Synthetic Symmetry in Cognitive Radio Networks

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CRT Cognitive Radio Technologies

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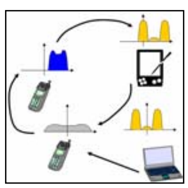
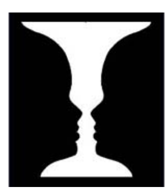
Presentation Overview

Motivation



A symmetry condition for distributed network optimization



Example techniques to induce this symmetry in practical networks

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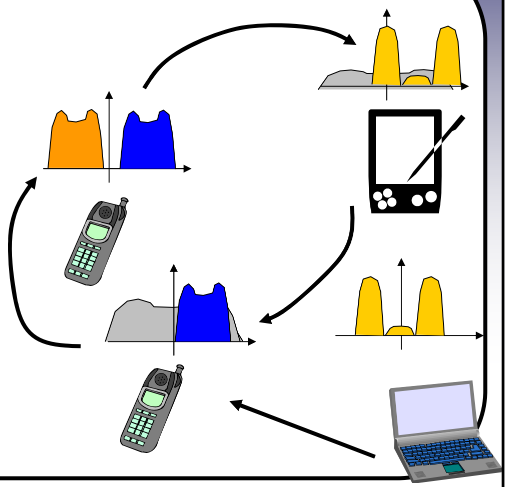
Dynamic Spectrum Access (DSA) is a success. So what's next?

- We're confident we can detect and rapidly vacate a band when a primary user (PU) shows up
- Confidence leads to 802.22, 802.16h, 802.11h, 802.11y, White Space Proposal
- But vacating one band means you're hopping into another band
- Successful networks are capacity constrained
- So vacating a PU's band will generally mean we're interfering with some SU



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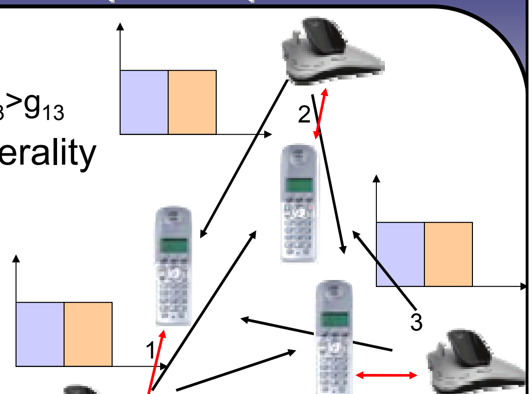
In heavily loaded networks, a single vacation can spawn an infinite adaptation process

- 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,…



Phone Image:
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Cradle Image:
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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

Generalized Insights from the DECT Example

- If # allocations > # channels, non-centralized DSA will have a non-zero probability of looping
- As # allocations $\rightarrow\infty$, probability of looping goes to 1
- Can be mitigated by increasing # of channels (DECT has 120) or reducing frequency of adaptations (DECT is every 30 minutes)
  - Both waste spectrum
  - And we're talking 100's of ms for vacation times
- "Centralized" solutions become distributed as networks scale
  - "Rippling" in Cisco WiFi Enterprise Networks
    - www.hubbert.org/labels/Ripple.html

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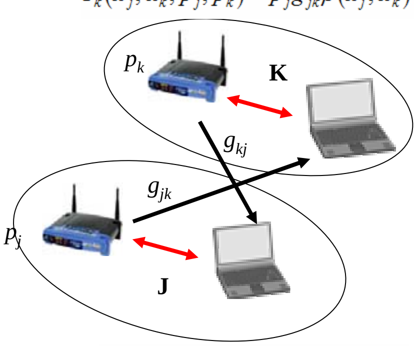
A "magical" condition for non-cooperative network behavior

- Link level Bilateral Symmetric Interference (BSI) if

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

- Network level BSI if link BSI holds for the observation metrics of all pairs of decision processes

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



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

Read the math behind the magic:
http://scholar.lib.vt.edu/theses/available/etd-12082006-141855/

