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Networking Cognitive Radios

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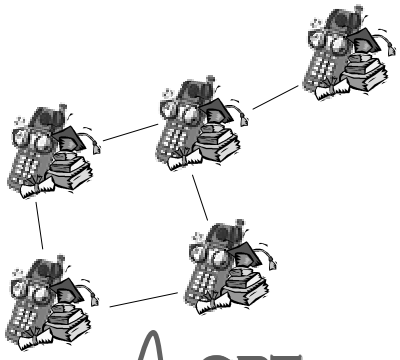

MPRG Symposium
Session D-2
June 8, 2007

CRT
Cognitive Radio Technologies

James Neel

- President, Cognitive Radio Technologies, LLC
- PhD, Virginia Tech 2006
  - http://scholar.lib.vt.edu/theses/available/etd-12082006-141855/
- Textbook chapters on:
  - Cognitive Network Analysis in
  - Data Converters in *Software Radio: A Modern Approach to Radio Engineering*
  - SDR Case Studies in *Software Radio: A Modern Approach to Radio Engineering*
  - UWB Simulation Methodologies in *An Introduction to Ultra Wideband Communication Systems*
- SDR Forum Paper Awards for 2002, 2004 papers on analyzing/designing cognitive radio networks
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CRT
Cognitive Radio Technologies

Presentation Overview

- (32) Overview of Cognitive Radio
- (20) Interactive Decision Problem
- (44) A “Quick” Review of Game Theory
- (62) Designing Cognitive Radio Networks
- (26) Examples of Networked Cognitive Radios
- (20) Future Directions in Cognitive Radio

3

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

4

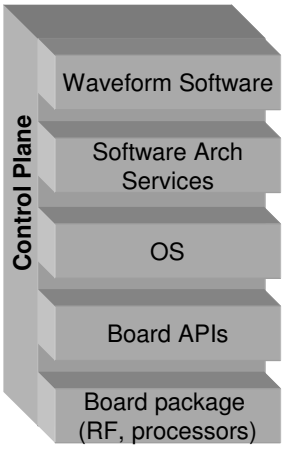
Overview of Cognitive Radio

Concepts, Definitions, Implementations

5

Cognitive Radio: Basic Idea

- Software radios permit network or user to control the operation of a software radio
- Cognitive radios enhance the control process by adding
  - Intelligent, autonomous control of the radio
  - An ability to sense the environment
  - Goal driven operation
  - Processes for learning about environmental parameters
  - Awareness of its environment
    - Signals
    - Channels
  - Awareness of capabilities of the radio
  - An ability to negotiate waveforms with other radios

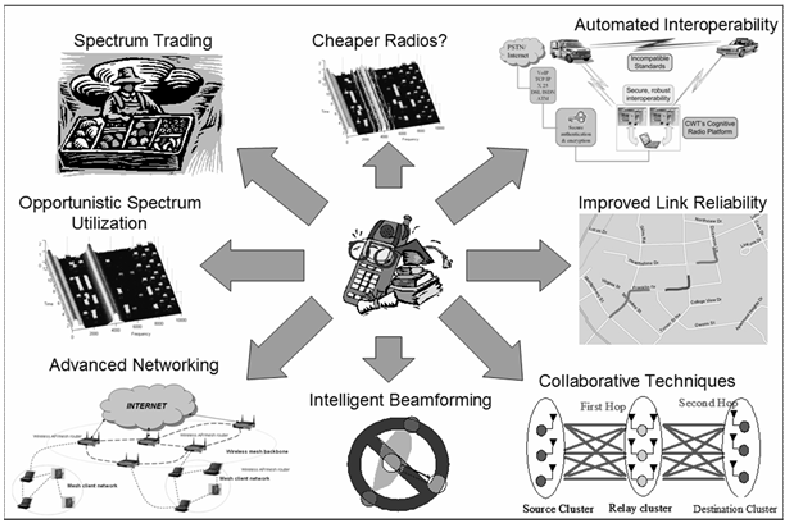


6

Cognitive Radio Capability Matrix

Definer	Adapts (Intelligently)	Autonomous	Can sense Environment	Transmitter	Receiver	"Aware" Environment	Goal Driven	Learn the Environment	"Aware" Capabilities	Negotiate Waveforms	No interference
FCC	•	•	•	•							
Haykin	•	•	•	•	•	•	•	•			
IEEE 1900.1	•	•	•	•	•						
IEEE USA	•	•	•	•	•	•					•
ITU-R	•	•	•	•	•	•					
Mitola	•	•	•	•	•	•	•	•	•	•	
NTIA	•	•	•	•	•	•	•				
SDRF CRWG	•	•	•	•	•		•				
SDRF SIG	•	•	•	•	•	•	•	•	•		
VT CRWG	•	•	•	•	•	•	•	•	•		

Cognitive Radio Applications



8

Why So Many Definitions?

