Presentation Overview

- Overview of Cognitive Radio
- Interactive Decision Problem
- A “Quick” Review of Game Theory
- Designing Cognitive Radio Networks
- Examples of Networked Cognitive Radios
- Future Directions in Cognitive Radio

These Slides Available Online:
http://www.crtwireless.com/Publications.html

Applications and Emerging Standards

Flavors of 802.11, 802.16, 802.22, and radios that collaborate

CRT
Cognitive Radio Technologies

802.11j – Policy Based Radio

- Explicitly opened up Japanese spectrum for 5 GHz operation
- Part of larger effort to force equipment to operate based on geographic region, i.e., the local policy

2.4 GHz

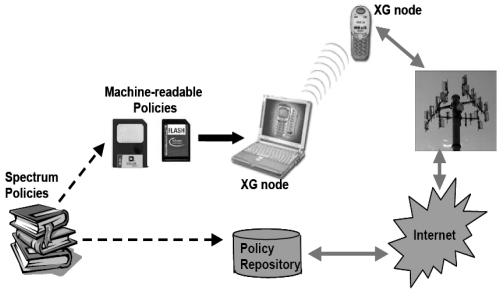
	Lower	Upper
U.S.	2.402	2.48
Europe	2.402	2.48
Japan	2.473	2.495
Spain	2.447	2.473
France	2.448	2.482

5 GHz

US
UNII Low 5.15 – 5.25 (4) 50 mW
UNII Middle 5.25 – 5.35 (4) 250 mW
UNII Upper 5.725-5.825 (4) 1 W
5.47 – 5.725 GHz released in Nov 2003
Europe
5.15-5.35 200 mW
5.47-5.725 1 W
Japan
4.9-5.091
5.15-5.25 (10 mW/MHz) unlicensed

DARPA XG Program – Policy Agility

- Issue:
  - How are radios "aware" of their environment and how do they learn from each other?
- Technical refinement:
  - "Thinking" implies some language for thought.
- Approaches
  - **R**adio **K**nowledge **R**epresentation **L**anguage
  - xG Policy Language
  - **W**eb-based **O**ntology **L**anguage (**OWL**)
- Spectrum agility and policy agility are envisioned
- Load new policy constraints "on the fly" using flash cards or internet



From "Vision RFC", http://www.darpa.mil/ato/programs/XG/

802.11e – Almost Cognitive

- Enhances QoS for Voice over Wireless IP (aka Voice over WiFi) and streaming multimedia
- Changes
  - Enhanced Distributed Coordination Function (EDCF)
    - Shorter random backoffs for higher priority traffic
  - Hybrid coordination function (orientation)
    - Defines traffic classes
    - In contention free periods, access point controls medium access (observation)
    - Stations report to access info on queue size. (Distributed sensing)

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802.11h – Unintentionally Cognitive

- **D**ynamic **F**requency **S**election (DFS)
  - Avoid radars
    - Listens and discontinues use of a channel if a radar is present
  - Uniform channel utilization
- **T**ransmit **P**ower **C**ontrol (TPC)
  - Interference reduction
  - Range control
  - Power consumption Savings
  - Bounded by local regulatory conditions

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802.11h: A simple cognitive radio

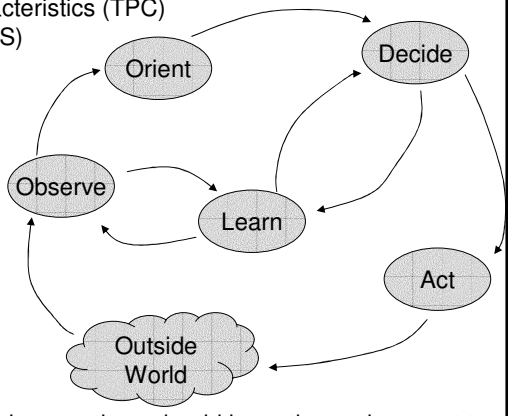
Observe
- Must estimate channel characteristics (TPC)
- Must measure spectrum (DFS)

Orientation
a) Radar present?
b) In band with satellite??
c) Bad channel?
d) Other WLANs?

