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

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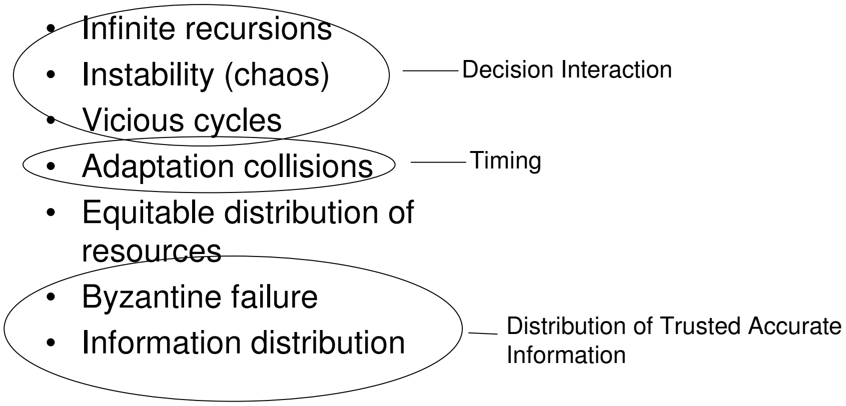
http://www.crtwireless.com/Publications.html

Designing Cognitive Radio Networks to Yield Desired Behavior

Policy, Cost Functions, Global Altruism, Potential Games

Potential Problems with Networked Cognitive Radios



Distributed

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

Working with Interactive Decisions

- Design network to be a potential game
  - Any self interested decision process will converge
- Limit decisions to processes known to converge
  - Best responses in a supermodular game
- Limit effects of interactions
  - Policy
- Eliminate interaction
  - Centralize decision making
  - Collaboration
  - Repeated game with punishment

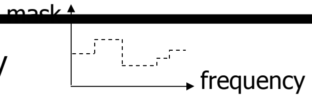
Policy

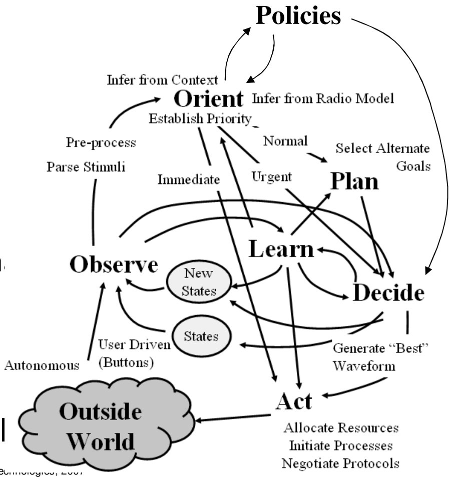
- Concept: Constrain the available actions so the worst cases of distributed decision making can be avoided
- Not a new concept –
  - Policy has been used since there's been an FCC
- What's new is assuming decision makers are the radios instead of the people controlling the radios

Γ	N
n	$(9.6,9.6)$

Policy applied to radios instead of humans

- Need a language to convey policy
  - Learn what it is
  - Expand upon policy later
- How do radios interpret policy
  - Policy engine?
- Need an enforcement mechanism
  - Might need to tie in to hum
- Need a source for policy
  - Who sets it?
  - Who resolves disputes?
- Logical extreme can be quite complex, but logical extreme may not be necessary





802.22 Example Policies

- Detection
  - Digital TV: -116 dBm over a 6 MHz channel
  - Analog TV: -94 dBm at the peak of the NTSC (National Television System Committee) picture carrier
  - Wireless microphone: -107 dBm in a 200 kHz bandwidth.
- Transmitted Signal
  - 4 W **E**ffective **I**sotropic **R**adiated **P**ower (**EIRP**)
  - Specific spectral masks

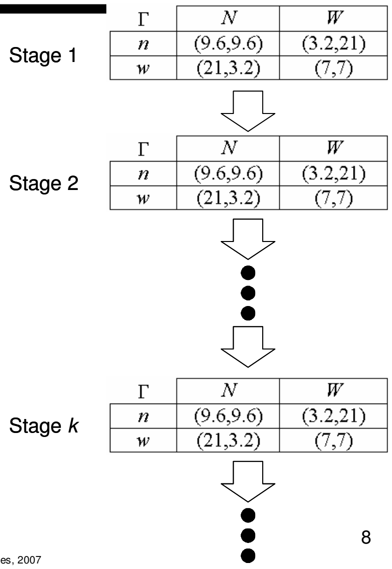
C. Cordeiro, L. Challapali, D. Birru, S. Shankar, "IEEE 802.22: The First Worldwide Wireless Standard based on Cognitive Radios," *IEEE DySPAN2005*, Nov 8-11, 2005 Baltimore, MD.

Repeated Games

- Same game is *repeated*
  - Indefinitely
  - Finitely
- Players consider discounted payoffs across multiple stages
  - Stage *k*

    $\tilde{u}_i\left(a^k\right) = \delta^k u_i\left(a^k\right)$
  - Expected value over all future stages

$$\hat{u}_i\left(\left(a^k\right)\right) = \sum_{k=0}^{\infty} \delta^k u_i\left(a^k\right)$$



Stage 1

Γ	N	W
n	(9.6,9.6)	(3.2,21)
w	(21,3.2)	(7,7)

Stage 2

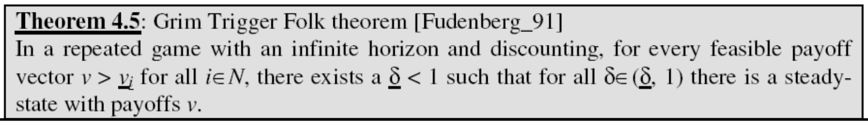
Γ	N	W
n	(9.6,9.6)	(3.2,21)
w	(21,3.2)	(7,7)

Stage *k*

Γ	N	W
n	(9.6,9.6)	(3.2,21)
w	(21,3.2)	(7,7)

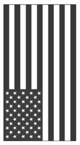
Impact of Strategies

- Rather than merely reacting to the state of the network, radios can choose their actions to influence the actions of other radios
- Threaten to act in a way that minimizes another radio's performance unless it implements the desired actions
- Common strategies
  - Tit-for-tat
  - Grim trigger
  - Generous tit-for-tat
- Play can be forced to any "feasible" payoff vector with proper selection of punishment strategy.


Theorem 4.5: Grim Trigger Folk theorem [Fudenberg_91]
In a repeated game with an infinite horizon and discounting, for every feasible payoff vector $v > \underline{v}_i$ for all $i \in N$, there exists a $\underline{\delta} < 1$ such that for all $\delta \in (\underline{\delta}, 1)$ there is a steady-state with payoffs v.

