Spectrum & Cognitive Radio Research

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Theory and Prototyping Effort funded by the National Science Foundation NeTS Program
The Spectrum Debate

• What everyone agrees on:
  - Spectrum use is inefficient
  - FCC licensing has yielded false scarcity

• **Open Access** (Commons)
  - The triumph of technology

• **Spectrum Property Rights**
  - The triumph of economics
The Open Access Conundrum

- Systems of end-user devices
- **Technology Panacea**
  - Spread spectrum, UWB, MIMO, OFDM
  - Short range communications
  - Ad hoc multi-hop mesh networks
- **Evidence**: success of 802.11 vs. 3G
- **Minor technical rules for transceivers**
  - power
  - spreading
The Open Access Conundrum -II

- Technical arguments against Open Access
  - Partially developed theory
    - Information theoretic relay & interference channel
  - Infant technology
    - UWB, antenna arrays
    - Transmitter agility
  - Technology not separable from user assumptions
    - Capabilities of technology vary with cooperation
What have we learned elsewhere?

Research themes that have emerged from adhoc/sensor networks research:

• **Hierarchical Architecture wins**
  - Capacity scaling, energy efficiency, increases lifetimes, facilitates discovery

• **Cooperation wins**
  - Fundamental performance limits via information theoretic relay and broadcast channels

• **“Global” awareness and coordination wins**
  - Space, time and frequency awareness and coordination beyond local measurements
Require radios that can:
- Discover
- Cooperate
- Collaborate
- Self-Organize into hierarchical networks

- Agility is necessary at every layer of the "protocol stack"
- But cannot yet predict environments

The Answer? "Cognitive Radios"
Network-Centric Cognitive Radio Platform

Requirements

- Spectrum scanning
- PHY layer adaptation
- Ad hoc network discovery
- Multi-hop routing
- Etiquette processing
WINLAB/Lucent Cognitive Radio Prototype

- Heterogeneous block-based architecture
  - FPGA for hardware implementation
  - Embedded RISC for software implementation
- Efficient unlicensed band coordination
  - Tri-band operation (700 MHz, 2.4 & 5.1 GHz)
  - Fast frequency scanning and agility

Bell Laboratories Software Defined Radio (Baseband Processor)

*Courtesy of Dr. T. Sizer*
Then What?

- A **behavioral** approach to the design of cognitive radio
  - Cognitive algorithms
- Infrastructure that can facilitate this
  - Network architectures
  - Information aids
- Need for understanding the fundamental performance limits
Cognitive Algorithms and Architectures

• **Discovery strategies for available spectrum**
  - Algorithms and protocols for frequency selection, coordination and cooperation

• **Coding strategies for efficient sharing**
  - Cooperative diversity and coding for increased spectrum utilization

• **Information strategies for efficient cooperation**
  - “Spectrum Servers” to advise/mediate sharing

• **Negotiation strategies for situations of conflict**
  - Pricing and game theoretic strategies to promote cooperation

• **Domination strategies for situations of conflict**
  - Spectrum warfare with agile waveforms
Cooperative Architectures for Wireless Networks

What can information theory tell us?

(joint with Lalitha Sankaranarayanan & Gerhard Kramer)
What is Cooperation?

- Nodes in a network share resources (bandwidth, time, power) to forward packets for each other.
- Cooperation between nodes achieves gains in
  - Capacity scaling
    - Coherent combining, Distributed “MIMO” gains
  - Energy efficiency
    - SNR gains from shorter hops (reduced path loss)
- Cooperative gains come at the cost of increased end-to-end latency.
Two Types of Cooperation

- **Cooperative Networks:**
  - Transmitting nodes duplex between transmitting their own data and cooperating
  - E.g. sensor networks, military (trust-based) networks

- **Hierarchical Networks:**
  - Dedicated relay nodes to forward data for all transmitters in the network
  - Source nodes only transmit but do not cooperate among themselves
  - E.g. managed wide-area networks; non-cooperative networks
A “Cooperative” Network

• **AP**: Data sinks, **SN**: Source nodes
• **Model** as multiple-access channel with generalized feedback (MAC-GF) with half-duplex constraints
Half-Duplex Multiple Access Channel with Generalized Feedback (MAC-GF)

The $m$th source transmits in time (or frequency) fraction $\alpha_m$ while all $M$ sources cooperate in fraction $\alpha_{M+1}$

