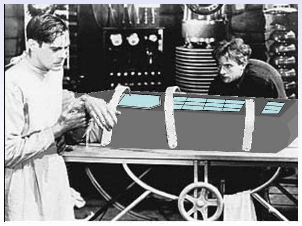
Designing Cognitive Radio Networks to Yield Desired Behavior

Policy, Cost Functions, Global Altruism, Supermodular Games, Potential Games



DySPAN 2007 April 17, 2007

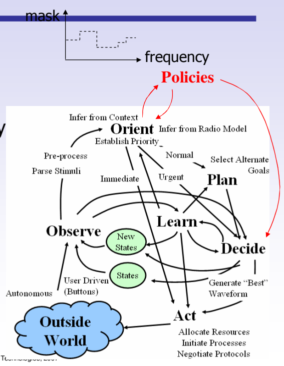
Policy

- 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 humans
- 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
  - Channel vacation times

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.

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

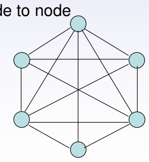
Γ	N	W
n	(9.6,9.6)	(3.2,9)
w	(9,3.2)	(-5,-5)

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)

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

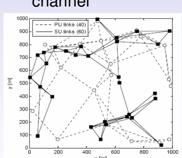


Improving Global Altruism

- 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:

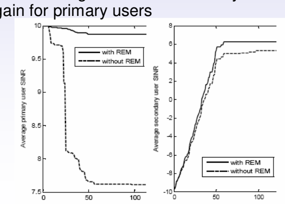
- Overlay network of secondary users (SU) free to adapt power, transmit time, and channel



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.

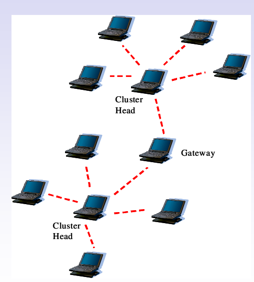
Supermodular Games

- A game such that
  - Action space is a lattice
  - Utility functions are supermodular
- Identification $\frac{\partial^2 u_i}{\partial a_i \partial a_j} \geq 0, \forall i,j \in N, a \in A$
- NE Properties
  - NE Existence: All supermodular games have a NE
  - NE Identification: NE form a lattice
- Convergence
  - Has weak FIP
  - Best response algorithms converge
- Stability
  - Unique NE is an attractive fixed point for best response

Ad-hoc power control

- Network description
- Each radio attempts to achieve a target SINR at the receiving end of its link.
- System objective is ensuring every radio achieves its target SINR

$$J(\mathbf{p}) = -\sum_{k \in N} (\hat{\gamma}_k - \gamma_k)^2$$



Generalized repeated game stage game

- Players – N
- Actions – $P_j = \left[0, p_j^{\max}\right]$
- Utility function
  $u_j(o) = -\left(\hat{\gamma}_j - \gamma_j\right)^2$
- Action space formulation

$$u_j(p) = -\left(\hat{\gamma}_j - 10\log_{10}\left(g_{jj}p_j\right) + 10\log_{10}\left(\sum_{k\in N\setminus j} g_{kj}p_k + N_j\right)\right)^2$$

g_{jk} fraction of power transmitted by j that can't be removed by receiving end of radio j's link
N_j noise power at receiving end of radio j's link

Model identification & analysis

- Supermodular game
  - Action space is a lattice
  - Implications
    - NE exists
    - Best response converges
    - Stable if discrete action space

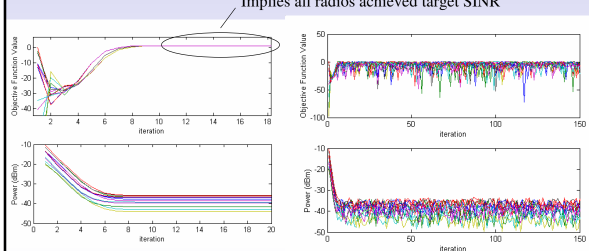
$$\frac{\partial^2 u_j(p)}{\partial p_j \partial p_k} = \frac{200 g_{kj}}{p_j\left(\sum_{k\in N\setminus j} g_{kj}p_k + N_j\right)\ln(20)} > 0$$