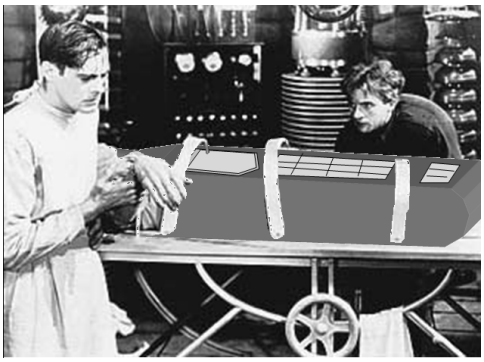
- People want cognitive radio to be something completely different
  - Wary of setting the hype bar too low
  - Cognitive radio evolves existing capabilities
  - Like software radio, benefit comes from the paradigm shift in designing radios
- Focus lost on implementation
  - Wary of setting the hype bar too high
  - Cognitive is a very value-laden term in the AI community
  - Will the radio be conscious?
- Too much focus on applications
  - Core capability: radio adapts in response changing operating conditions based on observations and/or experience
  - Conceptually, cognitive radio is a magic box

Used cognitive radio definition

- A *cognitive radio* is a radio whose control processes permit the radio to leverage situational knowledge and *intelligent* processing to autonomously adapt towards some goal.
- Intelligence as defined by [American Heritage_00] as "*The capacity to acquire and apply knowledge, especially toward a* ***purposeful goal***."
  - To eliminate some of the mess, I would love to just call cognitive radio, "intelligent" radio, i.e.,
  - a radio with the capacity to acquire and apply knowledge especially toward a purposeful goal

Overview of Implementation Approaches

How does the radio become cognitive?



11

Levels of Cognitive Radio Functionality

Level	Capability	Comments
0	Pre-programmed	A software radio
1	Goal Driven	Chooses Waveform According to Goal. Requires Environment Awareness.
2	Context Awareness	Knowledge of What the User is Trying to Do
3	Radio Aware	Knowledge of Radio and Network Components, Environment Models
4	Capable of Planning	Analyze Situation (Level 2& 3) to Determine Goals (QoS, power), Follows Prescribed Plans
5	Conducts Negotiations	Settle on a Plan with Another Radio
6	Learns Environment	Autonomously Determines Structure of Environment
7	Adapts Plans	Generates New Goals
8	Adapts Protocols	Proposes and Negotiates New Protocols

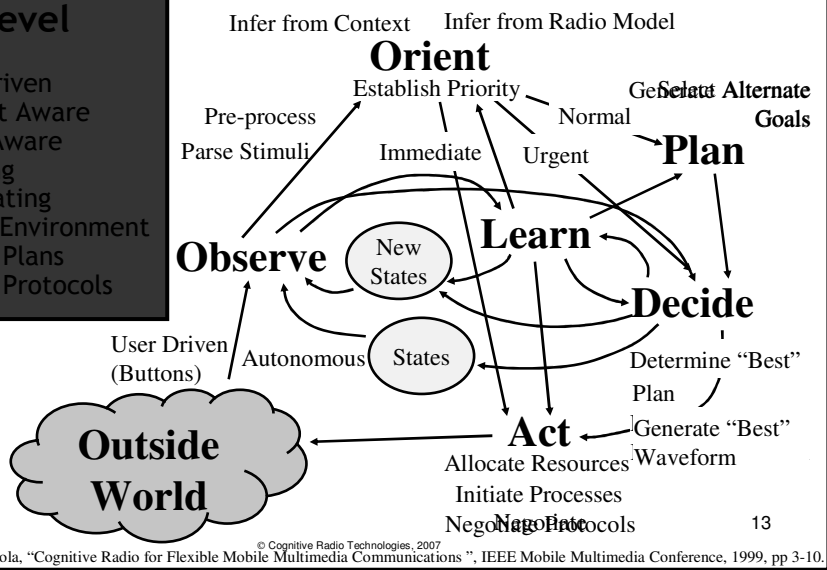
Adapted From Table 4-1Mitola, "Cognitive Radio: An Integrated Agent Architecture for Software Defined Radio," PhD Dissertation Royal Institute of Technology, Sweden, May 2000.

12

Cognition Cycle

Level

0 SDR
1 Goal Driven
2 Context Aware
3 Radio Aware
4 Planning
5 Negotiating
6 Learns Environment
7 Adapts Plans
8 Adapts Protocols



Adapted From Mitola, "Cognitive Radio for Flexible Mobile Multimedia Communications ", IEEE Mobile Multimedia Conference, 1999, pp 3-10.