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Selfish adaptations reduce sum network interference when BSI holds

- Sum network interference

$$\Phi(\omega,p)=\sum_{j\in N} I_j(\omega,p)$$

- With two links and BSI

$$I_j(\omega_j^1,\omega_k,p)<I_j(\omega_j^2,\omega_k,p)\Rightarrow I_k(\omega_j^1,\omega_k,p)<I_k(\omega_j^2,\omega_k,p)$$

$$\Phi(\omega_j^1,\omega_k,p)<\Phi(\omega_j^2,\omega_k,p)$$

$$\Phi(\omega_j^2,\omega_k,p)-\Phi(\omega_j^1,\omega_k,p)=2\left(I_j(\omega_j^2,\omega_k,p)-I_j(\omega_j^1,\omega_k,p)\right)$$

Network sees twice the benefit of the selfish adapter

With multiple links and BSI, the same relationship is seen

$$I_j(\omega,p)=\sum_{k\in N\setminus j} p_k g_{kj}\rho(\omega_j,\omega_k)$$

Change in interference for selfish adapter

$$I_j(\omega_j^1,\omega_{-j},p)-I_j(\omega_j^2,\omega_{-j},p)=\sum_{k\in N\setminus j} p_k g_{kj}\rho(\omega_j^1,\omega_{-j})-\sum_{k\in N\setminus j} p_k g_{kj}\rho(\omega_j^2,\omega_{-j})$$

Interference Terms Not Influenced by *j*

$$\Phi(\omega_j^1,\omega_{-j},p)-\Phi(\omega_j^2,\omega_{-j},p)=\sum_{k\in N\setminus j}\sum_{m\in N\setminus\{j,k\}} p_k g_{km}\rho(\omega_k,\omega_m)-\sum_{k\in N\setminus j}\sum_{m\in N\setminus\{j,k\}} p_k g_{km}\rho(\omega_k,\omega_m)+\cdots$$

$$\sum_{k\in N\setminus j} p_k g_{kj}\rho(\omega_j^1,\omega_k)-\sum_{k\in N\setminus j} p_k g_{kj}\rho(\omega_j^2,\omega_k)+\cdots$$ Interference Seen by *j*

$$\sum_{k\in N\setminus j} p_j g_{jk}\rho(\omega_j^1,\omega_k)-\sum_{k\in N\setminus j} p_j g_{jk}\rho(\omega_j^2,\omega_k)$$ Interference Caused by *j*

$$\Phi(\omega_j^1,\omega_{-j},p)-\Phi(\omega_j^2,\omega_{-j},p)=2\left(I_j(\omega_j^1,\omega_{-j},p)-I_j(\omega_j^2,\omega_{-j},p)\right)$$

Network sees twice the benefit of the selfish adapter

This correlation between selfish and social benefit yields desirable behavior

- Convergence
  - ***ALL*** sequences of unilateral selfish adaptations induce monotonically decreasing network interference levels
  - For finite waveform sets, completely unsynchronized adaptations form absorbing Markov chains
- Optimality of steady-states
  - Assuming exhaustive adaptations, interference minimizers are the only steady-states
- Stability
  - Sum network interference is a Lyapunov function in neighborhoods of isolated interference minimizers
  - In practice, many minimizers aren't isolated, so some hysteresis is needed

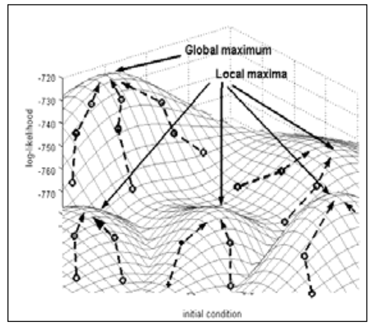
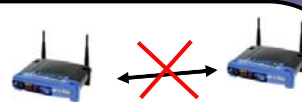


