Presentation Overview

- Overview of Cognitive Radio
- Interactive Decision Problem
- A “Quick” Review of Game Theory
- Approaches to Designing Cognitive Radio Networks
- Applications of Networked Cognitive Radios
- Research and Future Directions

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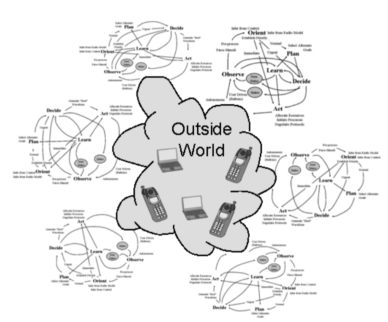
http://www.crtwireless.com/Publications.html

The Problem with Networked Cognitive Radios

Concept, Examples, and Modeling



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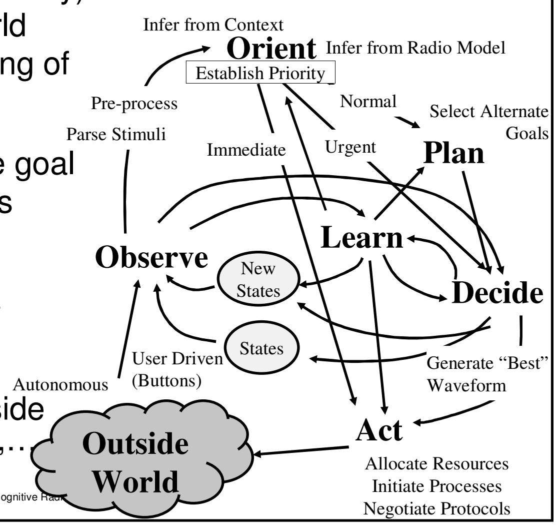
Conceptual Operation

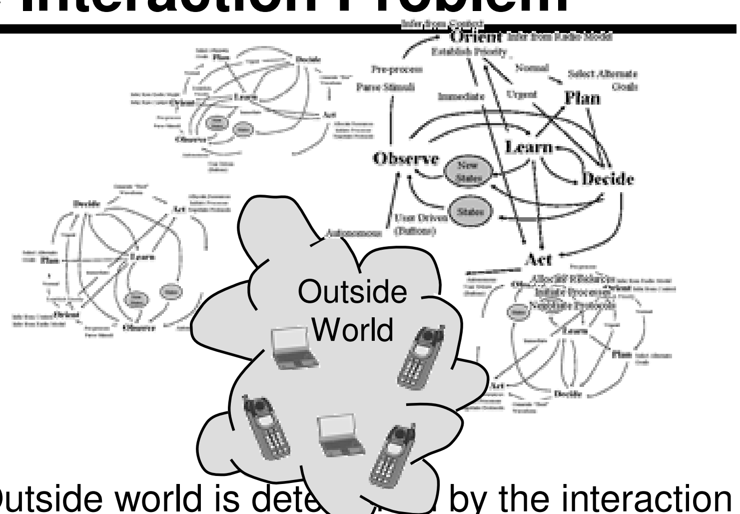
OODA Loop: (continuously)
- Observe outside world
- Orient to infer meaning of observations
- Adjust waveform as needed to achieve goal
- Implement processes needed to change waveform

Other processes: (as needed)
- Adjust goals (Plan)
- Learn about the outside world, needs of user,…

Cognition cycle [Mitola_99]



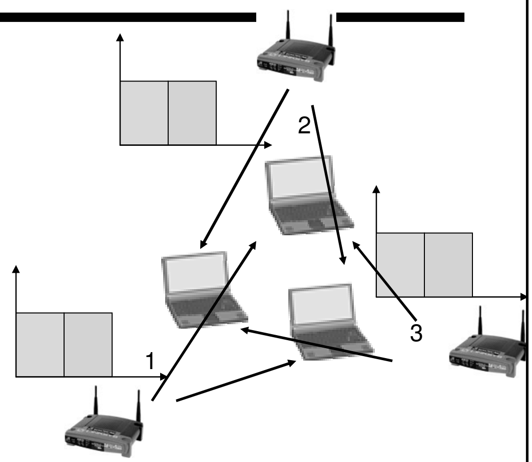
The Interaction Problem



- Outside world is dete… by the interaction of numerous cognitive radios
- Adaptations spawn adaptations

