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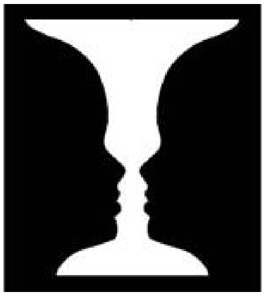
Bilateral Symmetry in Wireless Networks



Edgar Rubin, *Synsoplevede Figurer*, 1915

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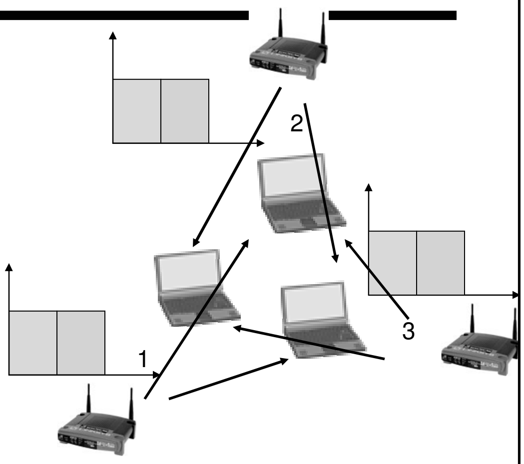
MPRG Symposium
June 6, 2007

CRT
Cognitive Radio
Technologies

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

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 $p\left(loop\right) \geq 1-\left(3/4\right)^{{}^{n}C_{3}}$
  - k channels $p\left(loop\right) \geq 1-\left(1-2^{-k+1}\right)^{{}^{n}C_{k+1}}$
- Even for apparently simple algorithms, ensuring convergence and stability will be nontrivial

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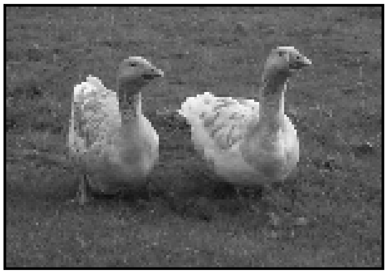
Bilateral Symmetric Interference

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

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

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

Emergent Behavior

- Each decision maker acts to reduce its observed interference

$$u_i(\omega) = -I_i(\omega) = -\sum_{j\in N\setminus i} g_{ji}\, p_j\, \rho(\omega_i, \omega_j)$$

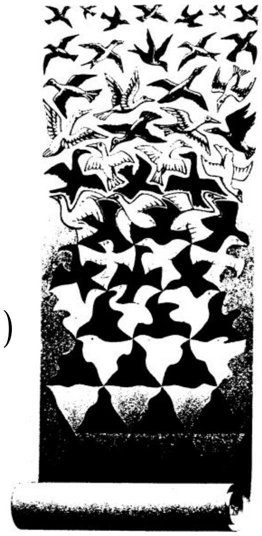
$$u_i\left(\omega_i^{k+1}, \omega_{-i}\right) > u_i\left(\omega_i^{k}, \omega_{-i}\right) \Rightarrow$$

$$\sum_{j\in N\setminus i} g_{ji}\, p_j\, \rho\left(\omega_i^{k+1}, \omega_j\right) < \sum_{j\in N\setminus i} g_{ji}\, p_j\, \rho\left(\omega_i^{k}, \omega_j\right)$$

- If BSI holds, $g_{ki}\, p_k\, \rho(\omega_k, \omega_i) = g_{ik}\, p_i\, \rho(\omega_i, \omega_k)$

$$u_i\left(\omega_i^{k+1}, \omega_{-i}\right) > u_i\left(\omega_i^{k}, \omega_{-i}\right) \Rightarrow$$

$$\sum_{j\in N} I_j\left(\omega_i^{k+1}, \omega_{-i}\right) < \sum_{j\in N} I_j\left(\omega_i^{k}, \omega_{-i}\right)$$



M.C. Escher, “Liberation”, 1965

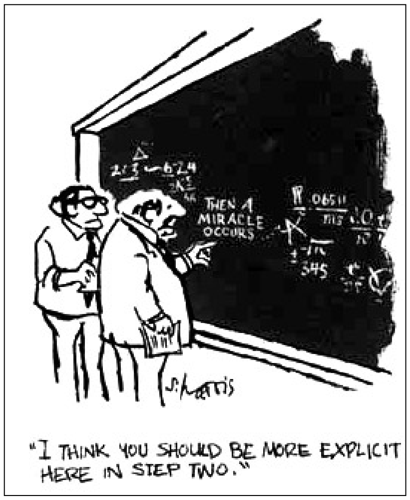
Implications of Emergent Behavior

- Emergent Behavior $u_i\left(\omega_i^{k+1}, \omega_{-i}\right) > u_i\left(\omega_i^{k}, \omega_{-i}\right) \Rightarrow$

$$\sum_{j\in N} I_j\left(\omega_i^{k+1}, \omega_{-i}\right) < \sum_{j\in N} I_j\left(\omega_i^{k}, \omega_{-i}\right)$$

