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

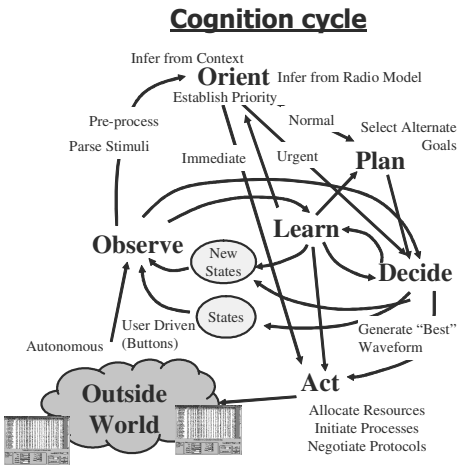
Research and Future Directions

Technology trends related to cognitive radio

CRT
Cognitive Radio Technologies

Increasing Availability of Network Information Databases

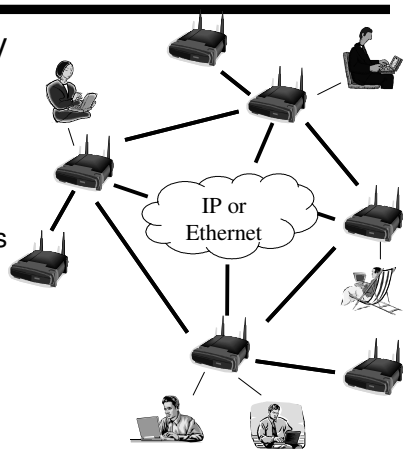
- Databases becoming available
  - 802.11k RRM
  - 802.11v Network management
  - 802.16f Network Management Information Base (MIB)
  - 802.16g Network management plane
  - 802.16i Mobile Management Information Base
- Cognitive radios need environmental information to make intelligent decisions
- Should simplify information gathering process



3

Increasing Flexibility in Network Topology

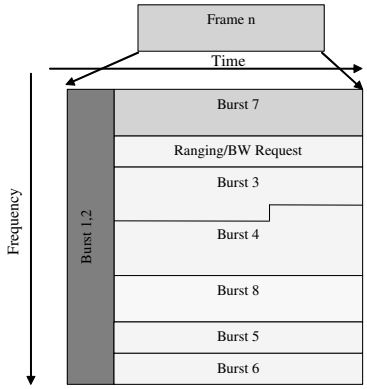
- Numerous emerging topology standards
  - 802.11s Mesh
  - 802.16 Ad-hoc
  - 802.16j MMR
  - 802.15 WPAN ad-hoc
  - 802.15.5 WPAN mesh networks
  - 802.22 MMR?
- Greater flexibility in network choice
  - 802.21
  - UMA
- Value in being able to recognize when ad-hoc modes or alternate networks are available and advisable => cognitive radio



4

Increasing Flexibility of PHY

- TDD OFDMA
- Beam Forming
- MIMO
- Adaptive coding/rate
- Adaptive modulation
- PHY and networking flexibility provides additional variables for cognitive radio to control
- Improved RRM, device performance

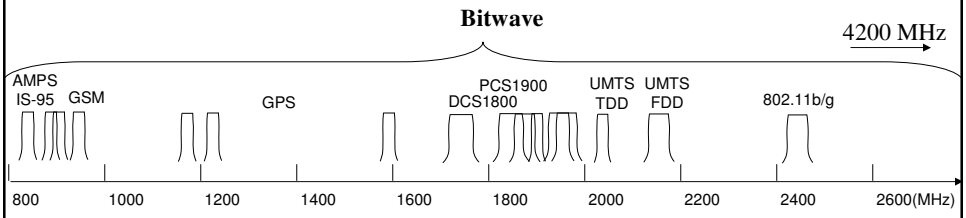


IEEE 802.22-06/0105r0

Emergence of "Cute" CR-type Features at Application Layer

- TeleNav
  - Uses GPS and Maps to give directions
  - Similar to some features described by Mitola
- GPS (perhaps network assisted/provided) will be a critical source of information
  - Policy, remembering coverage holes, spectrum mapping

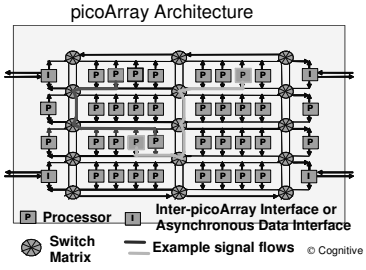
Increasing Sophistication of SDR Hardware



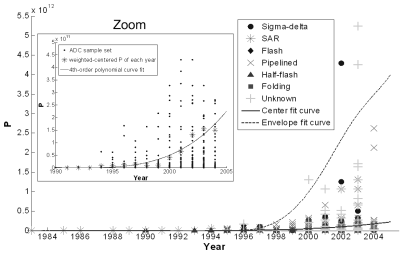
Bottom line: MEMS based RFICs dramatically expanding range

Improving processor capabilities

picoArray Architecture



Data converters improving exponentially



Bin Le, Tom Rondeau, Jeff Reed, Charles Bostian, "Past, Present, and Future of ADCs," *IEEE Signal Processing Magazine*, November 2005

Dominance of Weak CR and Continuous Aggregation of Algorithms

- Strong CR research unlikely to yield useful AI
  - More likely to yield scenario classification and negotiation routines useful for CBR systems
- Weak CR being implemented now
- Large number of conceivable and proposed applications suitable for Weak CR
- Simplest integration path is a good SDR with upgradeable control processes
  - Add applications as developed
  - Can become quite sophisticated
- Key will be scenario/opportunity recognition

Research Opportunities

What topics should we be experimenting with now?