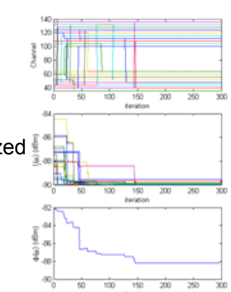
Figure from Fig 2.6 in I. Akbar, "Statistical Analysis of Wireless Systems Using Markov Models," PhD Dissertation, Virginia Tech, January 2007

This connection can be used to achieve minimal complexity

- Because selfish behavior is good for the network, no need to directly consider impact on other links
  - Means virtually no bandwidth lost to control messages
- Because selfish behavior is based solely on its own observations, there's no need to burden the network distributing observations
- Because unsynchronized adaptations converge, there no need for clock distribution
  - Will converge faster if properly synchronized
- Because ***ALL*** selfish adaptations converge, even trial and error, decision rules can be very simple
  - As simple as search through weighted RSSI measurements

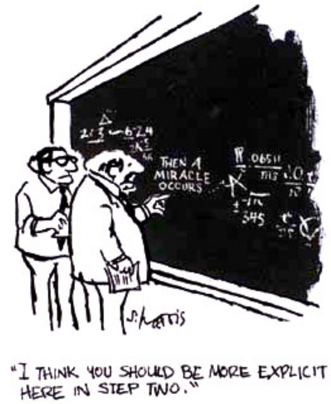


Example unsynchronized behavior



Situations where BSI occurs

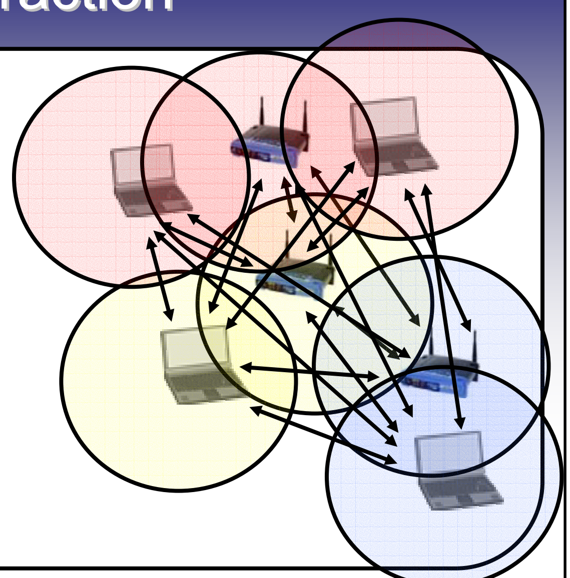
$$g_{kj} p_k \rho\left(\omega_j, \omega_k\right) = g_{jk} p_j \rho\left(\omega_k, \omega_j\right)$$



- 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 that waveform correlation effects dominate
- Controlled Observation Processes
  - Leverage knowledge of waveform protocol to create observation metrics which achieve BSI for the allowed adaptations

BSI by Subtraction

- Huge number of interference sources in a network
- Concept: constrain observations to only consider symmetric interference sources



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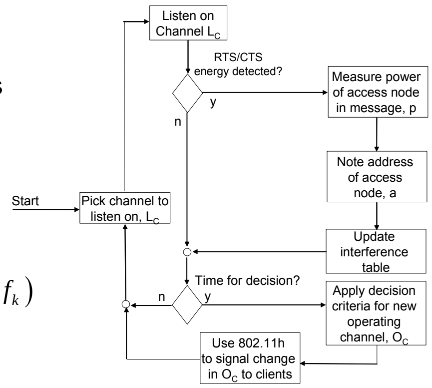
An IRN 802.11 DFS Algorithm

- 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
  - Ignore client interference
- Assumed out-of-channel interference is negligible and RTS/CTS transmitted at same power

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

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

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



J. Neel, J. Reed, "Performance of Distributed Dynamic Frequency Selection Schemes for Interference Reducing Networks," *Milcom 2006*, Washington DC, October 23-25, 2006

