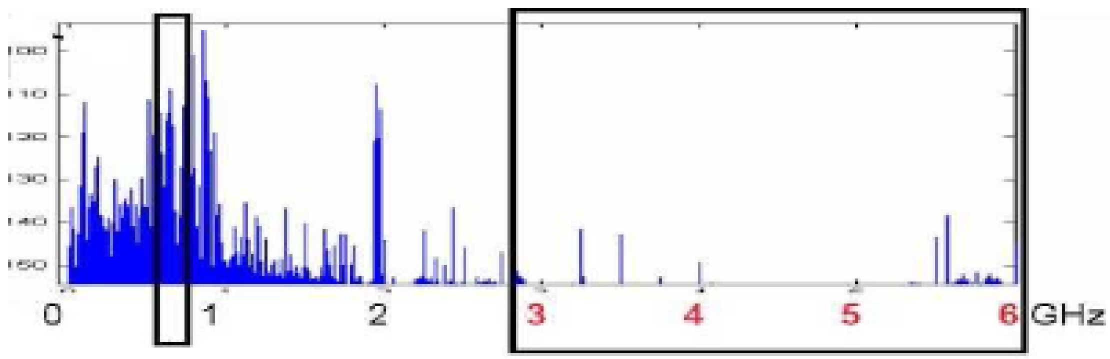


Overlay Challenges

- Complexity of transmission and detection
- Obtaining information about channel, other user's messages, etc.
- Full-duplex vs. half duplex
- Synchronization
- And many more …

Interweave Systems:
Avoid interference

- Measurements indicate that even crowded spectrum is not used across all time, space, and frequencies
  - Original motivation for “cognitive” radios (Mitola’00)



- These holes can be used for communication
  - Interweave CRs periodically monitor spectrum for holes
  - Hole location must be agreed upon between TX and RX
  - Hole is then used for opportunistic communication with minimal interference to noncognitive users

Interweave Challenges

- Spectral hole locations change dynamically
  - Need wideband agile receivers with fast sensing
    - Compresses sensing can play a role here
  - Spectrum must be sensed periodically
  - TX and RX must coordinate to find common holes
  - Hard to guarantee bandwidth
- Detecting and avoiding active users is challenging
  - Fading and shadowing cause false hole detection
  - Random interference can lead to false active user detection
- Policy challenges
  - Licensed users hate interweave even more than underlay
  - Interweave advocates must outmaneuver incumbents

Summary

- Interference avoidance a great topic for everyone getting “half the cake”
- Feedback in networks poorly understood
- Cross-layer design can be powerful, but can be detrimental if done wrong
- Cognitive radios can use spectrum more efficiently.
- Multiple paradigms, with different technical and commercial challenges

A Great Introduction

- Cognitive Radios: Brain empowered Wireless Communications by S. Haykin, IEEE Journal on Selected Areas in Communications, 2005.

- Presented by Matt Yu