These Slides Available Online:
http://www.crtwireless.com/Publications.html

Interference Reducing Networks

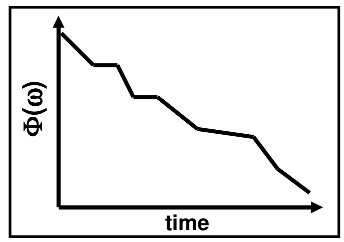
James Neel (CRT), Rekha Menon (Tyco Electronics), Allen B. MacKenzie (VT), Jeffrey H. Reed (VT/CRT), Robert P. Gilles (VT)

James Neel

James.neel@crtwireless.com

(540) 230-6012

www.crtwireless.com



CrownCom 07

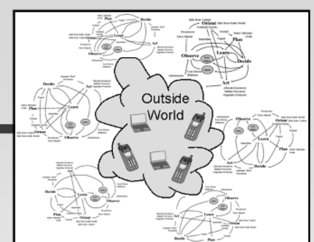
Session 2-A

August 1, 2007

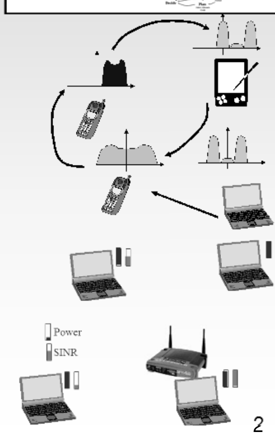
© Cognitive Radio Technologies, 2007

CRT Cognitive Radio Technologies

Problem Overview



- Cognitive radios naturally interact
- Interaction can spawn infinite adaptations
- Locally optimal decisions may be globally undesirable
- Some localization required for scalable networks
- How to design cognitive radio networks that overcome these problems while using local reasoning?

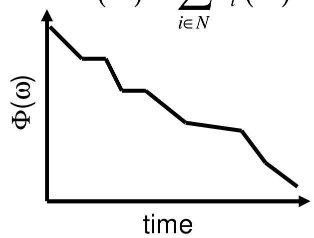


2

© Cognitive Radio Technologies, 2007

Interference Reducing Networks

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



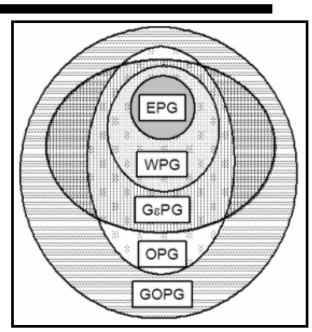
- Concept: Only permit adaptations which reduce the interference levels summed across all observations in the network
- Implies monotonic improvement in network performance – good convergence properties
- Utilitarian improvement, not necessarily Pareto
- Interference is a useful metric to minimize
  - Most networks are interference limited
  - Many other metrics monotonically improve with decreasing interference
  - Sum interference introduces symmetries exploitable for local reasoning

3

© Cognitive Radio Technologies, 2007

Potential Game Model

- A potential game is a game where a single function – the potential function – captures every player's incentives when considering a unilateral adaptation



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

Properties of Potential Games

- Monotonicity
  - Potential function **monotonically increases** with every self-interested unilateral adaptation
- Steady-state existence (compact space)
  - NE exist and can be identified by maximizers of potential function
- Convergence

Decision Rules	Timings: 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)

- Optimality
  - Only optimal if potential function is a function you want maximized

© Cognitive Radio Technologies, 2007

IRN and Potential Game

- Design potential game such that $V \propto -\Phi$
  - Self-interested adaptations will then monotonically increase V and decrease Φ

	Game	Utility Function Form	Potential Function
Altruism	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	$u_i(a) = C(a) + D_i(a_{-i})$	$V(a) = C(a)$
Isolated	Self-Motivated Game	$u_i(a) = S_i(a_i)$	$V(a) = \sum_{i \in N} S_i(a_i)$
Bilateral Symmetric Interference	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 $w_{S,i}(a_S) = w_{S,j}(a_S) \forall i, j \in S$	$V(a) = \sum_{S \in 2^N} w_S(a_S)$

© Cognitive Radio Technologies, 2007

Globally Altruistic Networks

Game	Utility Function Form	Deviation Relationship
Coordination Game	$u_i(a) = C(a)$	$V(a) = C(a)$

- Radio goal: minimize sum network interference

$$u_i(\omega) = -\Phi(\omega)$$

- Potential, Interference Function

$$V(\omega) = -\Phi(\omega)$$

- Works for all waveform adaptations
- Lots of overhead
  - Need to distribute observed interference levels to all decision processes
  - May be worse than a centralized solution

7

© Cognitive Radio Technologies, 2007

Locally Altruistic Networks

Game	Utility Function Form	Deviation Relationship
Coordination Game	$u_i(a) = C(a)$	$V(a) = C(a)$

- 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 $I_i = 0$)
- Benefits
  - Less overhead, just as generalizable
  - Scales better
- Drawback – Need extra routine to identify $\mathcal{I}_i$