9

Tools

- New technologies generally need new tools
- Examples:
  - Policy interpreters – intelligently and automatically combine policy languages from different vendors
  - CBR programming suite
  - Multi-core compilers
  - Development kits

10

Standards

- Portability and interoperability would greatly benefit from standardization of key aspects of cognitive radio
- Examples:
  - Standard cognitive language
  - RRM databases
  - Measurements (Interference temperature was an attempt)
  - Minimal competencies
  - Cognitive engine
  - Interference avoidance techniques
  - Software architectures
- Some of these will be addressed by the 1900 group

11

Apply CR Principles to Existing Standards

- Develop Cognitive WiMAX
  - Intelligent Radio Resource Management
  - Intelligent Physical/MAC layers
  - Intelligent Fault Detection
- Why?
  - Enable less trained and experience personnel to manage and install
  - Improve performance and reliability
  - Lower deployment and maintenance costs
  - Ability to leverage both licensed, unlicensed and refarmed spectrum

12

Some Example WiMAX Functions

- Radio Resource Management
  - Frequency management
    - Avoid interference at cell boundaries
    - Co-utilize license and unlicensed bands
  - Smart antenna management
    - Appropriate algorithm for the situation
    - Efficiently use limited smart antenna capabilities
  - Load balancing and coverage adjustments between cells
  - Optimum handoff strategy: Intra and Inter system
- Mapping Applications to QoS management
- Implications of cognitive mobile multi-hop relay (MMR) network

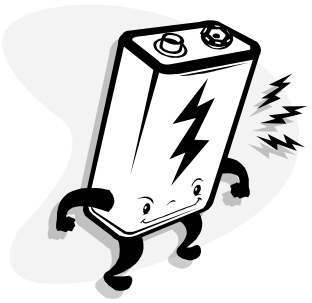
  Many parameters in the standard can be adjusted using cognitive radio principles.

Traditional Issues in a New Domain

- Cognitive radio is still a radio so traditional research areas still apply
- Examples:
  - Security
  - Code verification/validation
  - Code portability
  - Code/circuit optimization
  - Front end flexibility and performance

Reducing Power Consumption

- Keep min. power by varying
  - Modulation
  - Coding
  - Carrier
  - Filtering
  - Sample rate
  - Algorithms
  - Bias points
  - Application
- Radio knowledgeable of power consumed
  - Weight depends on hardware TX and RX
- Don't specifically care about bandwidth!



15

Speculation on the Future

16

Commercial Market

- 1-3 years
  - Start of several initiatives and standards explicitly leveraging cognitive radio
  - Initial devices will be procedural and will not have cognitive engines
  - Many market niche solutions
  - First cognitive networks from upgraded standards
- 3-7 years
  - General purpose cognitive radio solutions become available
  - Significant expansion of unlicensed bands
  - Emergence of cognitive certification bodies
  - Hacking your own cognitive radio becomes popular in certain circles
  - Privacy issues will emerge

17

Technologies

- Radios will not become “conscious”, but will be a lot more intelligent
- Implementations will bifurcate into low complexity limited application cognitive radios and high complexity general purpose cognitive radios
  - Some low complexity radios will leverage REMs
  - Some will gather observations, and implement network decisions
  - Some will implement simple procedural rules
- REMs will grow increasingly important
- Lacking a standard, commercializing ontological reasoning will prove more difficult than it first appears because of issues with verification and portability

18

Summary of Points to Remember

Points to Remember

- Used cognitive radio definition
  - a radio with the capacity to acquire and apply knowledge especially toward a purposeful goal
- Key Implementation aspects
  - Techniques have been proposed and prototyped for all of the core cognitive radio functionalities (observe, orient, decide, learn, act)
  - Major research efforts will be driven by applications
    - Standardizing ontologies for common applications
    - Refining classification methods for particular applications
    - Standardizing software architectures/APIs

Points to Remember

- Cognitive radios introduce interactive decision problems
- When studying a cognitive radio network should identify
  - Who are the decision makers
  - Available adaptations of the decision makers
  - Goals guiding the decision makers
  - Rules being used to formulate decisions
  - Any timing information

21

Points to Remember

Game	⇔	Cognitive radio network
Player	⇔	Cognitive radio
Actions	⇔	Actions
Utility function	⇔	Goal
Outcome space	⇔	Outside world
Utility function arguments	⇔	Observations/orientation
Order of play	⇔	Adaptation timings

- NE are always fixed points for self-interested adaptations
  - But may not be ALL fixed points
- Many ways to measure optimality
- Randomness helps convergence
- Unbounded noise implies network has a theoretically non-zero chance to visit every possible state

22

Points to Remember

- In addition to interactive decisions, timing and distribution of information are critical
- Policies are a good way to limit worst case scenarios
- Additive cost functions can shape behavior
- Collaboration and centralization can eliminate interactive decision problems
- Punishment can limit incentives to cheat on collaborative agreements
  - But is very sensitive to the design
- Under special conditions (bilateral symmetric interference), interactive decisions form a virtuous cycle

Points 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

Points to Remember

- Supporting technologies for cognitive radio rapidly developing
- Potential value to adding cognitive radio on top of existing standards
- Dubious that cognitive radio will be “conscious” radio
- Cognitive radio will tend to either be very low complexity or very high complexity
  - Bimodal distribution