Dynamic Spectrum Access Pitfall

- Suppose
  - $g_{31}>g_{21}$; $g_{12}>g_{32}$; $g_{23}>g_{13}$
- Without loss of generality
  - $g_{31}, g_{12}, g_{23} = 1$
  - $g_{21}, g_{32}, g_{13} = 0.5$
- Infinite Loop!
  - 4,5,1,3,2,6,4,…



Interference Characterization

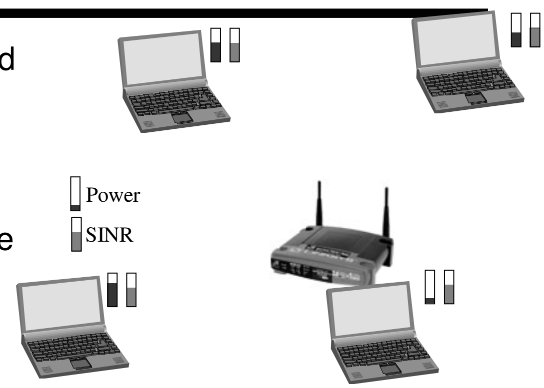
Chan.	(0,0,0)	(0,0,1)	(0,1,0)	(0,1,1)	(1,0,0)	(1,0,1)	(1,1,0)	(1,1,1)
Interf.	(1.5,1.5,1.5)	(0.5,1,0)	(1,0,0.5)	(0,0.5,1)	(0,0.5,1)	(1,0,0.5)	(0.5,1,0)	(1.5,1.5,1.5)
	0	1	2	3	4	5	6	7

Implications

- In one out every four deployments, the example system will enter into an infinite loop
- As network scales, probability of entering an infinite loop goes to 1;
  - 2 channels $p(loop) \geq 1-(3/4)^{n C_3}$
  - k channels $p(loop) \geq 1-\left(1-2^{-k+1}\right)^{n C_{k+1}}$
- Even for apparently simple algorithms, ensuring convergence and stability will be nontrivial

Locally optimal decisions that lead to globally undesirable networks

- Scenario: Distributed SINR maximizing power control in a single cluster
- For each link, it is desirable to increase transmit power in response to increased interference
- Steady state of network is all nodes transmitting at maximum power



Insufficient to consider only a single link, must consider interaction

Potential Problems with Networked Cognitive Radios

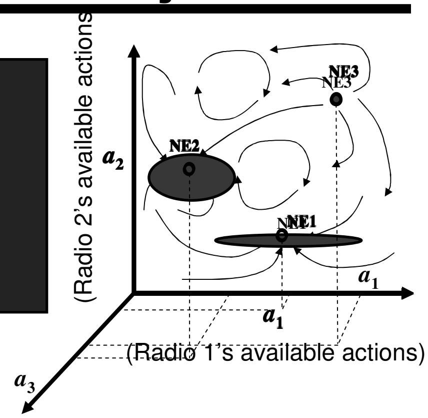
Distributed
- Infinite recursions
- Instability (chaos)
- Vicious cycles
- Adaptation collisions
- Equitable distribution of resources
- Byzantine failure
- Information distribution

Centralized
- Signaling Overhead
- Complexity
- Responsiveness
- Single point of failure

Network Analysis Objectives

focus

1. Steady state characterization
2. Steady state optimality
3. Convergence
4. Stability/Noise
5. Scalability



Steady State Characterization

[illegible] steady state?

[illegible] parameters?

[illegible] optimal?

Why focus on OODA loop, i.e., why exclude other levels?

- OODA loop is implemented now (possibly just ODA loop as little work on context awareness)
- Changing plans
  - Over short intervals plans don't change
  - Messy in the general case (work could easily accommodate better response equivalent goals)
- Negotiating
  - Could be analyzed, but protocols fuzzy
  - General case left for future work
- Learning environment
  - Implies improving observations/orientation. Over short intervals can be assumed away
  - Left for future work
- Creation of new actions, new goals, new decision rules makes analysis impossible
  - Akin to solving a system of unknown functions of unknown variables
  - Most of this learning is supposed to occur during "sleep" modes
    - Won't be observed during operation