- Each selfish adaptation reduces sum system interference
- System converges to minimizer (local/global) of sum system interference
  - No loops
- Information does not have to be shared between decision makers
  - No collaboration overhead
- Cognitive radio does not have to be complex radio

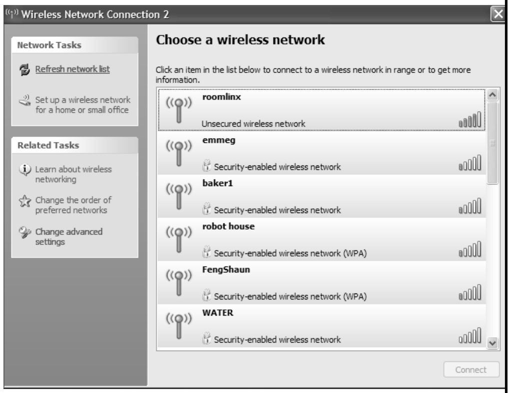
Situations where BSI Occurs



- 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

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

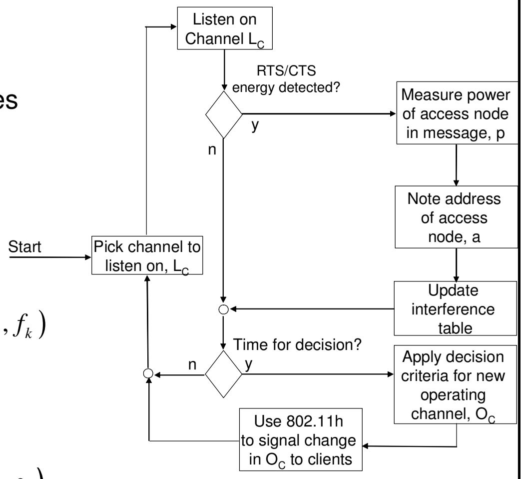
An IRN 802.11 DFS Algorithm

- 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

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

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

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



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

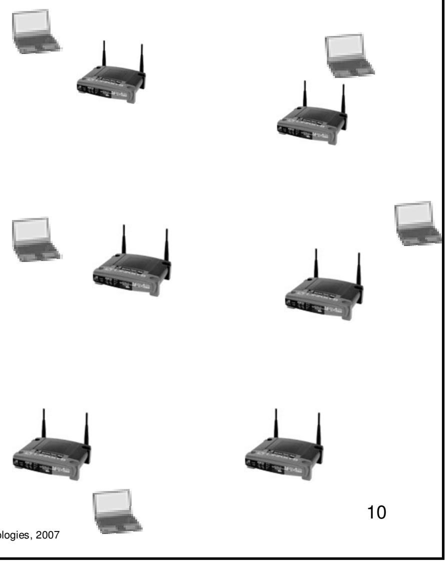
y

Apply decision criteria for new operating channel, O_C

Use 802.11h to signal change in O_C to clients

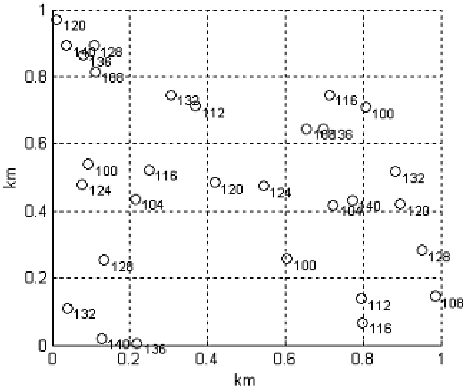
A DFS simulation of the process

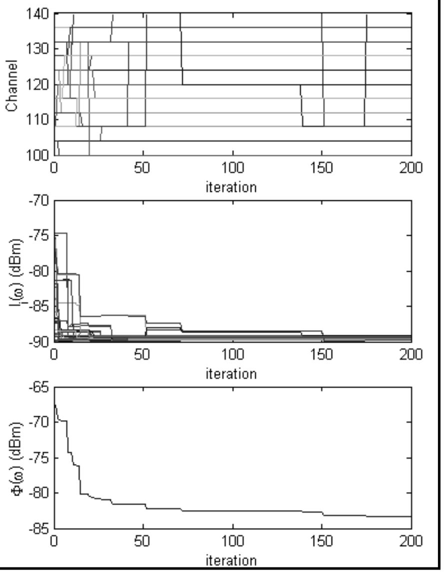
- 30 cognitive access nodes
- Upper 5 GHz 802.11 band
- Choose channel with lowest interference
- One randomly selected access node adapts at each instance
- n=3 path loss exponent
- Random initial channels
- Randomly distributed positions over 1 km^2
- Random timing