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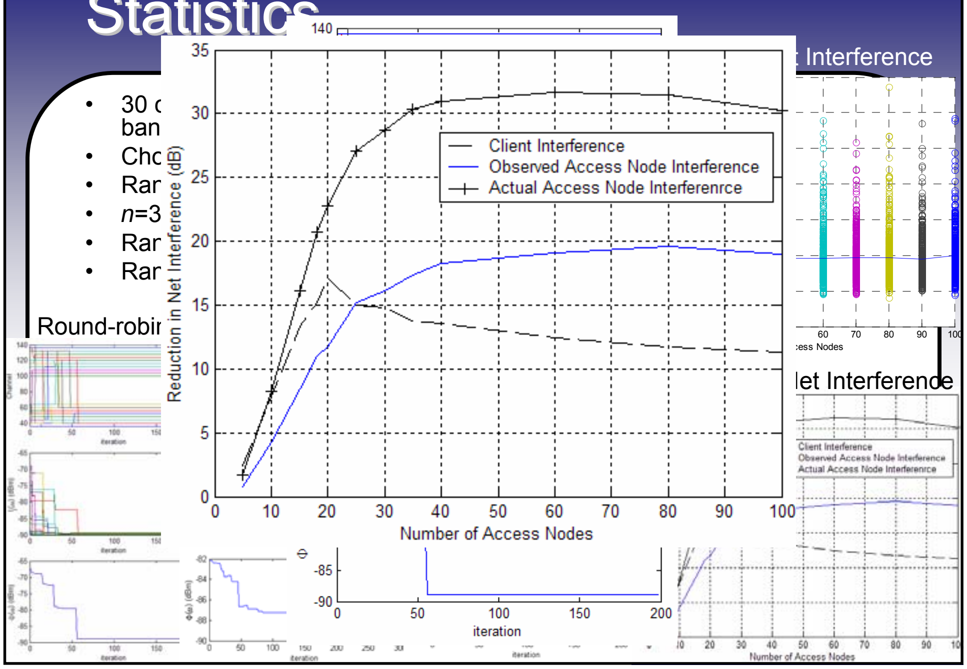
Statistics

- 30 c… ban…
- Chc…
- Rar…
- *n*=3…
- Rar…
- Rar…

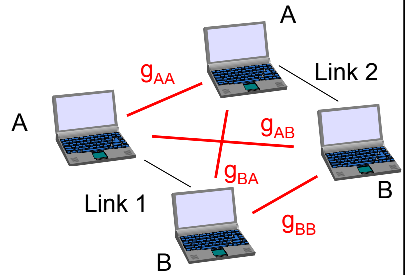
Round-robir…



BSI by Addition (Ad-hoc)

- 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 $p(g_{AA} + g_{AB} + g_{BA} + g_{BB})\rho(f_1, f_2)$



- Concept: Assuming TDD and equal powers, device-to-device interference is BSI. Observations formed as sum of device measurements for a link or a cluster is then also BSI.

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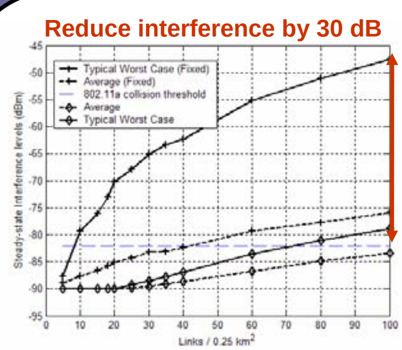
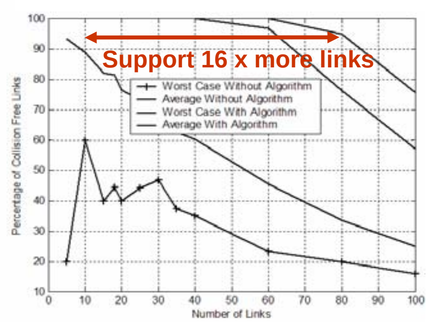
Aggregate Statistics for P2P Network





