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Networking Cognitive Radios

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• PhD, Virginia Tech 2006
  – http://scholar.lib.vt.edu/theses/available/etd-12082006-141855
• Textbook chapters on:
  – Cognitive Network Analysis in
  – 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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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
Overview of Cognitive Radio

Concepts, Definitions, Implementations

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
## Cognitive Radio Capability Matrix

<table>
<thead>
<tr>
<th>Definer</th>
<th>No interference</th>
<th>Negotiate</th>
<th>Waveforms</th>
<th>Capabilities</th>
<th>Goal Driven</th>
<th>Learn the Environment</th>
<th>Environment Aware</th>
<th>Can sense Environment</th>
<th>Autonomous Environment</th>
<th>Adapts (Intelligence)</th>
<th>FCC</th>
<th>Haykin</th>
<th>IEEE 1900.1</th>
<th>IEEE USA</th>
<th>ITU-R</th>
<th>Mitola</th>
<th>NTIA</th>
<th>SDRF CRWG</th>
<th>SDRF SIG</th>
<th>VT CRWG</th>
</tr>
</thead>
<tbody>
<tr>
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</tbody>
</table>

## Cognitive Radio Applications

- **Spectrum Trading**
- **Cheaper Radios?**
- **Opportunistic Spectrum Utilization**
- **Advanced Networking**
- **Intelligent Beamforming**
- **Automated Interoperability**
- **Improved Link Reliability**
- **Collaborative Techniques**
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?

Levels of Cognitive Radio Functionality

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

**Cognition Cycle**

<table>
<thead>
<tr>
<th>Level</th>
<th>0</th>
<th>SDR</th>
<th>1</th>
<th>Goal Driven</th>
<th>2</th>
<th>Context Aware</th>
<th>3</th>
<th>Radio Aware</th>
<th>4</th>
<th>Planning</th>
<th>5</th>
<th>Negotiating</th>
<th>6</th>
<th>Learns Environment</th>
<th>7</th>
<th>Adapts Plans</th>
<th>8</th>
<th>Adapts Protocols</th>
</tr>
</thead>
</table>

- **Observe**
  - User Driven (Buttons)
  - Autonomous

- **Learn**
  - New States
  - Parse Stimuli
  - Pre-process

- **Orient**
  - Establish Priority
  - Immediate

- **Plan**
  - Select Alternate Goals
  - Urgent
  - Urgent

- **Act**
  - Allocate Resources
  - Initiate Processes
  - Negotiate Protocols

**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...

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

DFS in 802.16h

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

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Modified from Figure H.1 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

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Observation Sources

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

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
**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

**Learning Processes**

- Informs radio when situation is not like one it's 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:
  – Radio Knowledge Representation Language
  – XML
  – Web-based Ontology Language (OWL)

<table>
<thead>
<tr>
<th>Language</th>
<th>Features</th>
<th>Reasoning</th>
<th>Complexity</th>
</tr>
</thead>
<tbody>
<tr>
<td>XTM</td>
<td>Higher order relationships</td>
<td>None</td>
<td>O(N)</td>
</tr>
<tr>
<td>RDF</td>
<td>Binary Relationships</td>
<td>None</td>
<td>O(N^2)</td>
</tr>
<tr>
<td>RDFs</td>
<td>RDF plus subclass, subproperty, domain, and range</td>
<td>Subsumption</td>
<td>O(N^4)</td>
</tr>
<tr>
<td>OWL Lite</td>
<td>RDF plus some class constructors, no crossing of metal levels</td>
<td>Limited form of description logic</td>
<td>O(e^N)</td>
</tr>
<tr>
<td>OWL-DL</td>
<td>All class constructors, no crossing of metal levels</td>
<td>General description logic</td>
<td>≤2N</td>
</tr>
<tr>
<td>OWL Full</td>
<td>No restrictions</td>
<td>Limited form of first order predicate logic</td>
<td>unbounded</td>
</tr>
</tbody>
</table>


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

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