Conceptual Operation

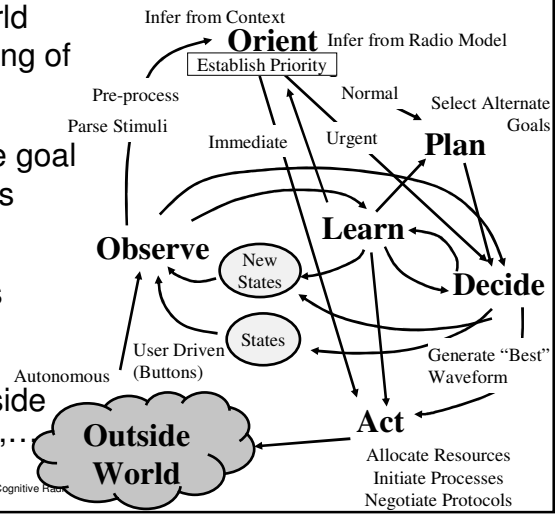
OODA Loop: (continuously)

- Observe outside world
- Orient to infer meaning of observations
- Adjust waveform as needed to achieve goal
- Implement processes needed to change waveform

Other processes: (as needed)

- Adjust goals (Plan)
- Learn about the outside world, needs of user,…

Cognition cycle [Mitola_99]



Implementation Classes

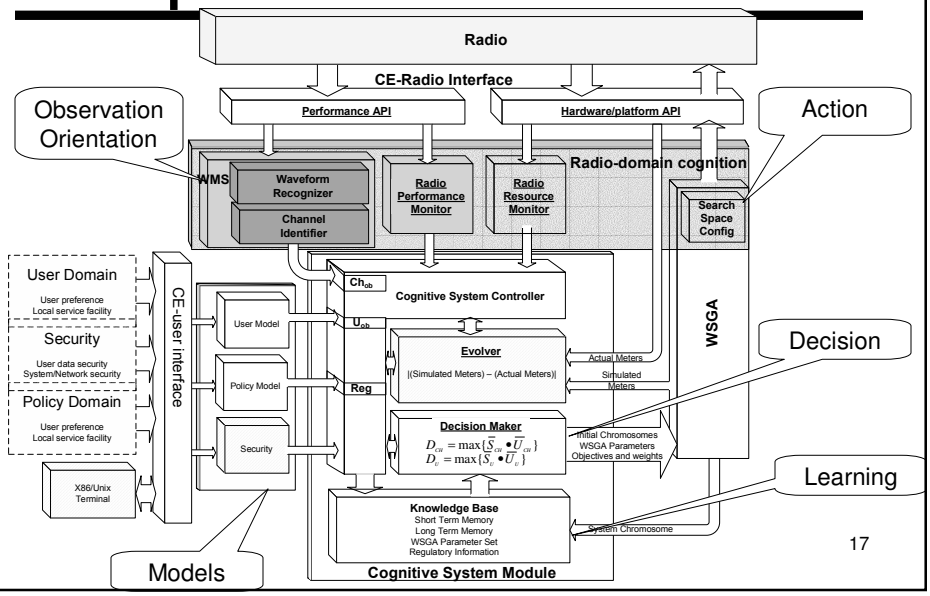
- **Weak** cognitive radio
  - Radio's adaptations determined by hard coded algorithms and informed by observations
  - Many may not consider this to be cognitive (see discussion related to Fig 6 in 1900.1 draft)
- **Strong** cognitive radio
  - Radio's adaptations determined by conscious reasoning
  - Closest approximation is the ontology reasoning cognitive radios

- In general, strong cognitive radios have potential to achieve both much better and much worse behavior in a network, but may not be realizable.

Brilliant Algorithms and Cognitive Engines

- Most research focuses on development of algorithms for:
  - Observation
  - Decision processes
  - Learning
  - Policy
  - Context Awareness
- Some complete OODA loop algorithms
- In general different algorithms will perform better in different situations
- Cognitive engine can be viewed as a software architecture
- Provides structure for incorporating and interfacing different algorithms
- Mechanism for sharing information across algorithms
- No current implementation standard