- Similar algorithm but cognitive decision processes span links
- No coordination/messaging between decision processes
- Localized reasoning yields steady-state performance equivalent to centralized local search
- No need to recover interfering signal – interference range is detection range

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BSI by Multiplication 1

- Power control + channel allocation can yield much better performance, but power control violates BSI assumptions

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

- Solution: devices weight interference observations by own power level

$$\tilde{I}_j(\omega) = p_j I_j(\omega) = p_j \sum_{k \in N \setminus j} g_{kj} p_k \rho(\omega_j, \omega_k)$$

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

- Comments
  - –Some interaction between power and channel choices
  - –Should not be used as objective for setting power levels

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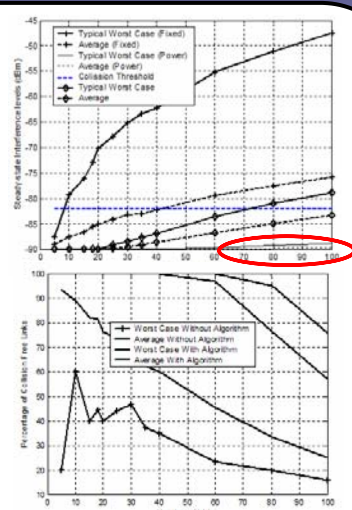
Aggregate Statistics for P2P Network

- Power control to achieve 16 dB SINR reception (typical SNR needed to recover 64-QAM with BER of 10^{-5})
- Lower slope & much less interference
- At 400 links/km^2 network is actually operating collision free (worst case interference remains below collision threshold)



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BSI by Multiplication 2

- Frequently, we want to prioritize access of certain transmissions
  - Voice versus email
  - General vs private
- Can accommodate this goal while preserving BSI by multiplying interference observations by weights of detected signals and then weighting aggregate levels by own weight

$$\tilde{I}_j(\omega) = w_j \sum_{k \in N \setminus j} w_k g_{kj} p_k \rho(\omega_j, \omega_k)$$

$$w_j w_k g_{jk} p \rho(\omega_j, \omega_k) = w_j w_k g_{kj} p \rho(\omega_k, \omega_j)$$

- Comments
  - Need some mechanism for distributing weighting factors
  - Interference range != detection range because of need to recover signal characteristics

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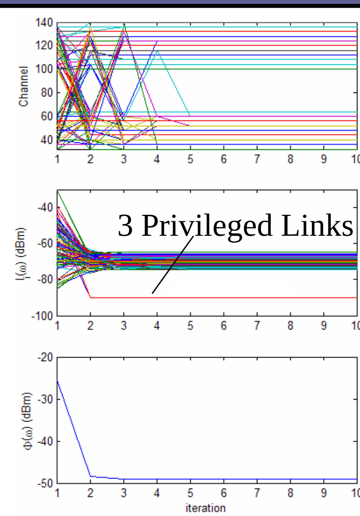
Example Simulation

- Basic parameters
  - 100 randomly distributed links in 0.5 x 0.5 km area
  - Round-robin iterations
  - 3 privileged links weighted at factor 100, others at 1
- 3 privileged links get their own channels
- (Weighted) Sum interference retains monotonic characteristic
- Note faster convergence from coordinated timings



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Summary

- BSI is a conceptually simple concept to evaluate

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

- When BSI holds
  - Network self-optimizes from selfish adaptations
    - No need to coordinate
    - No need to centralize
  - Complexity / overhead can be made very low
- BSI does not naturally occur frequently, but can be synthesized by careful design of the observation/objective functions
- CRT has developed techniques for synthesizing BSI observations for
  - Frequency, time, power, MIMO, beam forming, OFDM systems, accounting for varying traffic intensities, varying user priorities
  - Combinations of the preceding
- Applicability to
  - Ad-hoc nets, uncoordinated access points (e.g., apartments), femto-cells, home gateways, sensor nets
  - 802.11a/b/g/n, WiMAX, 802.22
  - Biggest benefit is in rapidly changing environments, large networks, and networks where management is impractical