Cognitive Radio
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Cognitive Radio Research
A Multidimensional Activity

- Spectrum Policy
  - Economics
  - Regulation
  - Legal
  - Business

- Theory and Algorithms
  - Fundamental Limits
  - Information & Coding Theory
  - Cooperative Communications
  - Game Theory & Microeconomics

- Hardware/Software Platforms & Prototyping
- Programmable agile radios
  - GNU platforms
  - Cognitive Radio Network Testbed
FCC Spectrum Management
False Scarcity

- All bands are allocated, many for multiple purposes.
- Most bands are actually largely unused.
Spectrum Policy Debate

- **Property Rights**
  - Triumph of Economics
  - [Coase, Hazlett, Faulhaber+Farber]
  - Owners can buy/sell/allocate spectrum
  - A spectrum market will yield an efficient solution

- **Open Access and Commons**
  - Triumph of Technology
  - [Noam, Benkler, Shepard, Reed]
  - Agile radios to dynamically share common spectrum
  - Open Access: Strict technology needs- sensing, interference
  - Commons: Distributed protocol followed in system
The Spectrum Debate & Cognitive Radio

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

- Possible middle ground?
  - Dynamic spectrum access
  - Short-term property rights
  - Spectrum use driven by both technology and market forces

- Cognitive Radios with ability to incorporate market forces?
  - Microeconomics based approaches to spectrum sharing
Cognitive Approaches: Outlook

- Lots of **network (and channel) state information** needed to enable efficient
  - Discovery
  - Self-organization
  - Cooperation Techniques

*Functionality can be quite challenging!*
Cognitive Radios need information

- Reactive schemes (without explicit coordination protocols) have limitations.
  - Interference is a receiver property.

- Alternative: Infrastructure-based coordination

- Examples of coordination mechanisms:
  - Information aids
    - “Spectrum Coordination Channel” to enable spectrum sharing
  - Network architectures
    - “Spectrum Servers” to advise/mediate sharing
Common Spectrum Coordination Channel (CSCC) [Jing, Raychaudhuri]

- CSCC can coordinate radios with incompatible PHY
  - Employs an out-of-band etiquette channel & protocol
    - Periodic TX of radio parameters on CSCC
    - TX at higher power to reach hidden nodes
  - Local contention resolved via protocol-independent etiquette policies
  - Also supports ad-hoc multi-hop routing associations

Periodic Announcements: User ID (MAC Address), Frequency Band, Power Level, Service Type, Technologies used, Priority, Cost/Price Bids, Multi-hop Forwarding capabilities, etc.
802.11 & 16 Co-Existence: Reactive vs. CSCC-based Power Control

CSCC frequency adaptation when $D_{SS-AP} = 200m$ and traffic load 2Mbps

Throughputs vs. $D_{SS-AP}$ by using CSCC power adaptation and traffic load 2Mbps
What can a Spectrum Policy Server do?  
(Anything & Everything)

- Secondary sensors
- Wireless LANs
- Home networking
- TV broadcasting

- Multiaccess/variable rate transmission schemes
- Orthogonal & non-orthogonal multiplexing schemes
- Interference channel / wideband transmissions

Implicit CSCC
Cognitive Radio: Spectrum Policy Server

- Internet-based Spectrum Policy Server (a “Google for spectrum”)
  - IP-based CSCC
  - Coarse location information
  - SPS provides centralized local spectrum coordination
Cognitive Radio Networks
Cross Layer Scheduling via a spectrum server

- **Scheduling Physical links** - achievable rates depend on PHY layer TX & RX
- **Routing** – decisions based on network/application layer metrics
- **Constraints**
  - Link Rate > \( \Sigma \) flows on link
- **Performance bounds via centralized scheduling**

**Low-complexity scheduling schemes**
- Randomized Distributed scheduling (RDS)
- Column generation methods for choosing good scheduling modes

[Raman, Mandayam, Yates]
Two Tier Dynamic Spectrum Access

Spectrum Policy Server/Regulator/Clearinghouse

Service Providers (SP) compete

Level I
SPs obtain spectrum from SPS

Level II
End users obtain spectrum from SPs

End Users: Adapt rate, power, spectrum use for max net utility

Examples: 802.22 Service Providers
OFDM tone allocation to end users
DimsumNet
Two Tier DSA Properties

- Develop engineering models for shaping spectrum policy

- Features:
  - **Dynamic Spectrum Access**: Short term allocation of spectrum resources
  - **Temporary Exclusive Usage**: Parties do not suffer interference
  - **Market Based Allocation**: Supply and demand determines who gets how much bandwidth
Two-Tier Spectrum Access Mechanisms

