

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

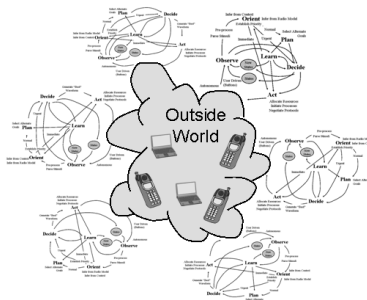
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1

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The Problem with Networked Cognitive Radios

Concept, Examples,
and Modeling



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2

Conceptual Operation

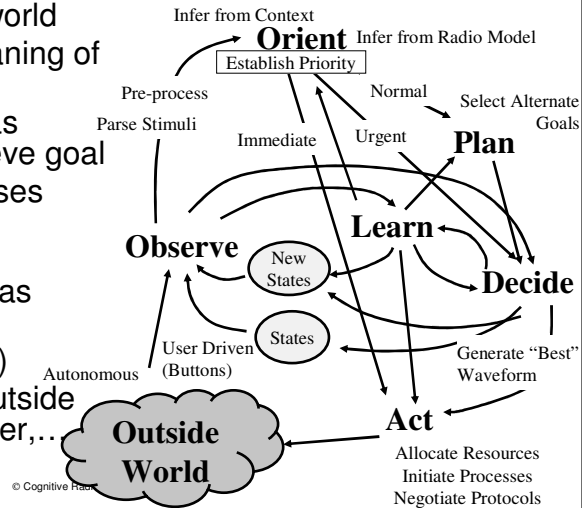
OODA Loop: (continuously)

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

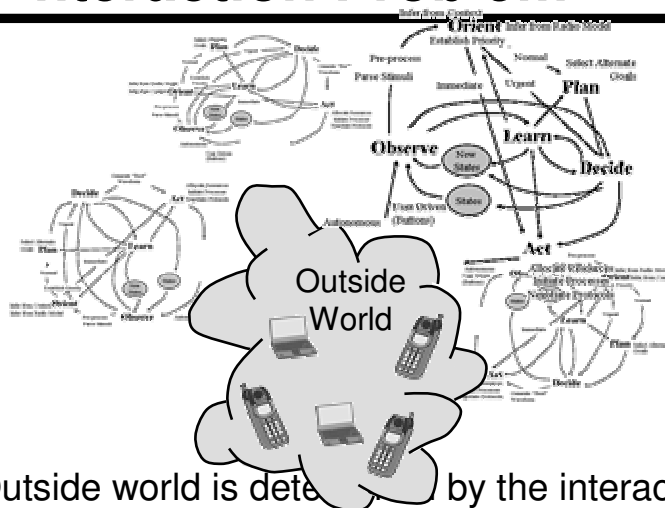
Other processes: (as needed)

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

Cognition cycle [Mitola_99]



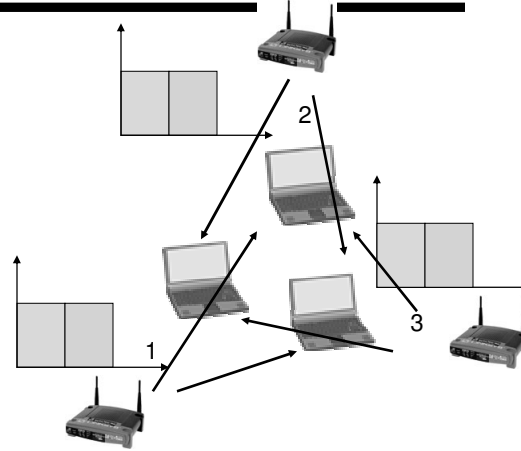
The Interaction Problem



- Outside world is determined 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