- Best response is also standard
  - Unique NE
  - Solvable (see prelim report)
  - Stable (pseudo-contraction) for infinite action spaces

$$\hat{B}_j(\mathbf{p}) = p_j^k \frac{\hat{\gamma}_j}{\gamma_j}$$

Validation

Implies all radios achieved target SINR



Noiseless Best Response

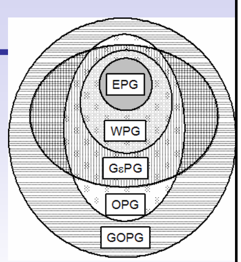
Noisy Best Response

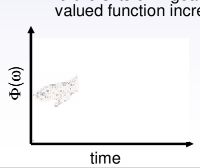
Comments on Designing Networks with Supermodular Games

- Scales well
  - Sum of supermodular functions is a supermodular function
  - Add additional action types, e.g., power, frequency, routing,..., as long as action space remains a lattice and utilities are supermodular
- Says nothing about desirability or stability of equilibria
- Convergence is sensitive to the specific decision rule and the ability of the radios to implement it

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 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 $w_{S,i}(a_S) = w_{S,j}(a_S)\ \forall i,j\in S$	$V(a) = \sum_{S\in 2^N} w_S(a_S)$

Implications of Monotonicity

- Monotonicity implies
  - Existence of steady-states (maximizers of *V*)
  - Convergence to maximizers of *V* for numerous combinations of decision timings decision rules – all self-interested adaptations
- Does not mean that that we get good performance
  - Only if *V* is a function we want to maximize

	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)

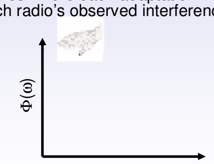
Other Potential Game Properties

- All finite potential games have FIP
- All finite games with FIP are potential games
  - Very important for ensuring convergence of distributed cognitive radio networks
- -*V* is a is a Lyapunov function for isolated maximizers
- Stable NE solvable by maximizers of *V*
- Linear combination of exact potential games is an exact potential game
- Maximizer of potential game need not maximize your objective function
  - Cognitive Radios' Dilemma is a potential game

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*

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



- Implementation:
  - Design DFS algorithms such that network is a potential game with $\Phi \propto -V$

Bilateral Symmetric Interference

- Two cognitive radios, $j,k \in N$, exhibit *bilateral symmetric interference* if

$$g_{jk} p_j \rho(\omega_j, \omega_k) = g_{kj} p_k \rho(\omega_k, \omega_j) \quad \forall \omega_j \in \Omega_j, \forall \omega_k \in \Omega_k$$

- 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,
- $\rho(\omega_k, \omega_j)$ - 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

Bilateral Symmetric Interference Implies an Interference Reducing Network

- Cognitive Radio Goal: $u_i(\omega) = -I_i(\omega) = -\sum_{j \in N \setminus i} g_{ji} p_j \rho(\omega_i, \omega_j)$
- By bilateral symmetric interference

$$g_{ki} p_k \rho(\omega_k, \omega_i) = g_{ik} p_i \rho(\omega_i, \omega_k) = b_{ki}(\omega_k, \omega_i) = b_{ik}(\omega_i, \omega_k)$$

- Rewrite goal $u_i(\omega) = -\sum_{k \in N \setminus i} b_{ik}(\omega_i, \omega_k)$
- Therefore a BSI game (S_i =0)

$$V(\omega) = -\sum_{i \in N} \sum_{k=1}^{i-1} g_{ki} p_k \rho(\omega_k, \omega_i)$$

- Interference Function $\Phi(\omega) = -2V(\omega)$
- Therefore profitable unilateral deviations increase *V* and decrease Φ(ω) – an IRN