Impact of Communication on Strategies

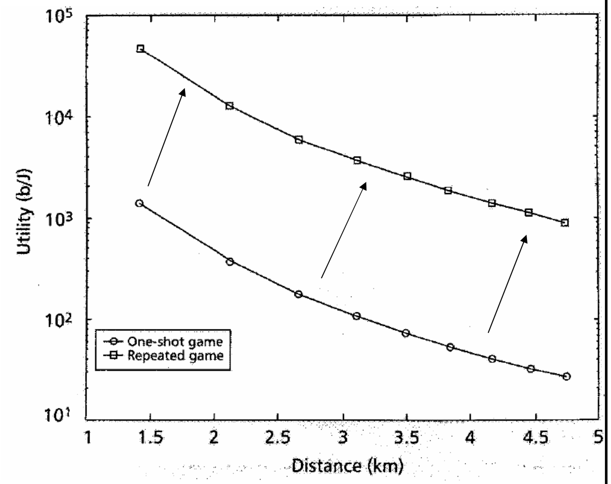
- Players agree to play in a certain manner
- Threats can force play to almost any state
  - Breaks down for finite number of stages



	Nada	C	N
nada	0,0	-5,5	-100,0
c	5,-5	-1,1	-100,-1
n	0,-100	-1,-100	-100,-100

Improvement from Punishment

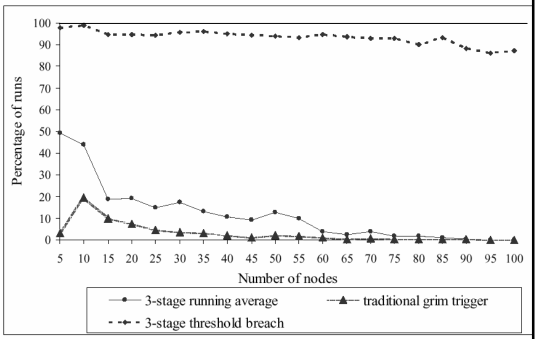
- Throughput/unit power gains be enforcing a common received power level at a base station
- Punishment by jamming
- Without benefit to deviating, players can operate at lower power level and achieve same throughput



A. MacKenzie and S. Wicker, “Game Theory in Communications: Motivation, Explanation, and Application to Power Control,” *Globecom2001*, pp. 821-825.

Instability in Punishment

- Issues arise when radios aren’t directly observing actions and are punishing with their actions without announcing punishment
- Eventually, a deviation will be falsely detected, punished and without signaling, this leads to a cascade of problems



V. Srivastava, L. DaSilva, “Equilibria for Node Participation in Ad Hoc Networks – An Imperfect Monitoring Approach,” ICC 06, June 2006, vol 8, pp. 3850-3855

Comments on Punishment

- Works best with a common controller to announce
- Problems in fully distributed system
  - Need to elect a controller
  - Otherwise competing punishments, without knowing other players' utilities can spiral out of control
- Problems when actions cannot be directly observed
  - Leads to Byzantine problem
- No single best strategy exists
  - Strategy flexibility is important
  - Significant problems with jammers (they nominally receive higher utility when "punished"
- Generally better to implement centralized controller
  - Operating point has to be announced anyways

Cost Adjustments

- Concept: Centralized unit dynamically adjusts costs in radios' objective functions to ensure radios operate on desired point

$$\tilde{u}_i(a) = u_i(a) + c_i(a)$$

- Example: Add -12 to use of wideband waveform

Γ	N	W
n	(9.6,9.6)	(3.2,9)
w	(9,3.2)	(-5,-5)

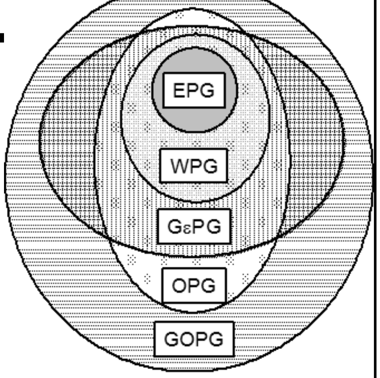
Comments on Cost Adjustments

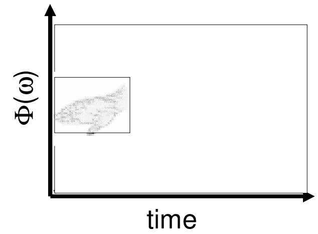
- Permits more flexibility than policy
  - If a radio really needs to deviate, then it can
- Easy to turn off and on as a policy tool
  - Example: protected user shows up in a channel, cost to use that channel goes up
  - Example: prioritized user requests channel, other users' cost to use prioritized user's channel goes up (down if when done)

Potential Games

Potential Games

- Existence of a function (called the potential function, *V*), that reflects the change in utility seen by a unilaterally deviating player.
- Cognitive radio interpretation:
  - Every time a cognitive radio unilaterally adapts in a way that furthers its own goal, some real-valued function increases.





Potential Game	Relationship ($\forall i \in N, \forall a \in A$)
Exact (EPG)	$u_i(b_i,a_{-i})-u_i(a_i,a_{-i})=V(b_i,a_{-i})-V(a_i,a_{-i})$
Weighted (WPG)	$u_i(b_i,a_{-i})-u_i(a_i,a_{-i})=\alpha_i\left[V(b_i,a_{-i})-V(a_i,a_{-i})\right]$
Ordinal (OPG)	$u_i(b_i,a_{-i})-u_i(a_i,a_{-i})>0 \Leftrightarrow V(b_i,a_{-i})-V(a_i,a_{-i})>0$
Generalized Ordinal (GOPG)	$u_i(b_i,a_{-i})-u_i(a_i,a_{-i})>0 \Rightarrow V(b_i,a_{-i})-V(a_i,a_{-i})>0$
Generalized ε (GεPG)	$u_i(b_i,a_{-i})>u_i(a_i,a_{-i})+\varepsilon_1 \Rightarrow V(b_i,a_{-i})>V(a_i,a_{-i})+\varepsilon_2$

Exact Potential Games

Definition Exact Potential Game

A normal form game whose objective functions are structured such that there exists some function $P: A \rightarrow \Re$ which satisfies the following property for all players:

$$V(a_i,a_{-i})-V(b_i,a_{-i})=u_i(a_i,a_{-i})-u_i(b_i,a_{-i})\ \forall a_i,b_i \in A_i, \forall a_{-i} \in A_{-i}$$

In other words it must be possible to construct a single-dimensional function whose change in value is exactly equal to the change in value of the deviating player.

Example Potential Game (1/2)

Coordination Game

	a_2	b_2
a_1	1,1	0, 0
b_1	0, 0	3, 3

$$V(a)=\begin{cases}1 & a=(a_1,a_2)\\ 0 & a=(a_1,b_2)\\ 0 & a=(b_1,a_2)\\ 3 & a=(b_1,b_2)\end{cases}$$

Note: *V* is not unique. Consider *V’* = *V* + *c* where *c* is a constant.

Also note the relation between CG Prop. 2 and *V*

$$u_1(a_1,a_2) - u_1(b_1,a_2) = 1 = V(a_1,a_2) - V(b_1,a_2)$$

$$u_2(a_1,a_2) - u_2(a_1,b_2) = 1 = V(a_1,a_2) - V(a_1,b_2)$$

$$u_1(b_1,b_2) - u_1(a_1,b_2) = 3 = V(b_1,b_2) - V(a_1,b_2)$$

$$u_2(b_1,b_2) - u_2(b_1,a_2) = 3 = V(b_1,b_2) - V(b_1,a_2)$$

Example Potential Game (2/2)

Coordination Game
(In Equilibriums)

	a_2	b_2
a_1	4,2	-1, 1
b_1	3,-2	2, 1

$$V(a)=\begin{cases}1 & a=(a_1,a_2)\\ 0 & a=(a_1,b_2)\\ 0 & a=(b_1,a_2)\\ 3 & a=(b_1,b_2)\end{cases}$$

The Same Potential!!
The Same NE!

$$u_1(a_1,a_2) - u_1(b_1,a_2) = 1 = V(a_1,a_2) - V(b_1,a_2)$$

$$u_2(a_1,a_2) - u_2(a_1,b_2) = 1 = V(a_1,a_2) - V(a_1,b_2)$$

$$u_1(b_1,b_2) - u_1(a_1,b_2) = 3 = V(b_1,b_2) - V(a_1,b_2)$$

$$u_2(b_1,b_2) - u_2(b_1,a_2) = 3 = V(b_1,b_2) - V(b_1,a_2)$$

Comments on Second Example

Second Game

	a_2	b_2
a_1	4,2	-1, 1
b_1	3,-2	2, 1

=

Coordination Game

	a_2	b_2
a_1	1,1	0, 0
b_1	0, 0	3, 3

+

Dummy Game

	a_2	b_2
a_1	3,1	-1, 1
b_1	3,-2	-1,-2

This is a property of all exact potential games.