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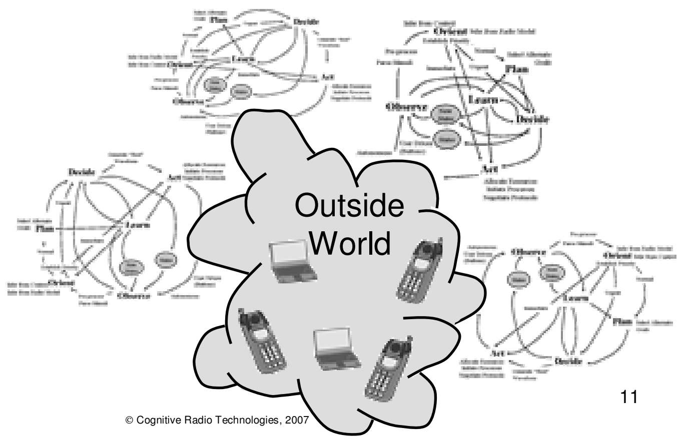
General Model (Focus on OODA Loop Interactions)

- Cognitive Radios
- Set N
- Particular radios, i, j



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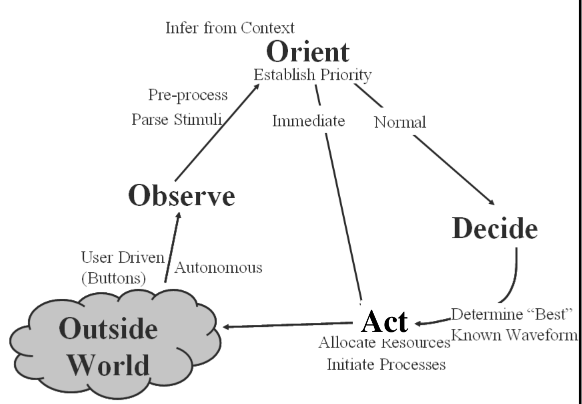
General Model (Focus on OODA Loop Interactions)

Actions

- Different radios may have different capabilities
- May be constrained by policy
- Should specify each radio's available actions to account for variations
- Actions for radio i
  - A_i



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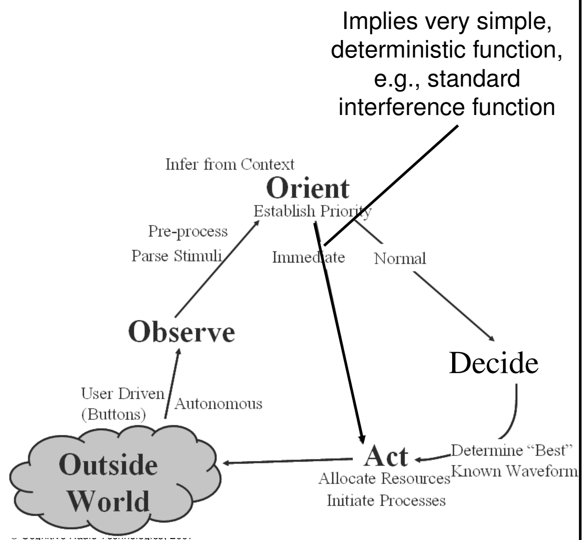
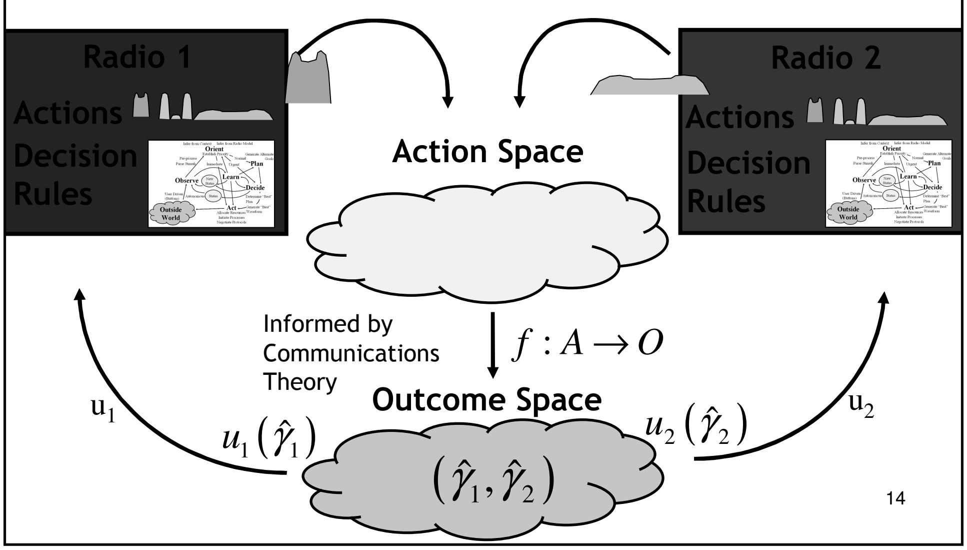
General Model (Focus on OODA Loop Interactions)

