Facilitating Spectrum Sharing Between Secondary Systems

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• Background / Theory
  – Definition
  – Game Models and general implications

• Coexistence Standards
  – 802.11 through 802.19.1
Coexistence

• **Coexistence Dictionary (paraphrased)**
  – a policy of living peacefully with others despite fundamental disagreements

• **802.15.2 Coexistence**
  – The ability of one system to perform a task in a given shared environment where other systems have an ability to perform their tasks and may or may not be using the same set of rules.

• **Electromagnetic Compatibility (EMC)**
  – The capability of electrical and electronic systems, equipments, and devices to operate in their intended electromagnetic environment within a defined margin of safety, and at design levels of performance without suffering or causing unacceptable degradation as a result of electromagnetic interference. (NATO)
  – The ability of a device, equipment, or system to function satisfactorily in its electromagnetic environment without introducing intolerable electromagnetic disturbances to anything in that environment. (IEEE Std 100-1996)
Motivating TV White Space

- **Need:**
  - Satisfying exploding demand for data apparently needs more spectrum

- **Opportunity**
  - Much spectrum is unused
    - Particularly in the TV Bands
  - Technically, TV band seems easy

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**Modified from Figure 1 in M. McHenry in “NSF Spectrum Occupancy Measurements Project Summary”, Aug 15, 2005.**

Available online: http://www.sharespectrum.com/?section=nsf_measurements
TVWS Rules

- Geolocation + Database
  - Sensing kinda allowed
  - 9 Database providers
  - Regs (kinda) finalized Sep 23, 2010
    - FCC 10-174

### Available Channels By Class

<table>
<thead>
<tr>
<th>TV Channel</th>
<th>Frequency Band</th>
<th>Frequency (MHz)</th>
<th>Allowed Devices</th>
</tr>
</thead>
<tbody>
<tr>
<td>2</td>
<td>VHF</td>
<td>64 – 88</td>
<td>Fixed</td>
</tr>
<tr>
<td>5 – 6</td>
<td>VHF</td>
<td>76 – 88</td>
<td>Fixed</td>
</tr>
<tr>
<td>7 – 13</td>
<td>VHF</td>
<td>174 – 216</td>
<td>Fixed</td>
</tr>
<tr>
<td>14 – 20</td>
<td>UHF</td>
<td>470 – 512</td>
<td>Fixed</td>
</tr>
<tr>
<td>21 – 38</td>
<td>UHF</td>
<td>512 – 602</td>
<td>Fixed &amp; Portable</td>
</tr>
<tr>
<td>36</td>
<td>UHF</td>
<td>602 – 608</td>
<td>Portable</td>
</tr>
<tr>
<td>38</td>
<td>UHF</td>
<td>614 – 520</td>
<td>Portable</td>
</tr>
<tr>
<td>39 – 61</td>
<td>UHF</td>
<td>620 – 698</td>
<td>Fixed &amp; Portable</td>
</tr>
</tbody>
</table>

- Above: no TVBD devices in 608-614 (adjacent to chan 37) in 13 metros (LMR conflict)
  - Channels 36,38 reserved for wireless mics

### Protected users:

- TV (including low power), TV translators, TV boosters, licensed mics, registered mics for major events, PLMRS/CMRS, MVPD receive sites, radio astronomy
More TVWS

- **Fixed**
  - HAAT restricted to 76 m, 30 m above ground
  - Not achievable in hilly terrain
- **Less power when adjacent to incumbent + TPC**
- **Identifications to geolocation database**
  - Fixed devices provide long list of identifying information. Stored in registration database (maintained with geolocation database)
  - Portables provide FCC ID
- Fixed / Mode II can pass along each others’ information for channel availability
- Mode I must receive “enabling signal” every 60s
- Secure and authenticate channel lists

Diagram:

- **Fixed Device**
  - Location (< 50m)
  - Available channels
- **Portable Mode II**
  - Location (< 50m)
  - Geolocation Database
  - Available Channels
- **Portable Mode I**
  - FCC ID
  - Available Channels
  - Database
  - Fixed-to-Fixed
    - Geo-location or professional installer
    - Secure access to TVB Database with device Id
    - 4W max power (ERP)
  - Fixed-to-Portable
    - Geo-location + 30m, check every 60s
    - Secure access to TVB Database with device Id
    - 100W max power, 40W when adjacent to incumbent TV channels
    - Secure access to TVB Database with device Id
  - Portable-to-Portable
    - Mode II device MUST access database
    - Initiates network on open channel
    - Beacons indicate channel availability to Mode I
Cognitive Radios in WiFi