Continuous Action Sets (1/2)

EPG Property 5 (Shapley)

Let G be a game in which the strategy sets are closed intervals of $\Re$. Suppose the objective functions are continuously differentiable. A function V is a potential iff V is continuously differentiable and

$$\frac{\partial V}{\partial a_i} = \frac{\partial u_i}{\partial a_i} \quad \text{for every } i \in N$$

EPG Property 6 (Shapley)

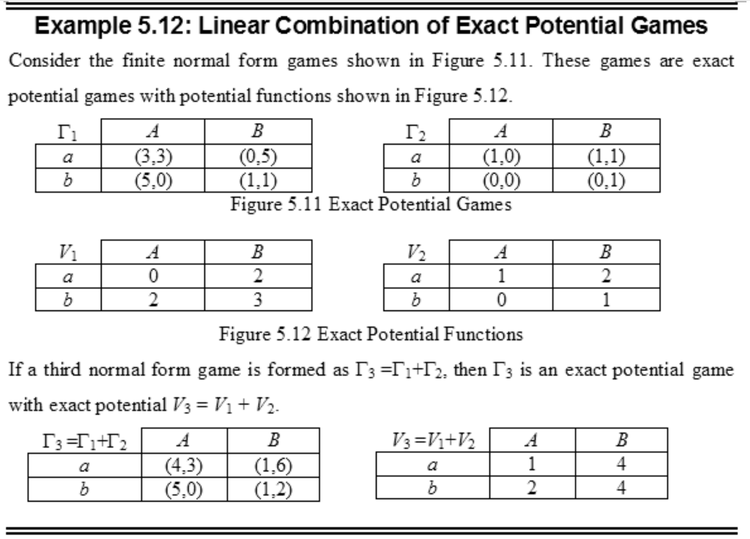
If objective functions are twice differentiable then a game is a EPG iff

$$\frac{\partial^2 V}{\partial a_i \partial a_j} = \frac{\partial^2 u_i}{\partial a_i \partial a_j} = \frac{\partial^2 u_j}{\partial a_i \partial a_j} \quad \text{for every } i, j \in N$$

Vector Operations

Consider the set of EPG {EPG^1, EPG^2,…,EPG^K}, with player set N and action space A, and objective functions $\left\{u_i^1, u_i^2, \ldots, u_i^K\right\}$, and potential functions $\left\{V^1, V^2, \ldots, V^K\right\}$. Form a new game, G, with player set N, action space A, and objective functions given by $u_i^G = \alpha^1 u_i^1 + \alpha^2 u_i^2 + \cdots + \alpha^K u_i^K + c \cdot$ Then G is an EPG with an EPF given by $V = \alpha^1 V^1 + \alpha^2 V^2 + \cdots \alpha^K V^K$

Example



Example 5.12: Linear Combination of Exact Potential Games

Consider the finite normal form games shown in Figure 5.11. These games are exact potential games with potential functions shown in Figure 5.12.

Γ_1	A	B
a	(3,3)	(0,5)
b	(5,0)	(1,1)

Γ_2	A	B
a	(1,0)	(1,1)
b	(0,0)	(0,1)

Figure 5.11 Exact Potential Games

V_1	A	B
a	0	2
b	2	3

V_2	A	B
a	1	2
b	0	1

Figure 5.12 Exact Potential Functions

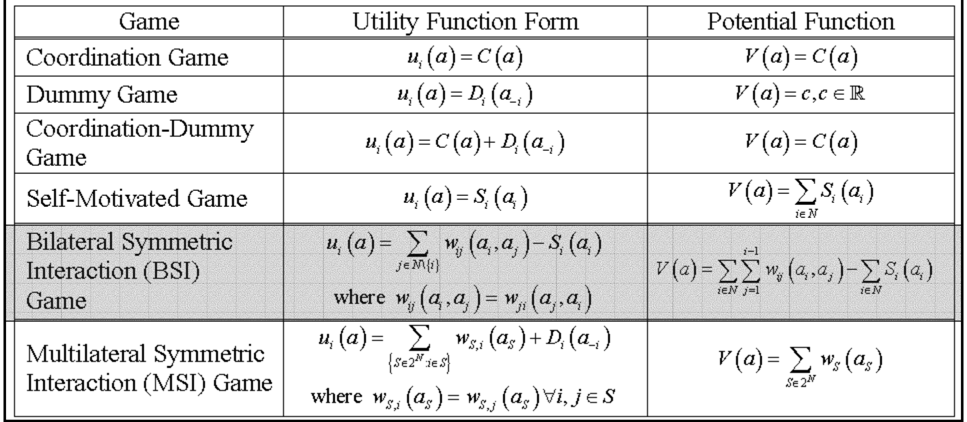
If a third normal form game is formed as $\Gamma_3 = \Gamma_1 + \Gamma_2$, then Γ_3 is an exact potential game with exact potential $V_3 = V_1 + V_2$.

$\Gamma_3 = \Gamma_1 + \Gamma_2$	A	B
a	(4,3)	(1,6)
b	(5,0)	(1,2)

$V_3 = V_1 + V_2$	A	B
a	1	4
b	2	4

Exact Potential Game Forms

- Many exact potential games can be recognized by the form of the utility function



Game	Utility Function Form	Potential Function
Coordination Game	$u_i(a) = C(a)$	$V(a) = C(a)$
Dummy Game	$u_i(a) = D_i(a_{-i})$	$V(a) = c, c \in \mathbb{R}$
Coordination-Dummy Game	$u_i(a) = C(a) + D_i(a_{-i})$	$V(a) = C(a)$
Self-Motivated Game	$u_i(a) = S_i(a_i)$	$V(a) = \sum_{i\in N} S_i(a_i)$
Bilateral Symmetric Interaction (BSI) Game	$u_i(a) = \sum_{j\in N\setminus\{i\}} w_{ij}(a_i,a_j) - S_i(a_i)$ where $w_{ij}(a_i,a_j) = w_{ji}(a_j,a_i)$	$V(a) = \sum_{i\in N}\sum_{j=1}^{i-1} w_{ij}(a_i,a_j) - \sum_{i\in N} S_i(a_i)$
Multilateral Symmetric Interaction (MSI) Game	$u_i(a) = \sum_{\{S\in 2^N : i\in S\}} w_{S,i}(a_S) + D_i(a_{-i})$ where $w_{S,i}(a_S) = w_{S,j}(a_S)\,\forall i,j\in S$	$V(a) = \sum_{S\in 2^N} w_S(a_S)$