- **D-Pass** (Dynamic Property-Rights Spectrum Access)
  - **Allocation based charges**
    - SPs pay for spectrum allocation
    - SPs then compete for users via simultaneous auctions

- **D-CPass** (Dynamic-Commons Property-Rights Spectrum Access)
  - **Usage based charges**
    - Clearinghouse mediates bidding among users
    - SPs only pay for spectrum actually used

- **D-CPass** yields better spectrum utilization

Ileri, Mandayam
Two Tier DSA
User and Service Provider Heterogeneity

**Level I**
SPs buy/lease spectrum from clearinghouse

**Level II**
End users lease spectrum from SPs

Service Providers (SP) compete to maximize profits

End Users: Adapt rate, power, spectrum use for max net utility

Acharya, Yates
Cost Model for the SP

- **Spectrum Cost**
  - \( C(X) = CX \), \( X \): sum of spectrum from all users
  - Constant C set by clearinghouse
    - Depends on Geographical region, urban/rural

- **Power Cost**
  - Transmit power = \( \nu X \)
  - \( F(\nu, X) = T \nu X \)
  - Constant T may depend on
    - Presence of other providers in band ‘\( X \)’
User j: spectrum & rates

- $h_j =$ downlink gain
- TX: fixed power spectral density $\nu$
- Spectral efficiency
  $$K_j = \log(1+\nu h_j/N_0)$$
- $x_j =$ allocated spectrum
- Rate $R_j = K_j x_j$
- Higher Spectral Efficiency $K_j$
  = Better Radio Technology
User j: utility functions

- Logarithmic
  \[ U(R_j) = \log(1+R_j) \]
  - Elastic data application (large file download)

- Exponential
  \[ U(R_j) = \Gamma_j[1-\exp(-R_j/\Gamma_j)] \]
  - Application with target rate \( \Gamma_j \)
Objective of the SP and Users

- Clearinghouse set spectrum price

- SP maximizes its net revenue
  - Expense: Spectrum purchase and transmit power
  - Income: Charges the users

- Users maximize their utility minus cost
  - Expense: Charge paid to the SP
  - Gain: Increase in utility due to spectrum
Elasticity of Demand

- Ratio of % change in demand to % change in price

\[ \varepsilon = - \frac{\mu}{X} \frac{\partial X}{\partial \mu} > 0 \]

- Logarithmic Utilities: Elastic demand \((\varepsilon>1)\) always
  - When price is increased, % fall in demand is higher
  - SP can’t arbitrarily overprice spectrum

- Exponential Utilities: Inelastic demand \((\varepsilon<1)\) for low \(\mu\)
  - Low \(\mu\): Enough spectrum for users to be rate saturated
  - Price changes in this regime, % change in demand is less
SP Profit vs Spectrum Cost C

Exponential Utilities
Target Rate = 1 Mbps
Power Cost, T=10
Total cost $C_e = C + TV$

- **High C**
  $$C_e = C + TV \sim C$$
  User Utility ↑ as $ν$ ↑
  SP incentive: High $ν$

- **Low C**
  $$C_e = C + TV \sim TV$$
  SP incentive: Low $ν$

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Graph:
- $ν = 50$ dBm/MHz
- $ν = 30$ dBm/MHz
- $ν = 20$ dBm/MHz
- $ν = 10$ dBm/MHz

Y-axis: Profit of SP
X-axis: Spectrum cost (C) $$/MHz$
User Net Utility

Exponential Utilities
Target Rate = 1 Mbps
Power Cost, $T=10$
Total cost $C_e = C+Tv$

- Low C and high $v$
  $C_e = C+Tv \sim Tv$
  SP costs rise with $v$
  - SP buys less spectrum
  - User net utility reduced

- High C and high $v$
  $C_e = C+Tv \sim C$
  SP costs indifferent to $v$
  User utility $\uparrow$ as $v \uparrow$
Barter Mechanisms

- Exchange goods that are of mutual value
  - Shared understanding of worth
  - More immediate appreciation of benefits

- Barter Mechanisms
  - **Content Exchange**
    - I relay for you, you give me access to some files
  - **Connectivity Exchange**
    - I relay for you, you relay for me at the same time
  - **Bandwidth Exchange**
    - Assume each user has an exclusive spectrum band
    - I relay for you, you lend me some bandwidth
Emerging Themes

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

- Cooperation wins
  - Achievable rates via information theoretic relay and broadcast channels

- "Global" awareness and coordination wins
  - Space, time and frequency awareness and coordination beyond local measurements

- Efficient operation requires radios that can:
  - Cooperate
  - Collaborate
  - Discover
  - Self-Organize into hierarchical networks