Decision
- Change frequency
- Change power
- Nothing

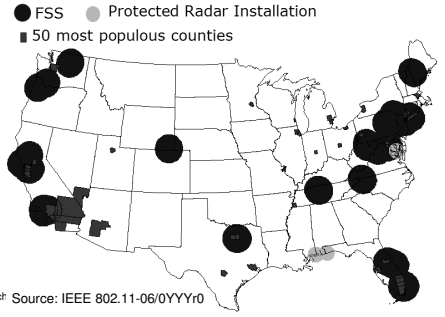
Action
Implement decision

Learn
- Not in standard, but most implementations should learn the environment to address intermittent signals



802.11y

- Ports 802.11a to 3.65 GHz – 3.7 GHz (US Only)
  - FCC opened up band in July 2005
  - Ready 2008
- Intended to provide rural broadband access
- Incumbents
  - Band previously reserved for fixed satellite service (FSS) and radar installations – including offshore
  - Must protect 3650 MHz (radar)
  - Not permitted within 80km of inband government radar
  - Specialized requirements near Mexico/Canada and other incumbent users
- Leverages other amendments
  - Adds 5,10 MHz channelization (802.11j)
  - DFS for signaling for radar avoidance (802.11h)
- Working to improve channel announcement signaling
- Database of existing devices
  - Access nodes register at http://wireless.fcc.gov/uls
  - Must check for existing devices at same site



 Source: IEEE 802.11-06/0YYYr0

IEEE 802.22

- **W**ireless **R**egional **A**rea **N**etworks (WRAN)
  - Aimed at bringing broadband access in rural and remote areas
  - Takes advantage of better propagation characteristics at VHF and low-UHF
  - Takes advantage of unused TV channels that exist in these sparsely populated areas
- 802.22 is to define:
  - Physical layer specifications
  - Policies and procedures for operation in the VHF/UHF TV Bands between 54 MHz and 862 MHz
  - Cognitive Wireless RAN Medium Access Control

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802.22 Deployment Scenario

- Devices
  - **B**ase **S**tation (BS)
  - **C**ustomer **P**remise **E**quipment (CPE)
- Master/Slave relation
  - BS is master
  - CPE slave
- Max Transmit CPE 4W

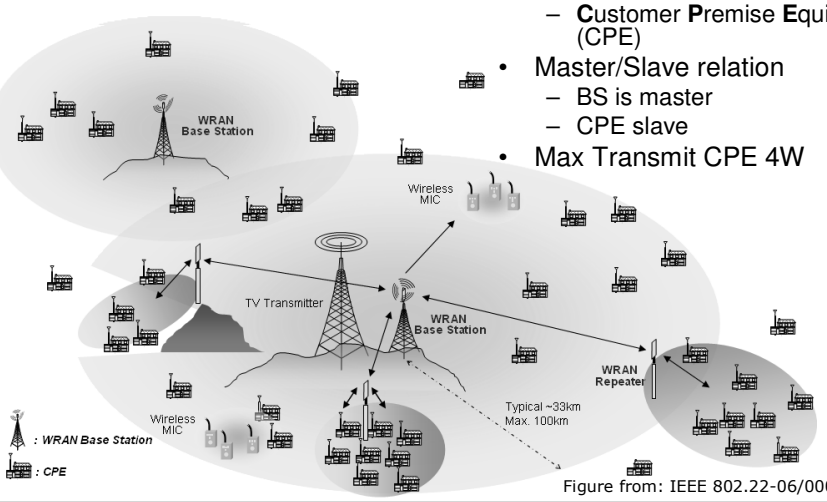

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Figure from: IEEE 802.22-06/0005r1

Proposed PHY Features of 802.22

- Data Rates 5 Mbps – 70 Mbps
- Point-to-multipoint TDD/FDD
- DFS, TPC
- Adaptive Modulation
  - QPSK, 16, 64-QAM, Spread QPSK
- OFDMA on uplink and downlink
- Use multiple contiguous TV channels when available
- Fractional channels (adapting around microphones)
- Space Time Block Codes
- Beam Forming
  - No feedback for TDD (assumes channel reciprocity)
- 802.16-like ranging

Possible MAC Features of 802.22

- 802.16 MAC plus the following
  - Multiple channel support
  - Coexistence
    - Incumbents
    - BS synchronization
    - Dynamic resource sharing
  - Clustering support
  - Signal detection/classification routines
- Security based on 802.16e security