Proving the BSI Relationship

$$u_i(a) = \sum_{j\in N\setminus\{i\}} w_{ij}(a_i,a_j) - h_i(a_i)$$

$$u_i(a_i,a_{-i}) - u_i(b_i,a_{-i}) =$$

$$\sum_{j\in N\setminus\{i\}} w_{ij}(a_i,a_j) - \sum_{j\in N\setminus\{i\}} w_{ij}(b_i,a_j) + h_i(a_i) - h_i(b_i)$$

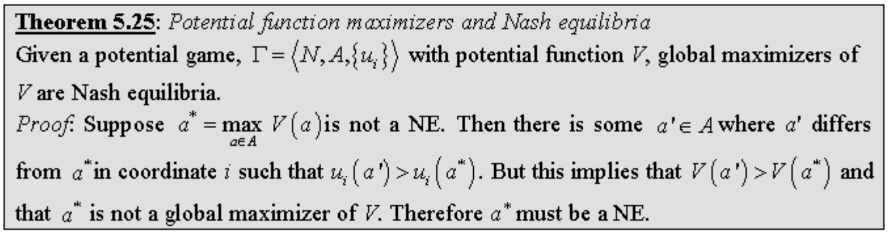
$$V(a) = \sum_{i\in N}\sum_{j=1}^{i-1} w_{ij}(a_i,a_j) - \sum_{i\in N} h_i(a_i)$$

$$V(a_i,a_{-i}) - V(b_i,a_{-i}) = \sum_{j\in N\setminus i} w_{ij}(a_i,a_j) - \sum_{j\in N\setminus i} w_{ij}(b_i,a_j) + h_i(a_i) - h_i(b_i)$$

$$\sum_{k\in N\setminus i}\sum_{j=1}^{k-1} w_{kj}(a_k,a_j) - \sum_{k\in N\setminus i}\sum_{j=1}^{k-1} w_{kj}(a_k,a_j) + \sum_{k\in N\setminus i} h_k(a_k) - \sum_{k\in N\setminus i} h_k(a_k)$$

Steady-states

- As noted previously, FIP implies existence of NE



Theorem 5.25: *Potential function maximizers and Nash equilibria*
Given a potential game, $\Gamma = \langle N, A, \{u_i\} \rangle$ with potential function V, global maximizers of V are Nash equilibria.
Proof: Suppose $a^* = \max_{a \in A} V(a)$ is not a NE. Then there is some $a' \in A$ where a' differs from a^* in coordinate i such that $u_i(a') > u_i(a^*)$. But this implies that $V(a') > V(a^*)$ and that a^* is not a global maximizer of V. Therefore a^* must be a NE.

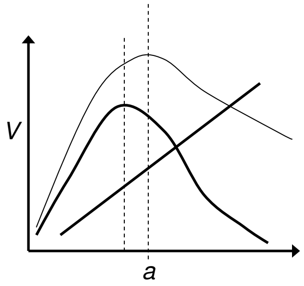
- Existence in infinite games for continuous potential function on compact action space
- Generally a subset of NE (which is a subset of steady-states)
- Sometimes only steady-states are maximizers of *V*

Optimality

- If u_i are designed so that maximizers of *V* are coincident with your design objective function, then NE are also optimal.
- (*) Can also introduce cost function to utilities to move NE.

$$u_i^*(a) = u_i(a) + NC(a)$$

$$\frac{\partial V(a^*)}{\partial a_i} + \frac{\partial NC(a^*)}{\partial a_i} = 0$$



- In theory, can make any action tuple the NE
  - May introduce additional NE
  - For complicated *NC*, might as well completely redesign u_i

FIP and Potential Games

- GOPG implies FIP ([Monderer_96])
- FIP implies GOPG for finite games ([Milchtaich_96])
- Thus we have a non-exhaustive search method for identifying when a CRN game model has FIP.
- Thus we can apply FIP convergence (and noise) results to finite potential games.

Convergence in Infinite Potential Games

- *ε-improvement path*
  - Given $\varepsilon > 0$, an *ε-improvement path* is a path such that for all $k \geq 1$, $u_i(a^k) > u_i(a^{k-1}) + \varepsilon$ where i is the unique deviator at step k.
- *Approximate Finite Improvement Property* (*AFIP*)
  - A normal form game, Γ, is said to have to have the *approximate finite improvement property* if for every $\varepsilon > 0$ there exists an such that the length of all ε-improvement paths in Γ are less than or equal to L.
- [Monderer_96] shows that exact potential games have AFIP, we showed that AFIP implies a generalized ε-potential game.

Convergence Implications

	Timings			
Decision Rules	Round-Robin	Random	Synchronous	Asynchronous
Best Response	1,2,4	1,2,4	-	1,2
Exhaustive Better Response	1,2	1,2	-	1,2
Random Better Response[(a)]	1,2,4	1,2,4	1,2	1,2
Random Better Response[(b)]	1,2	1,2	-	1,2
ε-Better Response[(c)]	1,2,3,4	1,2,3,4	-	1,2,3
Intelligently Random Better Response	1,4	1,4	-	1,2
Directional Better Response[(c)]	4	4	-	-
Averaged Best Response[(d)]	3,4	3,4	-	-

(a) Definition 4.12, (b) Definition 4.13, (c) Convergence to an ε-NE, (d) u_i quasi-concave in a_i

1.Finite game, 2. Infinite game with FIP, 3. Infinite game with AFIP, 4. Infinite game with bounded continuous potential function (implication of D^V)

- [Ermoliev] showed directional better response, averaged best response, best response in infinite games.
- Asynchronous convergence new, convergence for infinite games with FIP is new
- Associated convergence rates for bounded potential functions is new

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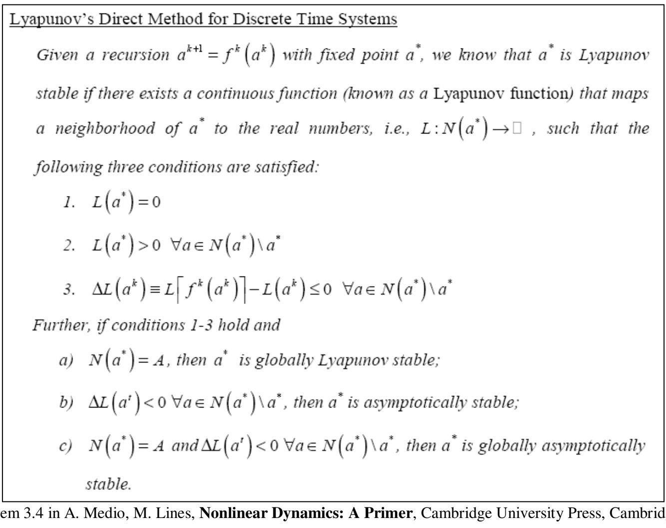
Direct Method for Discrete Time Systems



Lyapunov's Direct Method for Discrete Time Systems

Given a recursion $a^{k+1} = f^k\left(a^k\right)$ *with fixed point* a^*, *we know that* a^* *is Lyapunov stable if there exists a continuous function (known as a* Lyapunov function*) that maps a neighborhood of* a^* *to the real numbers, i.e.,* $L : N\left(a^*\right) \rightarrow □$, *such that the following three conditions are satisfied:*