- **CleanAir from Cisco for WiFi**
  - Detect / classify up to 20 types of interferers in ISM Band
  - Uniquely identify same interferer across nodes
  - Remember signals are there
  - Adapt channel usage to avoid accordingly

- **BeamFlex from Ruckus Wireless**
  - “The advanced BeamFlex system software _continually learns the environment_ with all its hostilities and interference sources, including disruptive RF conditions, numerous communicating devices, network performance issues, and application flows. Then, it selects the optimum antenna pattern for each communicating device in real time, while actively avoiding interference and minimizing noise to nearby networks and devices.”

### Other self-healing access points

<table>
<thead>
<tr>
<th>Interferer Distance from AP</th>
<th>Cisco</th>
<th>Aruba AP 125</th>
<th>Aruba AP 155</th>
<th>Motorola</th>
<th>HP</th>
<th>Trapeze</th>
<th>Meru</th>
</tr>
</thead>
<tbody>
<tr>
<td>Class (10ft)</td>
<td>30 sec</td>
<td>Never</td>
<td>Never</td>
<td>Never</td>
<td>Never</td>
<td>47 min</td>
<td>Never</td>
</tr>
<tr>
<td>Medium (50ft)</td>
<td>41 sec</td>
<td>2.10</td>
<td>Never</td>
<td>Never</td>
<td>Never</td>
<td>Never</td>
<td>Never</td>
</tr>
<tr>
<td>Far (100ft)</td>
<td>48 sec</td>
<td>2.22</td>
<td>Never</td>
<td>Never</td>
<td>Never</td>
<td>Never</td>
<td>Never</td>
</tr>
</tbody>
</table>

**Notes:**
- At the close location, noise remained at -87dBm.
- Noise varied at each location but never remained above the threshold.
- The number of retries did not cross the threshold to trigger a change.
- HP saw a noise level of -70dBm when camera was at 50ft.
- Noise level remained at -96dBm.
- Channel “Goodness” always remained at 100%.
The Cognition Cycle and Interactive Processes

Outside world is determined by the interaction of numerous cognitive radios.
Issues Can Occur When Multiple Intelligences Interact

Crash of May 6, 2010
- Not just a fat finger
- Combination of bad economic news, big bet by Universa, and interactions of traders and computers

Housing Bubble
- Bounce up instead of down
- Slower interactions lead to slower changes
- Also indicative of the role beliefs play in instability


A History of Home Values
In heavily loaded networks, a single adaptation 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!
  - $4, 5, 1, 3, 2, 6, 4, …$

**Interference Characterization**

<table>
<thead>
<tr>
<th>Chan.</th>
<th>(0,0,0)</th>
<th>(0,0,1)</th>
<th>(0,1,0)</th>
<th>(0,1,1)</th>
<th>(1,0,0)</th>
<th>(1,0,1)</th>
<th>(1,1,0)</th>
<th>(1,1,1)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Interf.</td>
<td>(1.5,1.5,1.5)</td>
<td>(0.5,1,0)</td>
<td>(1,0,0.5)</td>
<td>(0,0.5,1)</td>
<td>(0,0.5,1)</td>
<td>(1,0.5)</td>
<td>(0.5,1,0)</td>
<td>(1.5,1.5,1.5)</td>
</tr>
</tbody>
</table>
Generalized Insights from the DECT Example

• If # links / clusters > # channels, decentralized channel choices will have a non-zero looping probability
• As # links / clusters →∞, looping probability goes to 1
  – 2 channels
    \[ p(\text{loop}) \geq 1 - \left(\frac{3}{4}\right)^n \]
  – k channels
    \[ p(\text{loop}) \geq 1 - \left(1 - 2^{-k+1}\right)^n \]
• 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
• Also shows up in more recent proposals
  – Recent White Spaces paper from Microsoft
Locally optimal (selfish) decisions can lead to globally undesirable networks