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Implications

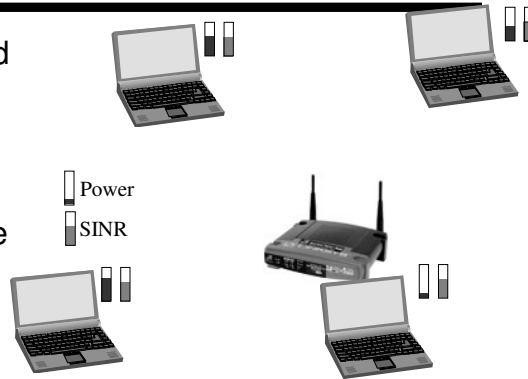
- In one out every four deployments, the example system will enter into an infinite loop
- As network scales, probability of entering an infinite loop goes to 1:
 - 2 channels $p(loop) \geq 1 - (3/4)^n$
 - k channels $p(loop) \geq 1 - (1 - 2^{-k+1})^n$
- Even for apparently simple algorithms, ensuring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

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6

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

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7

Potential Problems with Networked Cognitive Radios

Distributed

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

Centralized

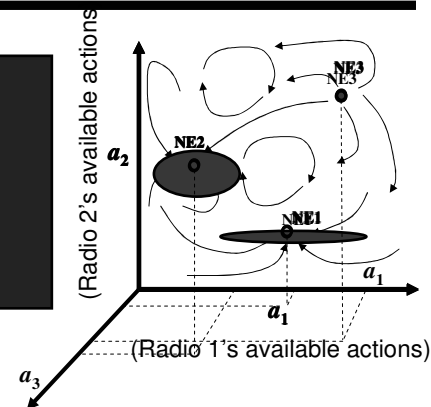
- Signaling Overhead
- Complexity
- Responsiveness
- Single point of failure

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8

Network Analysis Objectives

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



Steady State Characterization

- Not possible to find the steady state of the system?
- Do the steady state conditions satisfy the stability conditions?
- How long does it take to reach the steady state?

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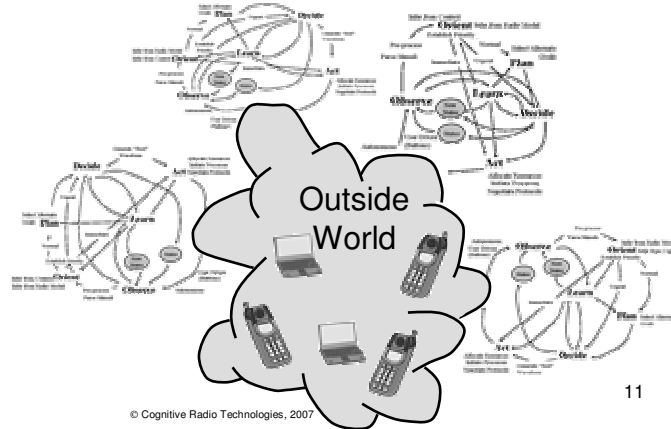
Why focus on OODA loop, i.e., why exclude other levels?

- 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

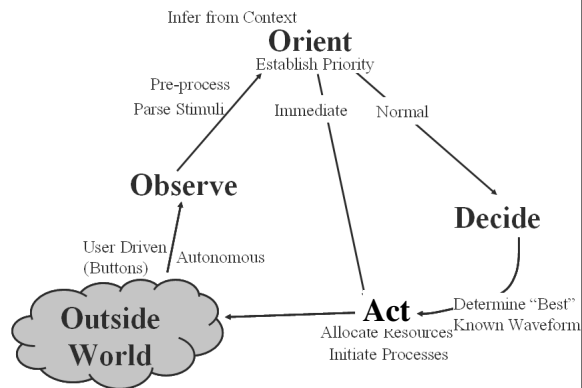


11

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



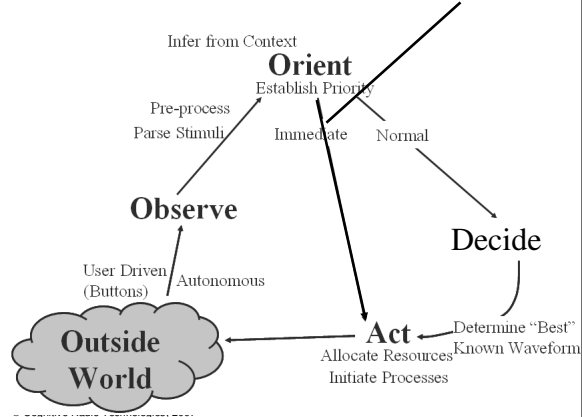
12

General Model (Focus on OODA Loop Interactions)