1. $L\left(a^*\right) = 0$
2. $L\left(a^*\right) > 0 \;\; \forall a \in N\left(a^*\right) \setminus a^*$
3. $\Delta L\left(a^k\right) \equiv L\left[f^k\left(a^k\right)\right] - L\left(a^k\right) \leq 0 \;\; \forall a \in N\left(a^*\right) \setminus a^*$

Further, if conditions 1-3 hold and

a) $N\left(a^*\right) = A$, *then* a^* *is globally Lyapunov stable;*

b) $\Delta L\left(a^t\right) < 0 \; \forall a \in N\left(a^*\right) \setminus a^*$, *then* a^* *is asymptotically stable;*

c) $N\left(a^*\right) = A$ *and* $\Delta L\left(a^t\right) < 0 \; \forall a \in N\left(a^*\right) \setminus a^*$, *then* a^* *is globally asymptotically stable.*

Theorem 3.4 in A. Medio, M. Lines, **Nonlinear Dynamics: A Primer**, Cambridge University Press, Cambridge, UK, 200

Stability of Potential games

- New result
  - Applying the discrete-time version of Lyapunov function to <u>isolated maximizers of *V*</u> with Lyapunov function

$$L^V(a) = -V(a) + V(a^*)$$

  - Indicates stability of any better response decision algorithm with round-robin or random timing

Potential Game Properties

- Steady-states
  - Finite game NE can be found from maximizers of *V.*
- Optimality
  - Can adjust exact potential games with additive cost function (that is also an exact potential game)
  - Sometimes little better than redesigning utility functions
- Game convergence
  - Potential game assures us of FIP (and weak FIP)
  - D^V satisfy Zangwill's (if closed)
- Noise/Stability
  - Isolated maximizers of *V* have a Lyapunov function for decision rules in D^V
- Remaining issue:
  - Can we design a CRN such that it is a potential game for the convergence, stability, and steady-state identification properties
  - AND ensure steady-states are desirable?

What does game theory bring to the design of cognitive radio networks? (1/2)

- A natural “language” for modeling cognitive radio networks
- Permits analysis of ontological radios
  - Only know goals and that radios will adapt towards its goal
- Simplifies analysis of random procedural radios
- Permits simultaneous analysis of multiple decision rules – only need goal
- Provides condition to be assured of possibility of convergence for all autonomously myopic cognitive radios

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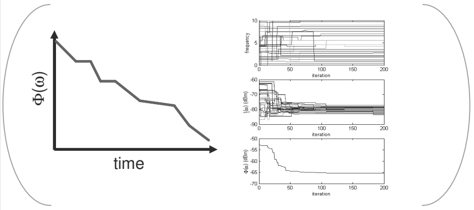
Interference Reducing Networks

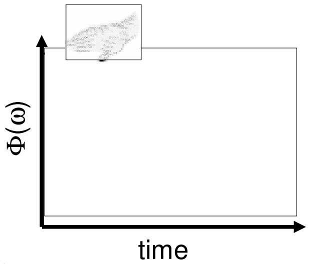


Designing desirable potential game cognitive radio networks

Interference Reducing Networks

- Concept
  - Cognitive radio network is a potential game with a potential function that is negation of observed network interference
- Definition
  - A network of cognitive radios where each adaptation decreases the sum of each radio's observed interference is an *IRN*

$$\Phi(\omega) = \sum_{i \in N} I_i(\omega)$$



- Properties:
  - Optimal steady-state exists
  - Network converges
  - Every adaptation improves performance
  - Stability for isolated minimizers of Φ
    - But are they isolated?

Implementing IRNs

Explicit information

- Gather interference information from other devices in the network
- Conceptually obvious implementations
- Scales badly
- A "bureaucratic nightmare"

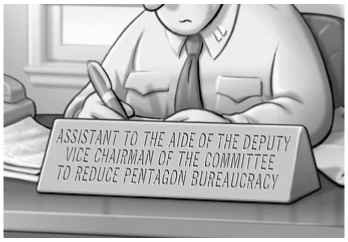
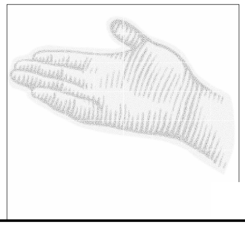


Image source: http://unbeknownst.net/images/bureaucracy.jpg

Implicit information

- Design network such that adaptations implement an IRN without gathering information on other devices' interference
- Scales well – ideal solution
- Non-obvious how to implement
  - Invisible hand of cognitive radio?



Globally Altruistic Networks (Explicit Information)

- Radio goal: minimize network interference

$$u_i(\omega) = -\sum_{k\in N}\sum_{j\in N\setminus k} I_i(\omega)$$

- Potential, Interference Function

$$\Phi(\omega) = -V(\omega) = \sum_{k\in N}\sum_{j\in N\setminus k} I_i(\omega)$$

- Unique benefit: Works for all waveform adaptations
- Unique drawback: Lots of overhead – may need functional radio environment map
- Proposed algorithms that satisfy GAN: [Sung], [Nie]

Locally Altruistic Networks (Explicit Information)

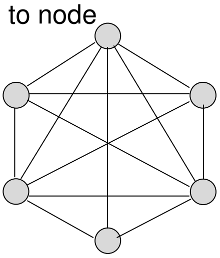
- Let $\mathcal{I}_i \subseteq N$ denote the set of radios which are close enough that *i* produces non-negligible interference.
- Goal: minimize interference of those within "range"

$$u_i(\omega) = -\sum_{k\in \mathcal{I}_i}\sum_{j\in \mathcal{I}_i\setminus k} I_i(\omega)$$

- Same interference and potential function as before (just eliminated terms for which $I_i = 0$)
- Benefit – Less overhead, just as generalizable
- Drawback – Need extra routine to identify $\mathcal{I}_i$

Global Altruism: distributed, but more costly

- Concept: All radios distributed all relevant information to all other radios and then each independently computes jointly optimal solution
  - Proposed for spreading code allocation in Popescu04, Sung03
  - Used in xG Program (Comments of G. Denker, SDR Forum Panel Session on “A Policy Engine Framework”) Overhead ranges from 5%-27%
- C = cost of computation
- I = cost of information transfer from node to node
- n = number of nodes
- Distributed
  - $nC + n(n\text{-}1)I/2$
- Centralized (election)
  - $C + 2(n\text{-}1)I$
- Price of anarchy = 1
- May differ if I is asymmetric

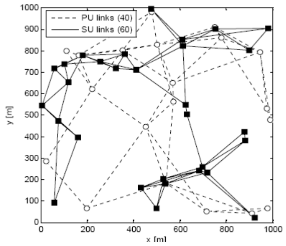


Improving Global Altruism

- Global altruism is clearly inferior to a centralized solution for a single problem.
- However, suppose radios reported information to and used information from a common database
  - $n(n\text{-}1)I/2 \Rightarrow 2nI$
- And suppose different radios are concerned with different problems with costs $C_1,\ldots,C_n$
- Centralized
  - Resources = $2(n\text{-}1)I + \text{sum}(C_1,\ldots,C_n)$
  - Time = $2(n\text{-}1)I + \text{sum}(C_1,\ldots,C_n)$
- Distributed
  - Resources = $2nI + \text{sum}(C_1,\ldots,C_n)$
  - Time = $2I + \max\,(C_1,\ldots,C_n)$

Example Application:

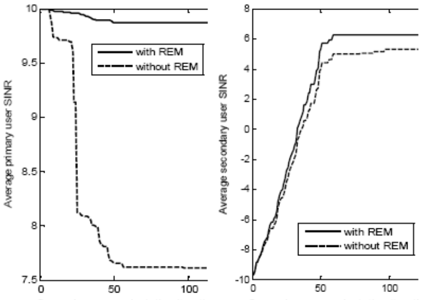
- Overlay network of secondary users (SU) free to adapt power, transmit time, and channel



Parameter	Value
Transmission range of radio node (PU or SU)	450 meters
Sensing range of SU	450 meters
Interference range of SU	450 meters
Speed of SUs	Uniformly distributed in (0, 10m/s)
Data rate of wireless link	2 Mbps
Interface queue length	50 packets
Radio channel model	two-ray ground model
Simulation period	200 seconds

- Without REM:
  - Decisions solely based on link SINR
- With REM
  - Radios effectively know everything

Upshot: A little gain for the secondary users; big gain for primary users



From: Y. Zhao, J. Gaeddert, K. Bae, J. Reed, "Radio Environment Map Enabled Situation-Aware Cognitive Radio Learning Algorithms," SDR Forum Technical Conference 2006.