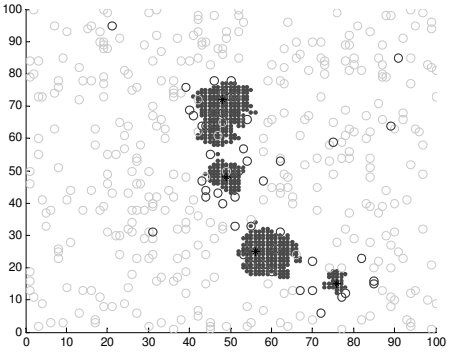
Cognitive Aspects of 802.22

- Observation
  - Signal strength and feature detection
  - Aided by distributed sensing (CPEs return data to BS)
  - Digital TV: -116 dBm over a 6 MHz channel
  - Analog TV: -94 dBm at the peak of the NTSC (National Television System Committee) picture carrier
  - Wireless microphone: -107 dBm in a 200 kHz bandwidth.
  - Possibly aided by spectrum usage tables
- Orientation
  - Infer type of signals that are present
- Decision
  - Frequencies, modulations, power levels, antenna choice (omni and directional)
- Policies
  - 4 W **E**ffective **I**sotropic **R**adiated **P**ower (**EIRP**)
  - Spectral masks, channel vacation times

C. Cordeiro, L. Challapali, D. Birru, S. Shankar, "IEEE 802.22: The First Worldwide Wireless Standard based on Cognitive Radios," *IEEE DySPAN2005*, Nov 8-11, 2005 Baltimore, MD.

Sensing Aspects of 802.22

- Region based sensing
  - Remote aided sensing
- Algorithm:
  - Partition cell into disjoint regions
  - For each region assign a remote (**C**ustomer **P**remise **E**quipment)
    - Example considered squares with 500 m sides
  - CPE feeds back what it finds
    - Number of incumbents
    - Occupied bands



Source: IEEE 802.22-06/0048r0

802.16h

- Draft to ballot Oct 06, 67% approve, resolving comments)
- Improved Coexistence Mechanisms for License-Exempt Operation
- Basically, a cognitive radio standard
- Incorporates many of the hot topics in cognitive radio
  - Token based negotiation
  - Interference avoidance
  - Network collaboration
  - RRM databases
- Coexistence with non 802.16h systems
  - Regular quiet times for other systems to transmit

non-collaborative mechanism	*(CXCC:) dynamic frequency selection (DFS) *6.4.2.2*
	*(CXCC:) GPS timing recovery (GPS/UTC) *15.2.1*
	Extended quiet periods (EQP) *6.4.3.3*
	Adaptive EQP *6.4.3.4*
	Listen before talk *6.4.3.5*
	Uncoordinated Coexistence Protocol (UCP) *6.4.2.4*
collaborative mechanism	IP network message (CXP message) *15.5.2*
	coexistence proxy (CXPRX) *15.1.6*
	*(CXCC:) coexistence signaling (CSI/ radio signature) *15.3.1*
	*(CXCC:) coexistence messaging (CMI/CCD) *15.3.2*
	sub frame sharing (master sub frame) *15.4.2*
	channel reallocation (ACS) *15.4.1*
	Subframe Reallocation (ASFA) *15.4.2.2*
	credit token *15.4.2.5*

From: M. Goldhamer, "Main concepts of IEEE P802.16h / D1," Document Number: IEEE C802.16h-06/121r1, November 13-16, 2006.

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General Cognitive Radio Policies in 802.16h

- Must detect and avoid radar and other higher priority systems
- All BS synchronized to a GPS clock
- All BS maintain a radio environment map (not their name)
- BS form an interference community to resolve interference differences
- All BS attempt to find unoccupied channels first before negotiating for free spectrum
  - Separation in frequency, then separation in time

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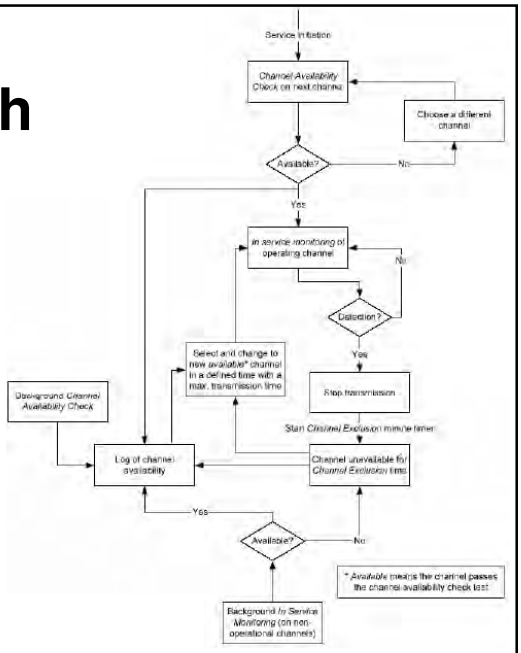
DFS in 802.16h