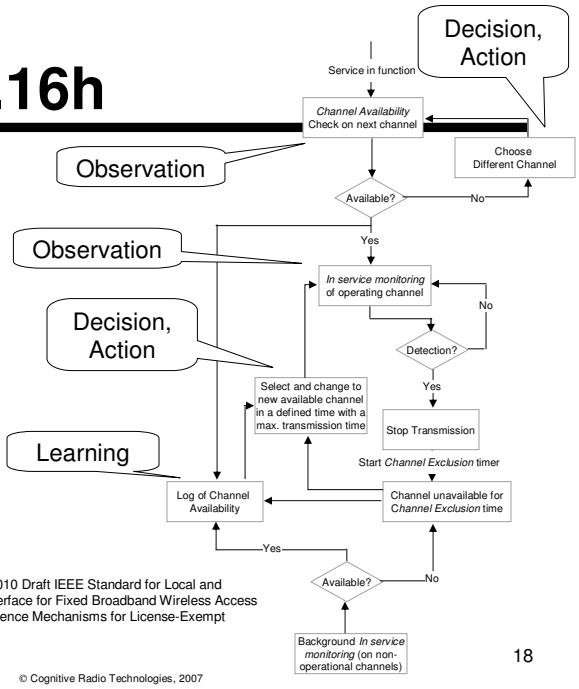
Example Architecture from CWT



17

DFS in 802.16h

- Drafts of 802.16h defined a generic DFS algorithm which implements observation, decision, action, and learning processes
- Very simple implementation

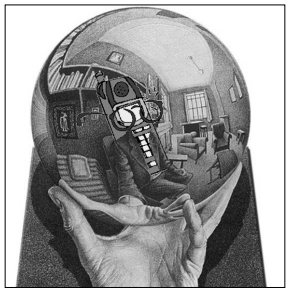


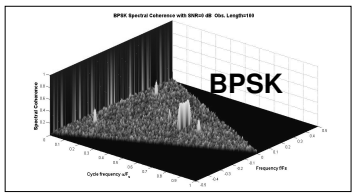
Modified from Figure h1 IEEE 802.16h-06/010 Draft IEEE Standard for Local and metropolitan area networks Part 16: Air Interface for Fixed Broadband Wireless Access Systems Amendment for Improved Coexistence Mechanisms for License-Exempt Operation, 2006-03-29

18

Observation Sources

- RF Chain
  - Signal detection/classification
  - Active ranging
- GPS
  - Location, time
- Network
  - Others' observations
- Device sensors
  - Biometrics, temperature
- User interfaces

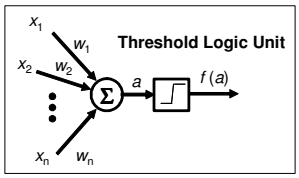


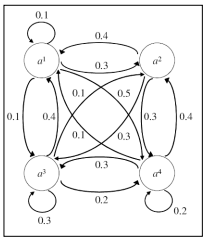


19

Orientation Processes

- Gives radio significance of observations
  - Does multipath profile correspond to a known location?
  - Really just hypotheses testing
- Algorithms
  - Data mining
  - Hidden Markov Models
  - Neural Nets
  - Fuzzy Logic
  - Ontological Reasoning





20

Decision Processes

- Purpose: Map what radio believes about network state to an adaptation
- Guided by radio goal and constrained by policy
  - May be supplemented with model of real world
- Common algorithms (mostly heuristics)
  - Genetic algorithms
  - Simulated annealing
  - Local search
  - Case based reasoning

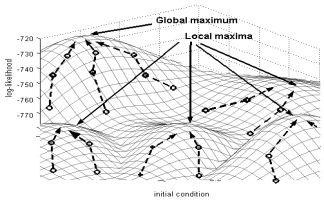


Figure from Fig 2.6 in I. Akbar, "Statistical Analysis of Wireless Systems Using Markov Models," PhD Dissertation, Virginia Tech, January 2007

Learning Processes

- Informs radio when situation is not like one its seen before or if situation does not correspond to any known situation
- Logically, just an extension to the orientation process with
  - a "none of the above" option
  - Increase number of hypotheses after "none of the above"
  - Refine hypotheses and models
- Algorithms:
  - Data mining
  - Hidden Markov Models
  - Neural Nets
  - Fuzzy Logic
  - Ontological Reasoning
  - Case based learning
  - Bayesian learning
- Other proposed learning tasks
  - New actions, new decision rules, new channel models, new goals, new internal algorithms

Knowledge Representation

- Issue:
  - How are radios "aware" of their environment and how do they learn from each other?
- Technical refinement:
  - "Thinking" implies some language for thought.
- Proposed languages:
  - **R**adio **K**nowledge **R**epresentation **L**anguage
  - XML
  - **W**eb-based **O**ntology **L**anguage (**OWL**)

Language	Features	Reasoning	Complexity
XTM	Higher order relationships	None	$O(N)$
RDF	Binary Relationships	None	$O(N)$
RDFS	RDF plus subclass, subproperty, domain, and range	Subsumption	$O(N^m)$
OWL Lite	RDFS plus some class constructors; no crossing of metalevels	Limited form of description logic	$O(e^N)$
OWL-DL	All class constructors; no crossing of metalevels	General description logic	$<\infty$
OWL Full	No restrictions	Limited form of first order predicate logic	**unbounded**

Modified from Table 13.1 in M. Kokar, *The Role of Ontologies in Cognitive Radio* in **Cognitive Radio Technology**, ed., B. Fette, 2006.

23

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

24