Decision Rules

- Maps observations to actions
  - $d_i: O \rightarrow A_i$
- Intelligence implies that these actions further the radio's goal
  - $u_i: O \rightarrow \Re$
- The many different ways of doing this merit further discussion



Modeling Interactions (1/3)



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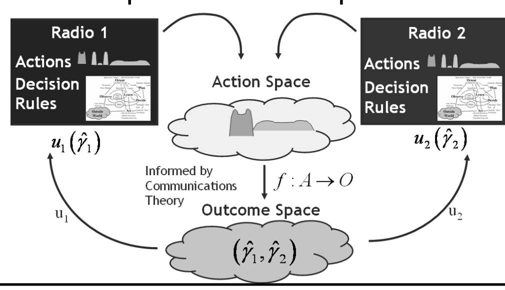
Modeling Interactions (2/3)

- Radios implement actions, but observe outcomes.
- Sometimes the mapping between outcomes and actions is one-to-one implying f is invertible.
- In this case, we can express goals and decision rules as functions of action space.
  - Simplifies analysis
- One-to-one assumption invalid in presence of noise.



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Modeling Interactions (3/3)

- When decisions are made also matters and different radios will likely make decisions at different time
- T_j – when radio j makes its adaptations
  - Generally assumed to be an infinite set
  - Assumed to occur at discrete time
    - Consistent with DSP implementation
- $T=T_1 \cup T_2 \cup \cdots \cup T_n$
- $t \in T$

Decision timing classes

- Synchronous
  - All at once
- Round-robin
  - One at a time in order
  - Used in a lot of analysis
- Random
  - One at a time in no order
- Asynchronous
  - Random subset at a time
  - Least overhead for a network

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Cognitive Radio Network Modeling Summary

- Radios
- Actions for each radio
- Observed Outcome Space
- Goals
- Decision Rules
- Timing

- $i,j \in N$, $|N| = n$
- $A = A_1 \times A_2 \times \cdots \times A_n$
- O
- $u_j: O \rightarrow \Re$ ($u_j: A \rightarrow \Re$)
- $d_j: O \rightarrow A_i$ ($d_j: A \rightarrow A_i$)
- $T = T_1 \cup T_2 \cup \cdots \cup T_n$

Symbol	Meaning	Symbol	Meaning
N	Set of cognitive radios	i, j	Particular cognitive radios
A_j	Adaptations for j	a_j	Adaptation chosen by j
a_{-j}	Adaptation vector excluding a_j	u_j	Goal of j
O	Set of outcomes	O_j	Outcome observed by j
d_j	Decision rule for j	T_j	Times when j adapts
T	Adaptation times $\forall j \in N$	t	An element of T

DFS Example

- Two radios
- Two common channels
  - Implies 4 element action space
- Both try to maximize Signal-to-Interference Ratio
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General Model Symbols	Modeled System Parameters
N (cognitive radio set)	$\{1,2\}$
A (action space)	$\{(\omega_{1_a},\omega_{2_a}),(\omega_{1_a},\omega_{2_b}),(\omega_{1_b},\omega_{2_a}),(\omega_{1_b},\omega_{2_b})\}$
$\{u_j\}$ (utility functions)	$u_j(a) = \dfrac{g_j}{g_{-j}\left\|\rho(\omega_j,\omega_{-j})\right\|}$
$\{d_j\}$ (decision rules)	$d_j(a) = \underset{\omega_j \in \{w_{j_a},\omega_{j_b}\}}{\arg\max}\, u_j(a)$
T_j (decision timings)	$T_2 - 0.5\text{s} = T_1 = \mathbb{N}$



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Items 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

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