- Adds a generic algorithm for performing Dynamic Frequency Selection in license exempt bands
- Moves systems onto unoccupied channels based on observations
- Works when there is no interaction



Generic DFS Operation Figure h1
(fuzziness in original)

Adaptive Channel Selection

- Used when BS turns on
- First – attempt to find a vacant channel
  - Passive scan
  - Candidate Channel Determination
  - Messaging with Neighbors
- Second – attempt to coordinate for an exclusive channel
- If unable to find an empty channel, then BS attempts to join the interference community on the channel it detected the least interference

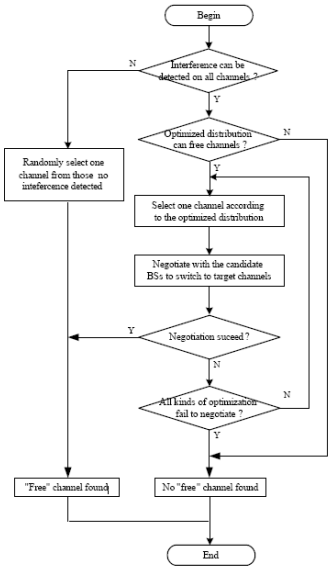


Figure h37: IEEE 802.16h-06/010 Draft IEEE Standard for Local and metropolitan area networks Part 16: Air Interface for Fixed Broadband Wireless Access Systems Amendment for Improved Coexistence Mechanisms for License-Exempt Operation, 2006-03-29

Collaboration in 802.16h

- BS can request interfering systems to back off transmit power
- Master BS can assign transmit timings
  - Intended to support up to 3 systems (Goldhammer)
- Slave BS in an interference community can "bid" for interference free times via tokens.
- Master BS can advertise spectrum for "rent" to other Master BS
  - Bid by tokens
- Collaboration supported via Base Station Identification Servers, messages, and RRM databases
- Interferer identification by finding power, angle of arrival, and spectral density of OFDM/OFDMA preambles
- Every BS maintains a database or RRM information which can be queried by other BS
  - This can also be hosted remotely

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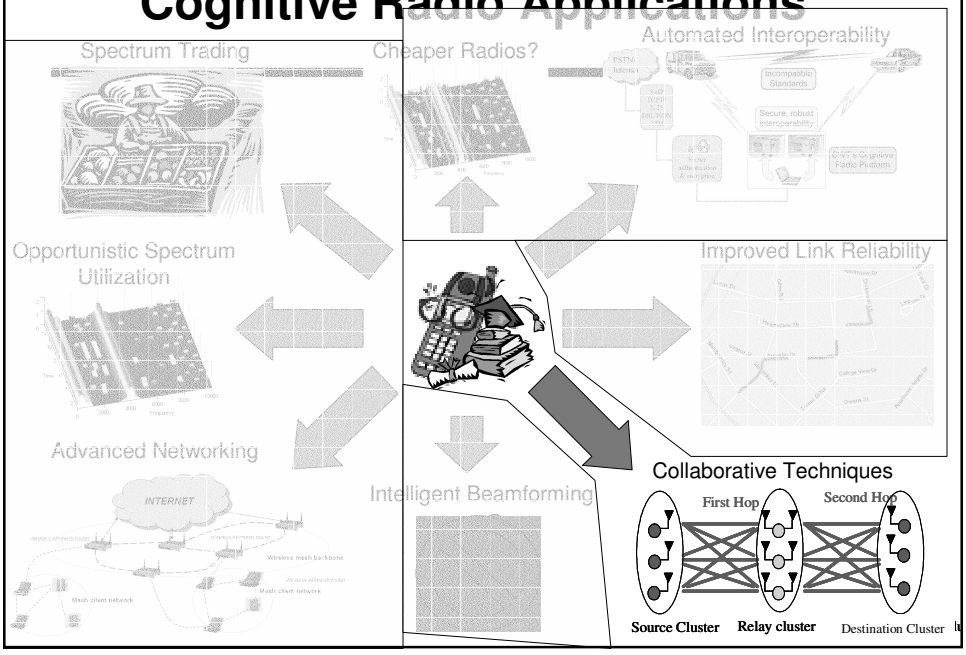
Cognitive Radio Applications