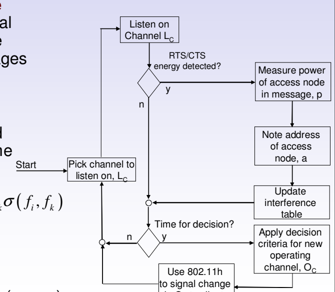
An IRN 802.11 DFS Algorithm

- 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

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

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

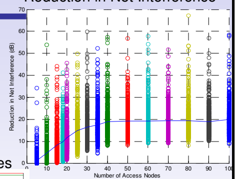
$$g_{jk} p_j \sigma(f_j, f_k) = g_{kj} p_k \sigma(f_k, f_j)$$



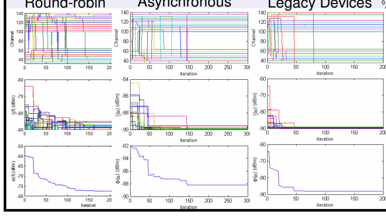
Statistics

- 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

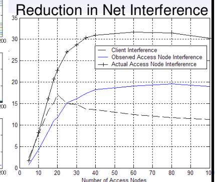
Reduction in Net Interference



Round-robin Asynchronous Legacy Devices

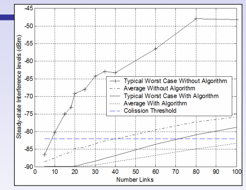


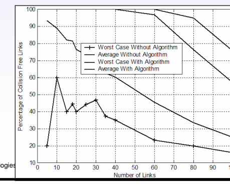
Reduction in Net Interference



Ad-hoc Network

- Possible to adjust previous algorithm to not favor access nodes over clients
- Suitable for ad-hoc networks
- CRT has IRN based distributed low-complexity algorithms for
  - Spreading codes
  - Power variations
  - Subcarrier allocation
  - Bandwidth variations
  - Activity levels weighted by interference
  - Noninteractive terms – modulation, FEC, interleaving
  - Beamforming
  - And combinations of the above





Comments on Potential Games

- All networks for which there is not a better response interaction loop is a potential game
- Before implementing fully distributed GA, SA, or most CBR decision rules, important to show that goals and action satisfy potential game model
- Sum of exact potential games is itself an exact potential game
  - Permits (with a little work) scaling up of algorithms that adjust single parameters to multiple parameters
- Possible to combine with other techniques
  - Policy restricts action space, but subset of action space remains a potential game (see J. Neel, J. Reed, "Performance of Distributed Dynamic Frequency Selection Schemes for Interference Reducing Networks," *Milcom 2006*)
  - As a self-interested additive cost function is also a potential game, easy to combine with additive cost approaches (see J. Neel, J. Reed, R. Gilles, "The Role of Game Theory in the Analysis of Software Radio Networks," *SDR Forum*02)
- Read more on potential games:
  - Chapter 5 in Dissertation of J. Neel, Available at http://scholar.lib.vt.edu/theses/available/etd-12082006-141855/

Token Economies

- Pairs of cognitive radios exchange tokens for services rendered or bandwidth rented
- Example:
  - Primary users leasing spectrum to secondary users
    - D. Grandblaise, K. Moessner, G. Vivier and R. Tafazolli, "Credit Token based Rental Protocol for Dynamic Channel Allocation," CrownCom06.
  - Node participation in peer-to-peer networks
    - T. Moreton, "Trading in Trust, Tokens, and Stamps," Workshop on the Economics of Peer-to-Peer Systems, Berkeley, CA June 2003.
- Why it works – it's a potential game when there's no externality to the trade
  - Ordinal potential function given by sum of utilities

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Comments on Network Options

- Approaches can be combined
  - Policy + potential
  - Punishment + cost adjustment
  - Cost adjustment + token economies
- Mix of centralized and distributed is likely best approach
- Potential game approach has lowest complexity, but cannot be extended to every problem
- Token economies requires strong property rights to ensure proper behavior
- Punishment can also be implemented at a choke point in the network

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