8

© Cognitive Radio Technologies, 2007

Isolated Adaptations

Game	Utility Function Form	Deviation Relationship
Self-Interested Game	$u_i(a) = S_i(a)$	$V(a) = \sum_{i \in N} S_i(a)$

- Concept: If an adaptation does not impact the performance of other radios then network is said to be an *isolated adaptation* network
- Radio goals: $u_i(\omega) = -I_i(\omega_i)$
- Potential and Interference Function Relationship

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

- Successful implementation is very much dependent on the action sets
- Limited (though non-trivial) set of allowable adaptations:
  - Receive beamforming
  - Internal settings (e.g., sampling rates, AGC gains. receive filters, MUD technique)
  - Error correction (assuming no raw data rate change)

9

© Cognitive Radio Technologies, 2007

Bilateral Symmetric Interference

Game	Utility Function Form	Deviation Relationship
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 $w_{ij}(a_i, a_j) = w_{ji}(a_j, a_i)$	$V(a) = \sum_{i \in N} \sum_{j=1}^{i-1} w_{ij}(a_i, a_j) - \sum_{i \in N} S_i(a_i)$

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

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

- 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).

Proof:

- By bilateral symmetric interference

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

- Radio goal $u_i(\omega) = -I_i(\omega) = -\sum_{k \in N \backslash i} b_{ik}(\omega_i, \omega_k)$
- Therefore a BSI game (S_i =0) (an EPG)

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

- Interference Function

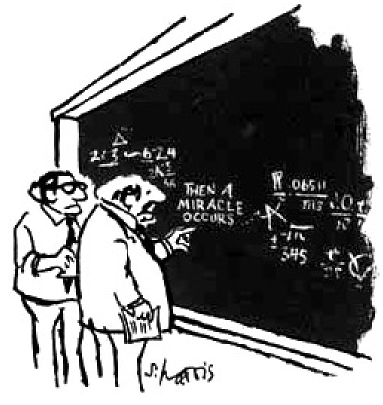
$$\Phi(\omega) = -2V(\omega)$$

- Therefore unilateral deviations increase *V* and decrease $\Phi(\omega)$ – an IRN