Collaborative Radio

- A radio that leverages the services of other radios to further its goals or the goals of the networks.
- Cognitive radio enables the collaboration process
  - Identify potential collaborators
  - Implies observations processes
- Classes of collaboration
  - Distributed processing
  - Distributed sensing

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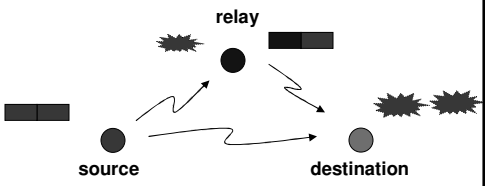
Cooperative Communication: Classical Relay Channel

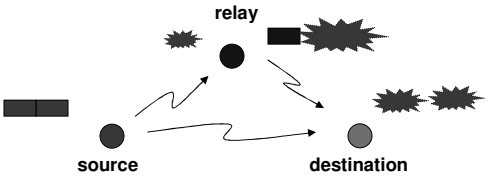
- Cooperation: relay nodes transmit its own information + source information
- Relay Operation:
  - Half duplex
    - Time division, Frequency division, Code division

$$y_{ij} = \alpha_{ij} x_i + n_j$$

- Dedicated version in 802.16j, could be logically extended to non-dedicated relays



Decode and Forward

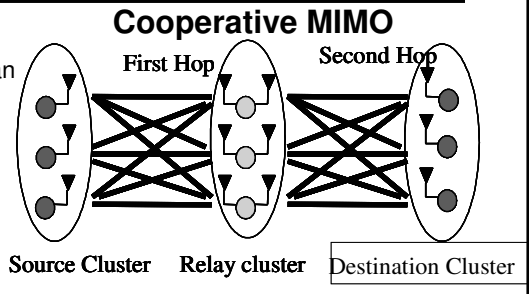


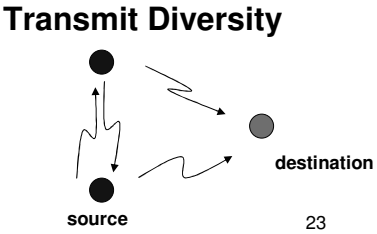
Amplify and Forward

Cooperative Antenna Arrays

- Concept:
  - Leverage other radios to effect an antenna array
- Applications:
  - Extended vehicular coverage
  - Backbone comm. for mesh networks
  - Range extension with cheaper devices
- Issues:
  - Timing, mobility
  - Coordination
  - Overhead
- Dissertation of Ramesh Chembil

http://scholar.lib.vt.edu/theses/available/etd-12132006-142934/





Other Opportunities for Collaborative Radio (1/3)

- Distributed processing
  - Exploit different capabilities on different devices
    - Maybe even for waveform processing
  - Bring extra computational power to bear on critical problems
    - Useful for most collaborative problems
- Collaborative sensing
  - Extend detection range by including observations of other radios
    - Hidden node mitigation
  - Improve estimation statistics by incorporating more independent observations
  - Immediate applicability in 802.22, likely useful in future adaptive standards

Other Opportunities for Collaborative Radio (2/3)

- Improved localization
  - Application of collaborative sensing
  - EMS location services for ad-hoc networks
  - Friend finders (Samsung USA working on this)
- Reduced contention MACs
  - Collaborative scheduling algorithms to reduce collisions
  - Perhaps of most value to 802.11
    - Some scheduling included in 802.11e

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Other Opportunities for Collaborative Radio (3/3)

- Distributed mapping
  - Gather information relevant to specific locations from mobiles and arrange into useful maps
  - Coverage maps
    - Collect and integrate signal strength information from mobiles
    - If holes are identified and fixed, should be a service differentiator
  - Congestion maps
    - Density of mobiles should correlate with traffic (as in automobile) congestion
    - Customers may be willing to pay for real time traffic information
- Theft detection
  - Devices can learn which other devices they tend to operate in proximity of and unexpected combinations could serve as a security flag (like flagging unexpected uses of credit cards)
  - Examples:
    - Car components that expect to see certain mobiles in the car
    - Laptops that expect to operate with specific mobiles nearby

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Items to Remember

- Initial standards ignored interaction, primary focus was on avoiding incumbents
- More recent standards act in a distributed fashion when possible to find non-interactive states, but collaborate to resolve interaction problem
- By collaborating, cognitive radios can provide performance beyond the capabilities of a single device
  - Collaborative MIMO, Collaborative Sensing

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