- Scenario: Distributed SINR maximizing power control in a single cluster
- For each link, it is desirable to increase transmit power in response to increased interference
- Steady state of network is all nodes transmitting at maximum power

**Insufficient to consider only a single link, must consider interaction**
Potential Problems with Networked Cognitive Radios

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

**Centralized**
- Signaling Overhead
- Complexity
- Responsiveness
- Single point of failure
Repeated Games

- Same game is *repeated*
  - Indefinitely
  - Finitely

- Players consider discounted payoffs across multiple stages
  - Stage $k$
    \[ \tilde{u}_i(a^k) = \delta^k u_i(a^k) \]
  - Expected value over all future stages
    \[ \tilde{u}_i((a^k)) = \sum_{k=0}^{\infty} \delta^k u_i(a^k) \]

<table>
<thead>
<tr>
<th>$\Gamma$</th>
<th>$N$</th>
<th>$W$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$n$</td>
<td>(9.6,9.6)</td>
<td>(3.2,21)</td>
</tr>
<tr>
<td>$w$</td>
<td>(21,3.2)</td>
<td>(7,7)</td>
</tr>
</tbody>
</table>

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<td>(7,7)</td>
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</table>
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.

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
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.

<table>
<thead>
<tr>
<th>Potential Game</th>
<th>Relationship ($\forall i = N, \forall a = A$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Exact (EPG)</td>
<td>$u_i(b_i,a_{-i}) - u_i(a_i,a_{-i}) = V(b_i,a_{-i}) - V(a_i,a_{-i})$</td>
</tr>
<tr>
<td>Weighted (WPG)</td>
<td>$u_i(b_i,a_{-i}) - u_i(a_i,a_{-i}) = \alpha_i[V(b_i,a_{-i}) - V(a_i,a_{-i})]$</td>
</tr>
<tr>
<td>Ordinal (OPG)</td>
<td>$u_i(b_i,a_{-i}) - u_i(a_i,a_{-i}) &gt; 0 \Leftrightarrow V(b_i,a_{-i}) - V(a_i,a_{-i}) &gt; 0$</td>
</tr>
<tr>
<td>Generalized Ordinal (GOPG)</td>
<td>$u_i(b_i,a_{-i}) - u_i(a_i,a_{-i}) &gt; 0 \Rightarrow V(b_i,a_{-i}) - V(a_i,a_{-i}) &gt; 0$</td>
</tr>
<tr>
<td>Generalized ε (GεPG)</td>
<td>$u_i(b_i,a_{-i}) &gt; u_i(a_i,a_{-i}) + \varepsilon_i \Rightarrow V(b_i,a_{-i}) &gt; V(a_i,a_{-i}) + \varepsilon_i$</td>
</tr>
</tbody>
</table>
A Dynamic Frequency Selection Algorithm

Most market / token economy based coexistence algorithms are potential games.
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
  - Arguably, token economies guarantee “good” performance as long as information is timely / reliable and resource distributions are “fair”

<table>
<thead>
<tr>
<th>Decision Rules</th>
<th>Round-Robin</th>
<th>Random</th>
<th>Synchronous</th>
<th>Asynchronous</th>
</tr>
</thead>
<tbody>
<tr>
<td>Best Response</td>
<td>1,2,4</td>
<td>1,2,4</td>
<td>-</td>
<td>1,2</td>
</tr>
<tr>
<td>Exhaustive Better Response</td>
<td>1,2</td>
<td>1,2</td>
<td>-</td>
<td>1,2</td>
</tr>
<tr>
<td>Random Better Response$^{(a)}$</td>
<td>1,2,4</td>
<td>1,2,4</td>
<td>1,2</td>
<td>1,2</td>
</tr>
<tr>
<td>Random Better Response$^{(b)}$</td>
<td>1,2</td>
<td>1,2</td>
<td>-</td>
<td>1,2</td>
</tr>
<tr>
<td>$\varepsilon$-Better Response$^{(c)}$</td>
<td>1,2,3,4</td>
<td>1,2,3,4</td>
<td>-</td>
<td>1,2,3</td>
</tr>
<tr>
<td>Intelligently Random Better Response</td>
<td>1,4</td>
<td>1,4</td>
<td>-</td>
<td>1,2</td>
</tr>
<tr>
<td>Directional Better Response$^{(d)}$</td>
<td>4</td>
<td>4</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Averaged Best Response$^{(d)}$</td>
<td>3,4</td>
<td>3,4</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>