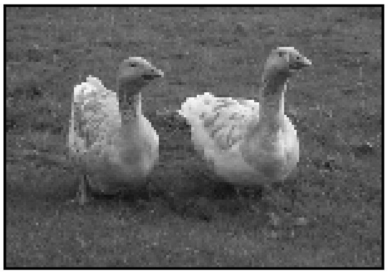
Comments on Radio Environment Map

- Local altruism also possible
  - Less information transfer
- Like policy, effectively needs a common language
- Nominally could be centralized or distributed database
- Read more:
  - Y. Zhao, B. Le, J. Reed, "Infrastructure Support – The Radio Environment MAP," in *Cognitive Radio Technology*, B. Fette, ed., Elsevier 2006.

Bilateral Symmetric Interference

- Two cognitive radios, *j,k*$\in$ *N*, exhibit *bilateral symmetric interference* if
  $$g_{jk} p_j \rho\left(\omega_j, \omega_k\right) = g_{kj} p_k \rho\left(\omega_k, \omega_j\right) \ \forall \omega_j \in \Omega_j, \forall \omega_k \in \Omega_k$$
- ω_k – waveform of radio *k*
- p_k - the transmission power of radio *k*'s waveform
- g_{kj} - link gain from the transmission source of radio *k*'s signal to the point where radio *j* measures its interference,
- $\rho\left(\omega_k, \omega_j\right)$ - the fraction of radio *k*'s signal that radio *j* cannot exclude via processing (perhaps via filtering, despreading, or MUD techniques).

What's good for the goose, is good for the gander…

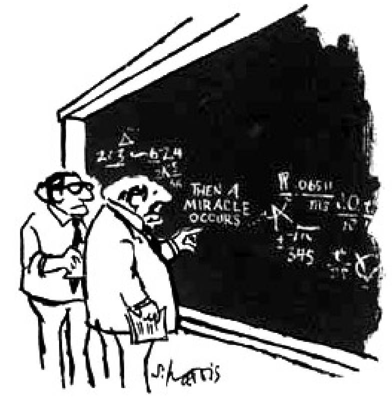


Source: http://radio.weblogs.com/0120124/Graphics/geese2.jpg

Proof:

- By bilateral symmetric interference
  $$g_{ki} p_k \rho\left(\omega_k, \omega_i\right) = g_{ik} p_i \rho\left(\omega_i, \omega_k\right) = b_{ik}\left(\omega_i, \omega_k\right)$$
- Rewrite goal $u_i\left(\omega\right) = -\sum_{k \in N \backslash i} b_{ik}\left(\omega_i, \omega_k\right)$
- Therefore a BSI game (S_i =0) (an EPG)
  $$V\left(\omega\right) = -\sum_{i \in N} \sum_{k=1}^{i-1} g_{ki} p_k \rho\left(\omega_k, \omega_i\right)$$
- Interference Function
  $$\Phi\left(\omega\right) = -2V\left(\omega\right)$$
- Therefore unilateral deviations increase *V* and decrease $\Phi(\omega)$ – an IRN

Situations where BSI occurs



"I THINK YOU SHOULD BE MORE EXPLICIT HERE IN STEP TWO."

- Isolated Network Clusters
  - All devices communicate with a common access node with identical received powers.
  - Clusters are isolated in signal space
- Close Proximity Networks
  - All devices are sufficiently close enough that waveform correlation effects dominate
- Controlled Observation Processes
  - Leverage knowledge of waveform protocol to control observations to achieve BSI

Isolated Network Clusters

- In this operational scenario, the network consists of a set of clusters *C* for which the following operational assumptions hold:
  - Perhaps through judicious frequency or code reuse between clusters, each radio *i* is operating in a cluster c∈C for which is a subset of the cluster.
  - The cluster head enforces a uniform receive power, r_c, on all radios *k* for signals transmitted to the cluster head.
  - Waveforms are restricted to those waveforms for which

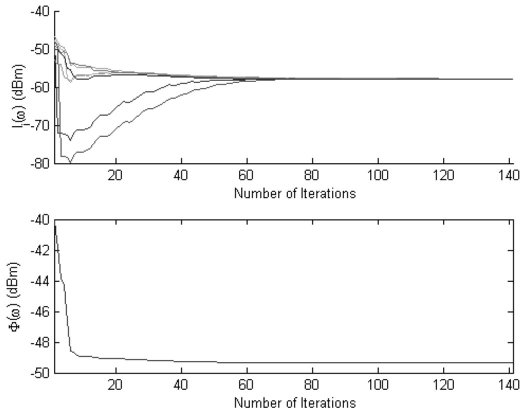
$$\rho(\omega_k,\omega_i)=\rho(\omega_i,\omega_k)$$

  - Cluster heads provide interference measurements to all client radios in the cluster.
- Therefore

$$g_{jk}p_j\rho(\omega_j,\omega_k)=g_{kj}p_k\rho(\omega_k,\omega_j)$$

Example Simulation

- Single cell
- 7 cognitive radios
- 6 code dimensions
- Interference minimizing
- Round-robin

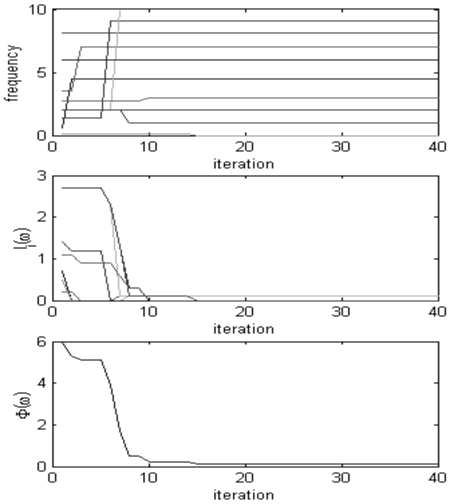


Close Proximity Networks

- In this operational scenario it is assumed that the radios are operating as an ad-hoc network in sufficiently close proximity and transmitting with sufficiently similar power levels that waveform correlation dominates the distance and transmitted power effects are negligible. Under these assumptions -*I*$_i$ is equivalent to $u_i(\omega) = -\sum_{k\in N\setminus i} \rho(\omega_k,\omega_i)$
- Further, assume $\rho(\omega_k,\omega_i) = \rho(\omega_i,\omega_k)$