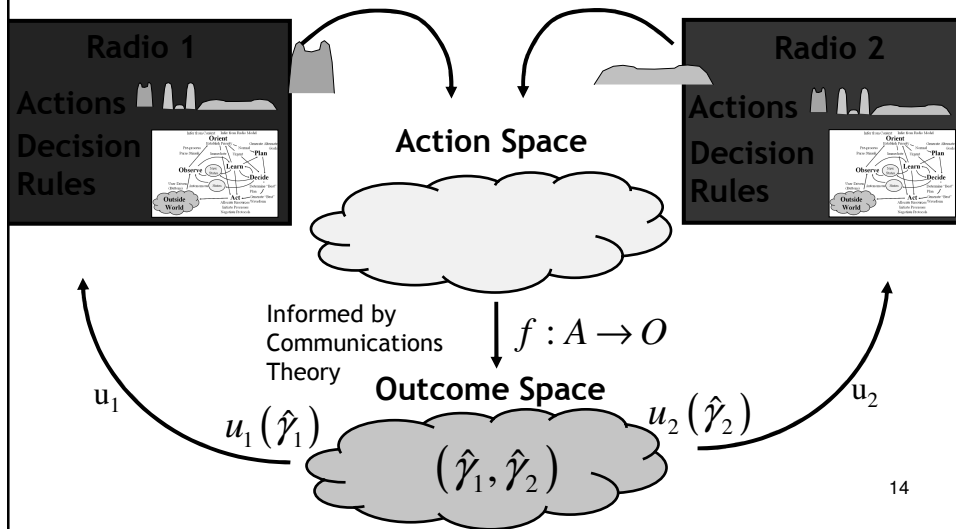
Decision Rules

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

Implies very simple, deterministic function, e.g., standard interference function

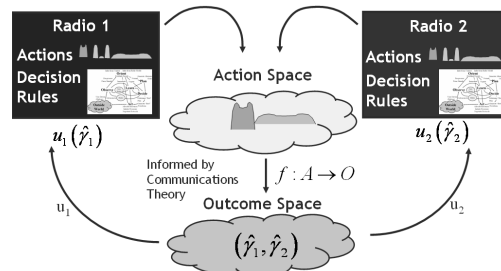


Modeling Interactions (1/3)



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.



15

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
- $T = T_1 \cup T_2 \cup \dots \cup T_n$
- $t \in T$
- 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

16

Cognitive Radio Network Modeling Summary

- Radios
 - Actions for each radio
 - Observed Outcome Space
 - Goals
 - Decision Rules
 - Timing
- $i, j \in N, |N| = n$
 - $A = A_1 \times A_2 \times \dots \times A_n$
 - O
 - $u_j: O \rightarrow \mathcal{R} \ (u_j: A \rightarrow \mathcal{R})$
 - $d_j: O \rightarrow A_j \ (d_j: A \rightarrow A_j)$
 - $T = T_1 \cup T_2 \cup \dots \cup T_n$

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

General Model Symbols	Modeled System Parameters
N (cognitive radio set)	$\{1, 2\}$
A (action space)	$\{(\omega_{1a}, \omega_{2a}), (\omega_{1b}, \omega_{2b}), (\omega_{1c}, \omega_{2c}), (\omega_{1d}, \omega_{2d})\}$
$\{u_j\}$ (utility functions)	$u_j(a) = \frac{g_j}{g_{-j} p(\omega_j, \omega_{-j}) }$
$\{d_j\}$ (decision rules)	$d_j(a) = \arg \max_{a_j \in \{a_{1a}, a_{1b}\}} u_j(a)$
T_j (decision timings)	$T_2 - 0.5s = T_1 = \mathbb{N}$



18

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