(a) Definition 4.12, (b) Definition 4.13, (c) Convergence to an $\varepsilon$-NE, (d) $u_t$ quasi-concave in $\alpha_t$
Notions of Fairness

• What is “Fair”?  
  – Abstractly “fair” means different things to different analysts  
  – In every day life, “unfair” is short hand for “I deserve more than I got”  

• Nonetheless is used to evaluate how equitably radio resources are distributed  

• Examples  
  – Prioritized access  
  – Gini coefficient, Theill Index, Atkinson Index
Price of Anarchy

\[ \frac{\text{Performance of Centralized Algorithm Solution}}{\text{Performance of Distributed Algorithm Solution}} \geq 1 \]

- Centralized solution always at least as good as distributed solution
- Ignores costs of implementing algorithms
  - Sometimes centralized is infeasible (e.g., routing the Internet)
  - Distributed can sometimes (but not generally) be more costly than centralized

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\[ \frac{\text{Performance of Centralized Algorithm Solution}}{\text{Performance of Distributed Algorithm Solution}} = \frac{9.6}{7} \]
Pareto efficiency (optimality)

- **Formal definition**: An action vector $a^*$ is *Pareto efficient* if there exists no other action vector $a$, such that every radio’s valuation of the network is at least as good and at least one radio assigns a higher valuation.

- **Informal definition**: An action tuple is *Pareto efficient* if some radios must be hurt in order to improve the payoff of other radios.

- **Important note**
  - Like design objective function, unrelated to fixed points (NE)
  - Generally less specific than evaluating design objective function
Example Games

Legend

Pareto Efficient

NE

NE + PE

May have to leave some resources on the table for sensing or other applications
Example coexistence protocols

802.11, 802.11h, 802.11y, 802.16h, 802.22, 802.19.1
802.11 Distributed Coordination Function

- Intended to combat “hidden nodes” in an uncoordinated network and generate fair access to channel
- Basic components:
  - After waiting DIFS after last detected transmission, source sends Request to Send (RTS)
  - Destination replies with Clear to Send (if OK)
  - Data is then transferred and ACKed
  - If an error occurs (e.g., collision), then station has to wait for DIFS + random backoff.
    - Random backoff grows with # of collisions

  - Network allocation vector
    - Acts as virtual carrier sense
    - Duration given in RTS/CTS fields
  - DIFS = DCF Interframe Space
  - SIFS = Short Interframe Space

Example of a Polite Etiquette
Point Coordination Function (PCF)

- Intended to provide service more appropriate for real-time applications
  - Not widely utilized initially

- Basic steps
  - Access node (AN) implementing PCF “wins” the channel by cheating (SIFS < PIFS < DIFS)
  - AN announces contention free period in Beacon (realized in NAV) to lock out DCF
  - Polls each client in its polling list
    - Frames separated by PIFS
    - If client fails to respond within PIFS, AN moves onto next
  - At end of contention-free period a contention free message is sent ending the contention free period
  - DCF holds until AN initiates another contention free period
    - Various ratios permitted between contention based and contention free
802.11 overhead

- Significant overhead involved in 802.11
  - RTS/CTS/ACK SIFS
  - TCP, IP, MAC framing
  - Real throughput is rarely close to PHY raw rate
802.11h

- **Dynamic Frequency Selection (DFS)**
  - Avoid radars
    - Listens and discontinues use of a channel if a radar is present
  - Uniform channel utilization
- **Transmit Power Control (TPC)**
  - Interference reduction
  - Range control
  - Power consumption Savings
  - Bounded by local regulatory conditions

- Added politeness in protocol improves capacity
802.11y

- Ports 802.11a to 3.65 GHz – 3.7 GHz (US Only)
  - FCC opened up band in July 2005
  - Completed 2008
- Intended to provide rural broadband access
- Basis for 802.11af
- Adds
- Key features:
  - Database of existing devices
    - Access nodes register at http://wireless.fcc.gov/uls
    - Must check for existing devices at same site
  - “Light” licensing
    - Right to transmit, but not protected
  - Automatic policy recognition
    - Varies by channel location
  - Tiered policy enforcement
    - Enabling – determines operating regs
    - Dependent – follows instructions
- Adds energy detection threshold (+ 10 dB) for non-802.11y systems
802.11af