Dynamic Frequency Selection

Final channels by access node

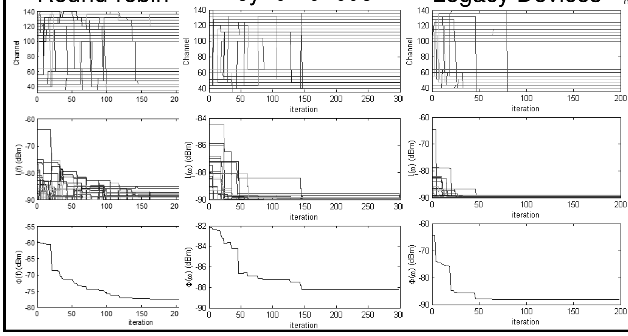




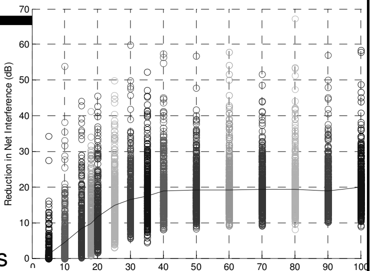
© Cognitive Radio Technol

Statistics

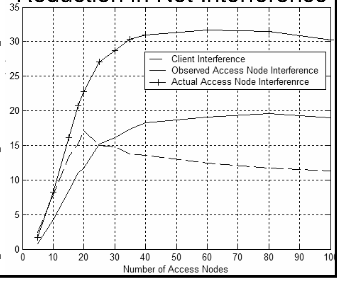
- 30 cognitive access nodes in European UNII bands
- Choose channel with lowest interference
- Random timing
- n=3
- Random initial channels
- Randomly distributed positions over 1 km^2


Round-robin Asynchronous Legacy Devices

Reduction in Net Interference

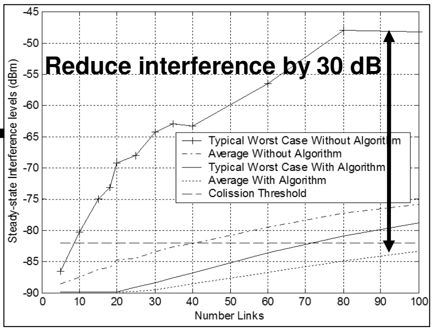


Reduction in Net Interference

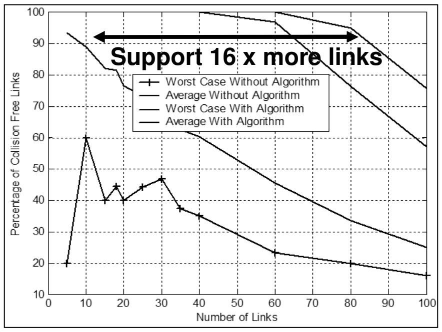


Ad-hoc Network

- Possible to adjust previous algorithm to not favor access nodes over clients
- Suitable for ad-hoc networks
- CRT has IRN based distributed zero-overhead low-complexity algorithms for
  - Joint power/frequency adaptation
  - Subcarrier allocation
  - Bandwidth variations
  - Activity levels weighted by interference
  - Noninteractive terms – modulation, FEC, interleaving
  - Beamforming
  - MIMO
  - Different user priorities
  - And combinations of the above



Reduce interference by 30 dB



Support 16 x more links

Take Aways

- Simple algorithms, big gain (19-30 dB)
  - No explicit coordination between cognitive radios
  - Key tasks are measuring RSS and decoding addresses from frames – something the radio must already do.
  - Example of a weak CR
  - Can also be implemented as a strong CR if:
    - Keep observation process
    - Keep goal
    - Keep allowable adaptations
  - **Cognitive Radio does not have to be Complicated Radio**
- If you consider the relationships between the observation, orientation, decision, and action processes of your cognitive radio, the interactions between radios, and the deployment setting, you can get good results from simple algorithms
  - **Push complexity out of implementation and into design**
  - **Design simplified even more if you can show BSI**

Slides online: www.crtwireless.com/publications.htm

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