DFS Close Proximity Network Simulation

- Specific parameters
  - Signal bandwidth = 1 MHz
  - Channel bandwidth = 10 Mhz
  - 10 (decision making) links
  - Frequency discretized with center frequencies every 0.1 MHz
  - Random initial frequencies



Controlled Observation Process

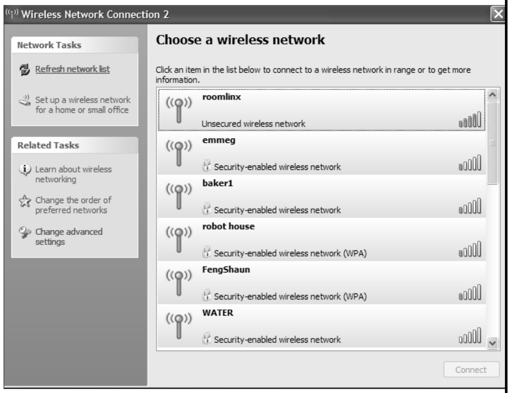
- Concept:
  - Control the radios' observation processes so that they only observe signals where

$$g_{jk} p_j \rho\left(\omega_j, \omega_k\right) = g_{kj} p_k \rho\left(\omega_k, \omega_j\right)$$

- Is this possible to do with meaningful results?

802.11 – A victim of its own success

- Extremely large number of 802.11 deployments
  - Overlapping coverage produces interference and contention
  - Reduces throughput
- Solution 1: Deploy David nationally
- Solution 2: Cognitive Radio and DFS



Wireless Network Connection 2

Choose a wireless network

Click an item in the list below to connect to a wireless network in range or to get more information.

roomlinx
Unsecured wireless network

emmeg
Security-enabled wireless network

baker1
Security-enabled wireless network

robot house
Security-enabled wireless network (WPA)

FengShaun
Security-enabled wireless network (WPA)

WATER
Security-enabled wireless network

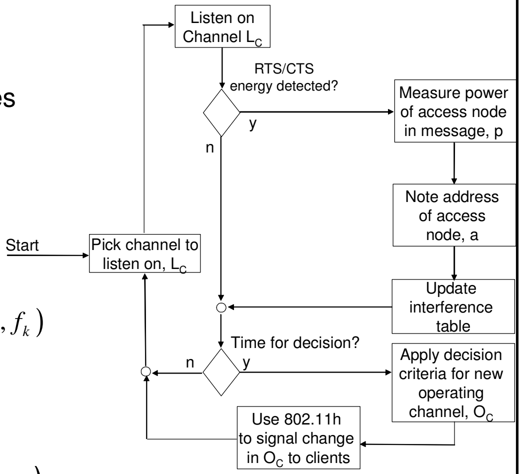
An IRN 802.11 DFS Algorithm

- Suppose each **access node measures** the received signal **power** and **frequency** of the RTS/CTS (or BSSID) messages sent by observable access nodes in the network.
- Assumed out-of-channel interference is negligible and RTS/CTS transmitted at same power

$$u_i(f) = -I_i(f) = -\sum_{k \in N \backslash i} g_{ki} p_k \sigma(f_i, f_k)$$

$$\sigma(f_i, f_k) = \begin{cases} 1 & f_i = f_k \\ 0 & f_i \neq f_k \end{cases}$$

$$g_{jk} p_j \sigma(f_j, f_k) = g_{kj} p_k \sigma(f_k, f_j)$$



Start

Pick channel to listen on, L_C

Listen on Channel L_C

RTS/CTS energy detected?

y

n

Measure power of access node in message, p

Note address of access node, a

Update interference table

Time for decision?

n

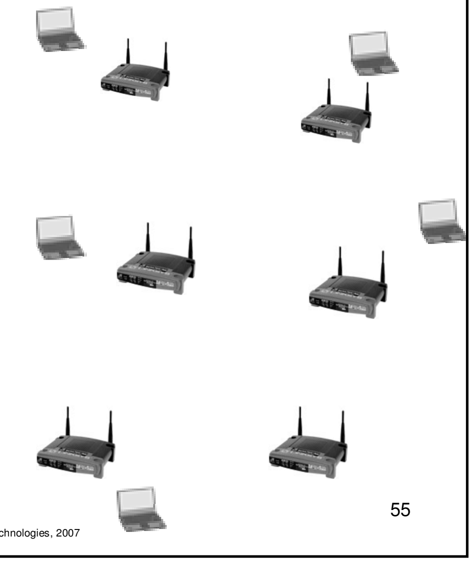
y

Apply decision criteria for new operating channel, O_C

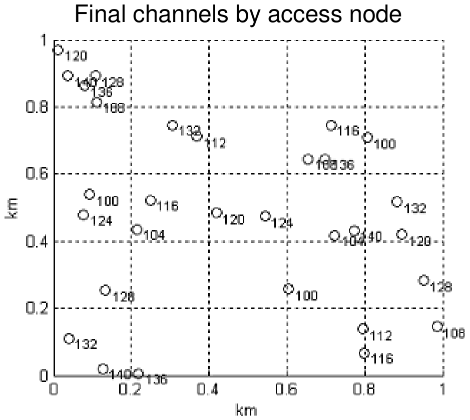
Use 802.11h to signal change in O_C to clients

A DFS simulation of the process

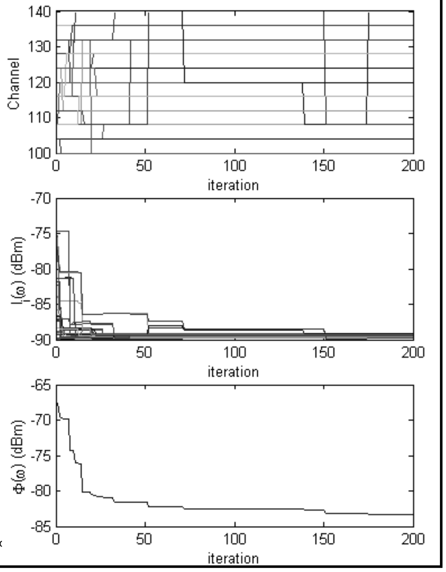
- 30 cognitive access nodes
- Upper 5 GHz 802.11 band
- Choose channel with lowest interference
- One randomly selected access node adapts at each instance
- *n*=3 path loss exponent
- Random initial channels
- Randomly distributed positions over 1 km^2
- Random timing



Dynamic Frequency Selection

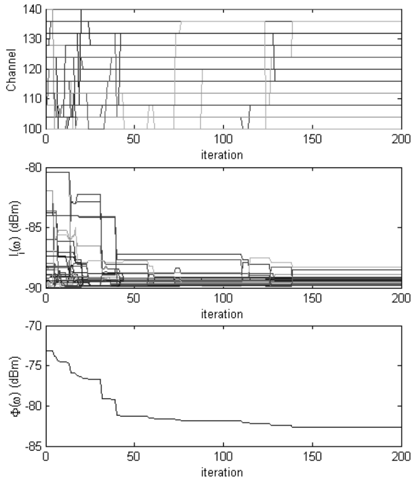


Final channels by access node

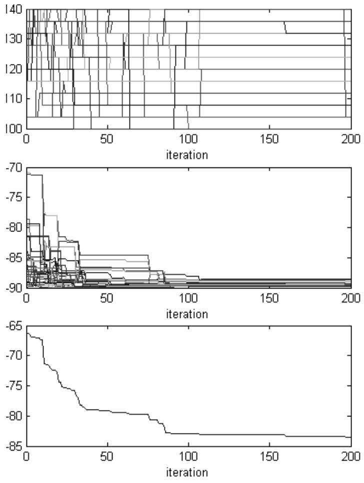


Noiseless suboptimal adaptations

(lowest frequency that improves)