- Builds on 802.11y
  - DFS, TPC, quiet periods, policy enabling
  - Hope to be done in two years
  - Maybe only 15 pages...
  - Started in January 2010

- Multiband support
- Looking for techniques to speed up channel sensing
- Sharing MAP information
802.16h

Started as WiMAX for unlicensed
- Focus on 3.65 GHz

• Migrated to TVWS
• Improved Coexistence Mechanisms for License-Exempt Operation
• Explicitly, a cognitive radio standard
• Incorporates many of the hot topics in cognitive radio
  – Token based negotiation
  – Interference avoidance
  – Network collaboration
  – RRM databases
• Coexistence with non 802.16h systems
  – CX-CBP
  – Regular quiet times for other systems to transmit
  – Exponential backoff, listen-before talk
• Location-aware, time-aware scheduling to allow non-interfering parallel transmissions, and sequential transmissions of transmissions that would interferer
  – Also in 802.22
Scheduling in 802.16h

- Coordinate on times to deconflict users
  - “Interference free” operation
  - Fractional Time Reuse (my term)
  - Requires significant coordination and information awareness

Modified from CRC pub.
Coexistence Signaling Interval

- Coexistence Signaling Interval
  - Scheduled every N frames
  - Initialization and over the air
  - BS<->BS via SS via CT-CXP

- Transmit BS Identifiers when no BS interference server exists

Note need for common time base
Collaboration

- BS can request interfering systems to back off transmit power
  - Master BS can assign transmit timings
    - Intended to support up to 3 systems (Goldhammer)
- Slave BS in an interference community can “bid” for interference free times via tokens.
  - Master BS can advertise spectrum for “rent” to other Master BS
    - Bid by tokens
- Collaboration supported via Base Station Identification Servers, messages, and RRM databases
- Interferer identification by finding power, angle of arrival, and spectral density of OFDM/OFDMA preambles
- Every BS maintains a database or RRM information which can be queried by other BS
  - This can also be hosted remotely
- Updates neighbors when adapting channels
- Broadcasts information on initialization during initial coexistence signaling interval (ICSI)
802.22

- 802.22.1
  - Enhanced interference protection
  - Particularly for mics
- 802.22.2
  - Best practices for deployment
- Reduce frame size based on traffic *(polite)*
- Spectrum manager adjusts mechanism based on perception of current scenario
Contestation / Coexistence

- Variable contention strategies
  - Tries to backoff power first
    - Minimum SNR
  - Can rent spectrum exchange tokens
    - Both sides bid (request and holder)
- Inter-BS communication / negotiation
  - Over-the-air and Via Backhaul
  - Contention number exchange and comparison
- Coexistence beacon
  - Transmitted during the self-coexistence windows at the end of some frames by the BS and/or some designated CPE
  - Monitored by BSs and other CPEs from same and different cells on same channel or different channel for future channel switching
  - Signals IP address of BS and CPE every 15 min. as asked by R&O

Coexistence Beacon Protocol (CBP) burst
802.19.1 (TVWS Coexistence)

- Coexistence mechanisms for heterogeneous networks in TVWS
- Device discovery
- Manage coexistence info
  - Database, shared info
- Support reconfiguration requests
- Automate analysis of info
- Make coexistence decisions
- Support multiple topologies
- Support sensing
Summary / Conclusions

- Wireless coexistence issues and solutions pre-date TV White Spaces (e.g., WiFi / Bluetooth)
- If we ignore cost of overhead / infrastructure, the performance of distributed solutions no better than centralized solutions (price of anarchy)
  - Distributed also faces decision stability / convergence issues, but this can be addressed with potential games
- Satisfying TVWS regs results in convenient infrastructure for coordinated coexistence
  - GPS for location / time
  - Conceptually common interface for discovery and low-cost (but low-speed) coordination
- All approaches need to account for information quality (security / authentication)
- Performance can degrade if assumptions are wrong – discovery / information
  - If assume what’s not there - 802.11 legacy coexistence
  - If fail to account for what’s there – 802.11 and video cameras
  - Different role for “cognitive” radio