Cooperative Network Model
A “Hierarchical” Network

- **AP**: Data sinks, **SN**: Source nodes, **FN**: Forwarding nodes
- Model as *multiple-access relay channel (MARC)* with half-duplex constraints
Constrained Multiple Access Relay Channel (MARC)

Relay receives and transmits in time (or frequency) fraction $\alpha$ and $(1 - \alpha)$ respectively
• The cooperating nodes or relays can aid the transmitting node in the following ways:

  - **Decode-and-Forward (DF):** decode and re-encode received signals before forwarding
  - **Compress-and-Forward (CF):** forward a compressed version of the received signal
  - **Amplify-and-Forward (AF):** scale and forward the received soft observations

• Choice of strategy dictated by
  - network geometry, node/relay processing power, latency tolerance
“Cooperation” vs. “Hierarchy”

- **Cooperation** requires incentives
- **Hierarchy** incurs infrastructure costs
- **Compare** cooperation and hierarchy
  - Using total power as the cost metric
  - For fixed total power, rate and diversity gains for both networks are geometry dependent
  - The gains can be used to choose the network architecture and cooperative strategy
Example: A Network with 2 Sources

- Cooperation (no relay) vs. Hierarchy (relay) for 2 source network
- Decode-and-Forward strategy
- Path-loss exponent $\gamma = 4$; power $P_{m}^{(j)}$ at $m^{th}$ node in $j^{th}$ network

\[
\sum_{m=1}^{M} P_{m}^{(C)} = \sum_{m=1}^{M+1} P_{m}^{(H)} = P_{\text{tot}}
\]
Achievable Rates (No Fading)

\[ \text{Sum Rate } R_1 + R_2 \text{ (bits/ch. use)} \]

\[ \text{Distance of sources from origin (} d \text{)} \]

\[ \text{MAC} \]

\[ (C) \]

\[ P_r = 75\% \]

\[ P_r = 12.5\% \]

\[ P_r = 2.5\% \]

\[ P_r = 0.25\% \]

\[ \text{Full Coop.} \]

\[ \text{SNR}_{\text{tot}} = 9 \text{ dB} \]

\[ P_r = P_{\text{ratio}} \]

\[ P_1 = P_2 \]
Outage Probability (Rayleigh Fading)

\[ P_{\text{out}} = \Pr(R_1 = R_2 < R) \]

- \( P_{\text{tot}} = 9 \, \text{dB} \)
- \( P_1 = P_2 \)
- \( 2d = .5 \)

- MAC
- (C)
- (H): \( P_3^{(H)} = 75\% \)
- (H): \( P_3^{(H)} = 50\% \)
- (H): \( P_3^{(H)} = 25\% \)
- (H): \( P_3^{(H)} = 12.5\% \)
- (H): \( P_3^{(H)} = 2.5\% \)
- Full Cooperation
Evaluation of Cognitive Approaches

- **Capacity performance**: Rates, energy efficiency, BER/FER, outage
- **Cost performance**: Hardware and software complexity
- **Emulation of large-scale networks of cognitive radios**
  - ORBIT Testbed
  - Emergent behavior

[Diagram showing various cognitive radio schemes and their relationships with protocol complexity and hardware complexity.]
Information Aids for Open Access
(sort of a “Google” for Spectrum)

(joint work with folks @ WINLAB)
Internet-based Spectrum Policy Server can help to coordinate wireless networks

- needs connection to Internet even under congested conditions (...low bit-rate OK)
- some level of position determination needed (..coarse location OK)
- spectrum coordination achieved via etiquette protocol centralized at server
**SPS Methodology**

- New users get an SPS address
  - Analogous to DHCP
- Users send activity traces to SPS server
- SPS maintains database of activity traces

**SPS Issues**

- What to measure?
- Coarseness of measurements?
- Trace update frequency?
- SPS database organization to facilitate fast searching?

**SPS Actions**

- Share wireless node descriptors?
- Coordinate comm. between nodes?
- Mediate spectrum sharing among nodes?
Triumph of Technology vs. Triumph of Economics

- **Open Access (Commons)**
  - [Noam, Benkler, Shepard, Reed ...]
  - Agile wideband radios will dynamically share a commons

- **Spectrum Property Rights**
  - [Coase, Hazlett, Faulhaber+Farber]
  - Owners can buy/sell/trade spectrum
  - Flexible use, flexible technology, flexible divisibility, transferability
  - A spectrum market will (by the force of economics) yield an efficient solution