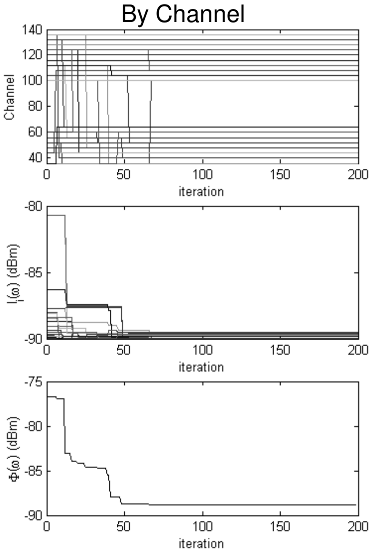


(highest frequency that improves)

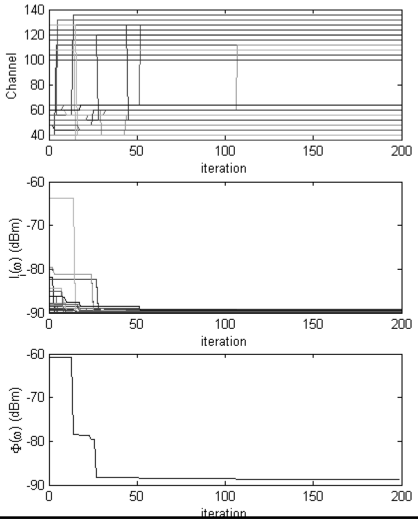


Policy Variations

By Channel

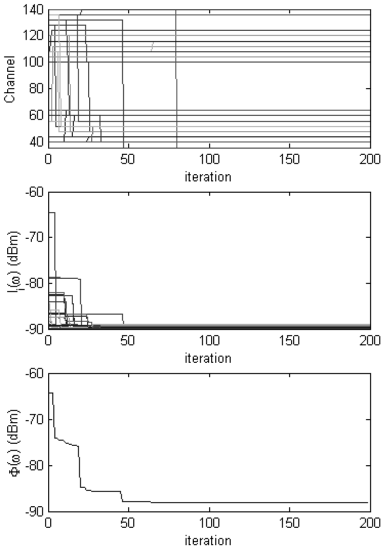


By Radio (10 radios only low channels)



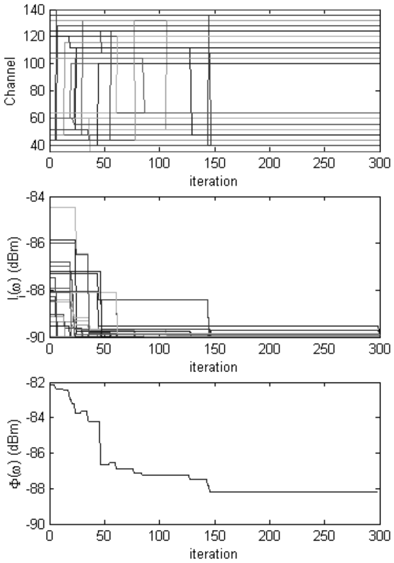
Local Frequency Preferences

- Each radio has a random real constant added to its observation of each channel
- Exact potential game
  - BSI + Self-motivated
- Equivalent to having legacy devices present
  - If legacy devices are transmitting at the same power as cognitive radios,



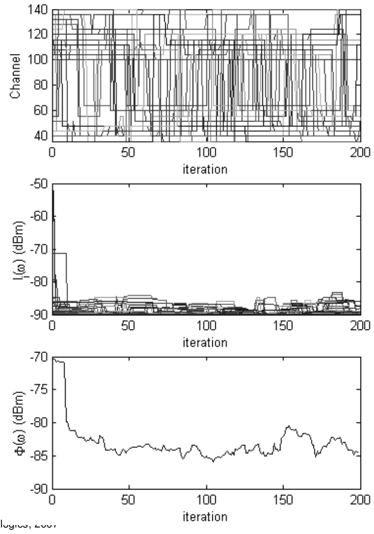
Asynchronous Timing

- Best Response
  - p = 0.02
- Not monotonic, but still an absorbing Markov chain as FIP and potential game theory predicts



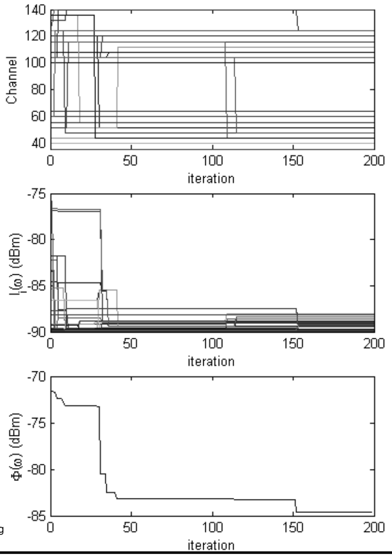
Noisy Observations

- Observations corrupted by clipped noise modeled as Gaussian
  - Mean = -90 dBm
  - Var = - 90 dBm
- Not stable
- Why?
  - Large number of equilibria, not isolated
  - Fails Lyapunov's direct method



Stabilized Process

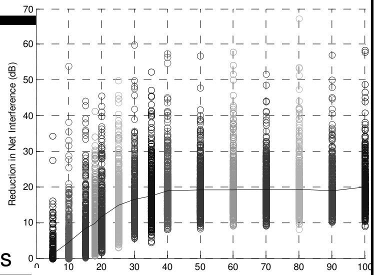
- Threshold adaptation (ε-better response)
  - Only adapt if adaptation expected to reduce interference by at least -85 dBm
- Stabilizes $d_i:O\rightarrow A$ not $d_i:A\rightarrow A$
  - Small variations

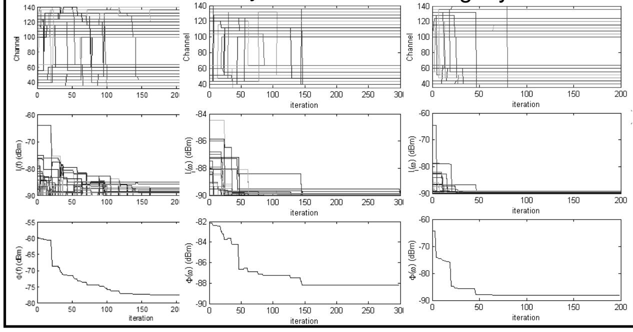


Statistics

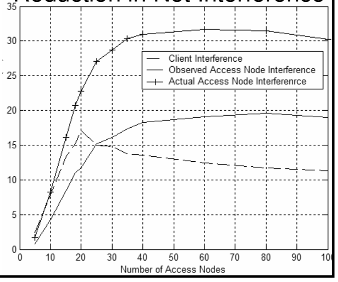
- 30 cognitive access nodes in European UNII bands
- Choose channel with lowest interference
- Random timing
- *n*=3
- Random initial channels
- Randomly distributed positions over 1 km^2

Reduction in Net Interference




Round-robin
Asynchronous
Legacy Devices

Reduction in Net Interference



Items 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