11

© Cognitive Radio Technologies, 2007

Situations where BSI occurs



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

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

- 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

12

© Cognitive Radio Technologies, 2007

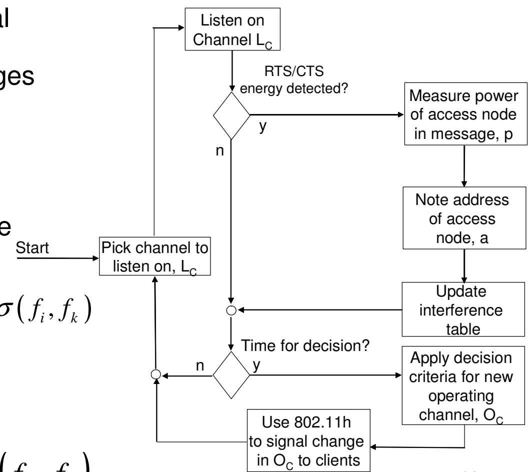
An IRN 802.11 DFS Algorithm

- 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

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

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

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

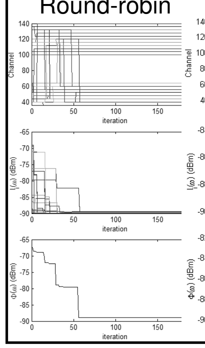


© Cognitive Radio Technologies, 2007

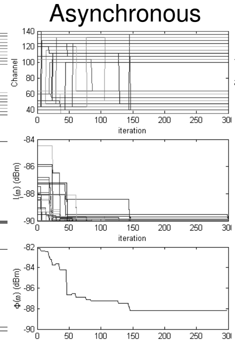
Statistics

- 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

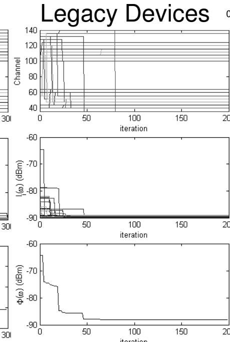
Round-robin



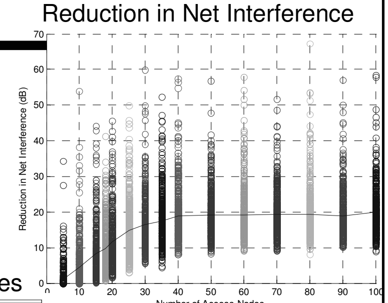
Asynchronous



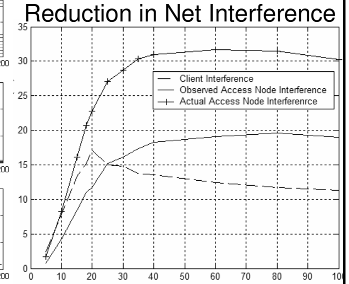
Legacy Devices



Reduction in Net Interference

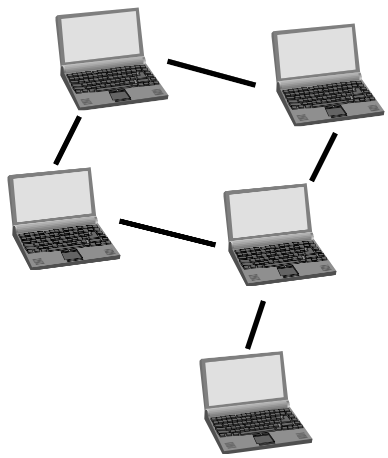


Reduction in Net Interference



Problems Applying to Ad-hoc/P2P Network

- No clear master node
- No clear reason to privilege one observation over others
- Link gain asymmetry violates BSI (previous trick required all observations to be made at transmitters)
- Could designate master devices (ala Bluetooth) and then run the same algorithm as the infrastructure algorithm

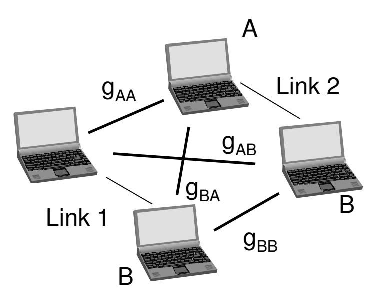


15

© Cognitive Radio Technologies, 2007

Achieving BSI A Different Way

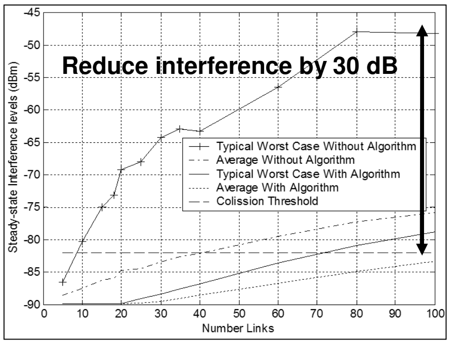
- Define players (decision processes) as links
  - Both sides of a link collaborate to make a decision
  - Permits incorporation of observations from both radios
- Consider Interference levels
  - Link 1
    - A $p(g_{AA} + g_{AB})\rho(f_1, f_2)$
    - B $p(g_{BA} + g_{BB})\rho(f_1, f_2)$
    - A+B $p(g_{AA} + g_{AB} + g_{BA} + g_{BB})\rho(f_1, f_2)$
  - Link 2
    - A $p(g_{AA} + g_{BA})\rho(f_1, f_2)$
    - B $p(g_{AB} + g_{BB})\rho(f_1, f_2)$
    - A+B $p(g_{AA} + g_{AB} + g_{BA} + g_{BB})\rho(f_1, f_2)$

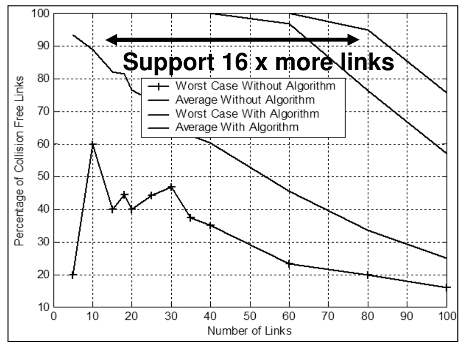


16

© Cognitive Radio Technologies, 2007

Aggregate Statistics for P2P Network





- Similar algorithm but cognitive decision processes span links
- No coordination between decision processes
- Localized reasoning leads to global optima
- Steady-state performance equivalent to centralized local search

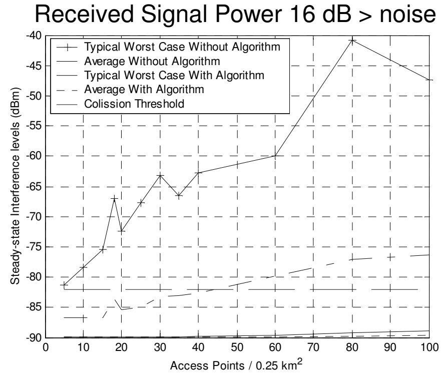
17

© Cognitive Radio Technologies, 2007

More examples of synthesizing BSI

- Possible to create BSI where it does not naturally exist
  - Frequency + power
  - Activity rates
  - Transmit beamforming
  - Transmission times
- Come see my paper at the SDR Forum in November

Received Signal Power 16 dB > noise



5 trials

18

© Cognitive Radio Technologies, 2007

Summary

- Framework for designing local reasoning cognitive radio algorithms that lead to resource allocations that minimize interference

Scenario	Special Topology	Waveform Restrictions	Observation Restrictions	Relative Overhead
Globally Altruistic	N	N	N	Very High
Locally Altruistic	N	N	N	High
Isolated Cluster	Y	Y	N	Low
Close Proximity	Y	Y	N	Low
Controlled Observation	N	Y	Y	Very Low

- BSI yields least overhead (no direct coordination between decision processes), but least applicable
- Techniques exist for synthesizing BSI conditions which still satisfy IRN framework

19

© Cognitive Radio Technologies, 2007

Questions?

These Slides Available Online:

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

20

© Cognitive Radio Technologies, 2007