Facilitating Spectrum Sharing Between Secondary Systems

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August 28, 2012

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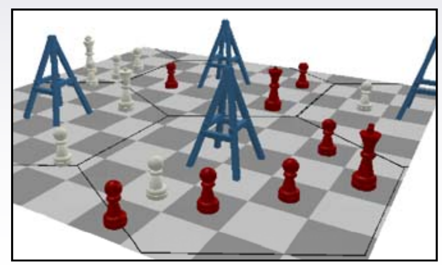
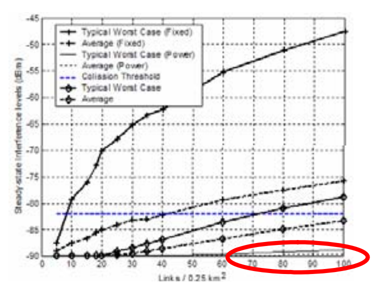
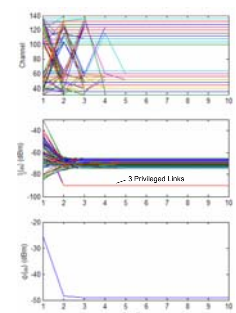


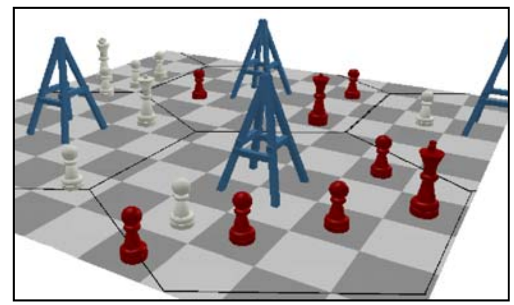




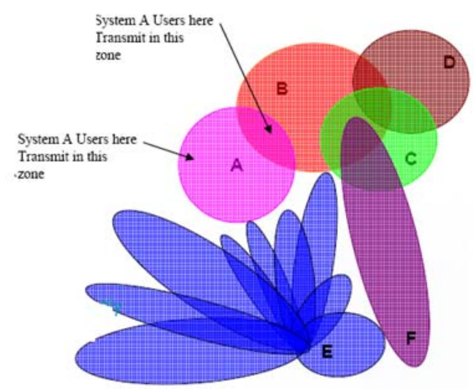
Cognitive Radio Technologies

Presentation Material

- Background / Theory
  - Definition
  - Game Models and general implications



- Coexistence Standards
  - 802.11 through 802.19.1



Spatial Occupancy of Systems A-F

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)

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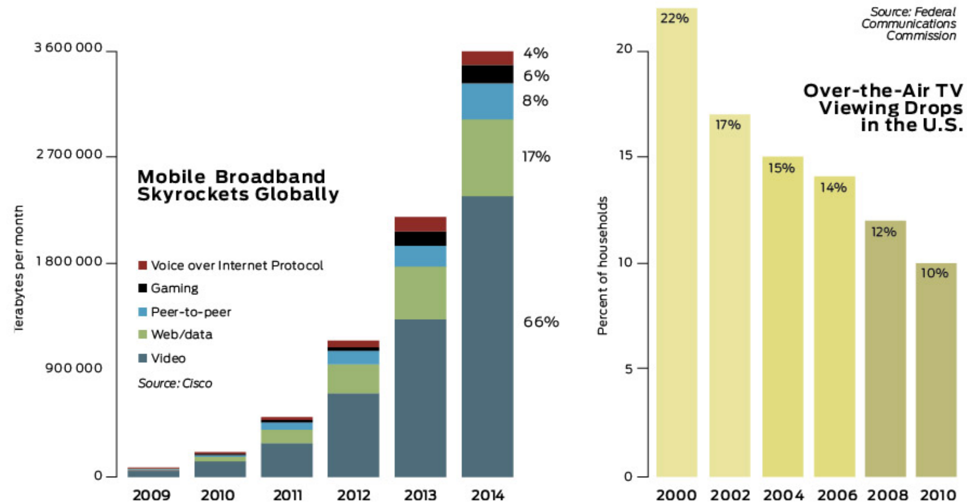
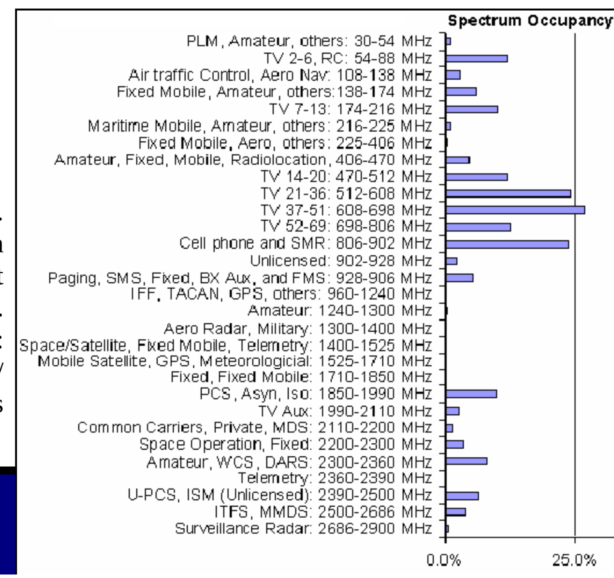
Motivating TV White Space

- 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

Source: http://spectrum.ieee.org/telecom/wireless/the-great-radio-spectrum-famin



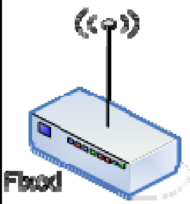
CHANGING TASTES: The amount of data being sent wirelessly over the Internet has shot up globally [left], while the small fraction of television-owning households that rely on over-the-air broadcasts has been steadily diminishing in the United States [right].



Modified from Figure 1 in M. McHenry in "NSF Spectrum Occupancy Measurements Project Summary", Aug 15, 2005. Available online: http://www.sharedspectrum.com/?section=nsf_measurements

TVWS Rules

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



Fixed TVBD
- Geo-location +/- 50m
- Geo-location capable or professional installer
- Secure access to TVB Database with device Id
- 4W max power (EIRP)
- TV channels useable: 2 (54-60Mhz), 5,6 (76-88Mhz), 7-13 (174-216Mhz) and 21-36, 38-51 (470-692 Mhz)
- Max antenna height <30m and <76m for site

Mode II Personal Portable TVBD
- Geo-location +/- 50m, check every 60 seconds
- Secure access to TVB Database with device Id
- 100mW power, 40mW when adjacent to incumbent
- TV channels useable: 21-36, 38-51 (470-692 Mhz)
- Secure access to TVB Database with device Id

Mode I Personal Poratble TVBD
- MUST obtain channels from Mode II or Fixed TVBD
- 100mW power, 40mW when adjacent to incumbent
- TV channels useable: 21-36, 38-51 (470-692 Mhz)

Sensing Only TVBD
- MUST sense for incumbents prior to channel use
- 50mW power
- TV channels useable: 21-36, 38-51 (470-692 Mhz)

- Available Channels By Class

TV Channel	Frequency Band	Frequency (MHz)	Allowed Devices
2	VHF	54 – 60	Fixed
5 – 6	VHF	76 – 88	Fixed
7 – 13	VHF	174 – 216	Fixed
14 – 20	UHF	470 – 512	Fixed
21 – 35	UHF	512 – 602	Fixed & Portable
36	UHF	602 – 608	Portable
38	UHF	614 – 620	Portable
39 – 51	UHF	620 – 698	Fixed & Portable

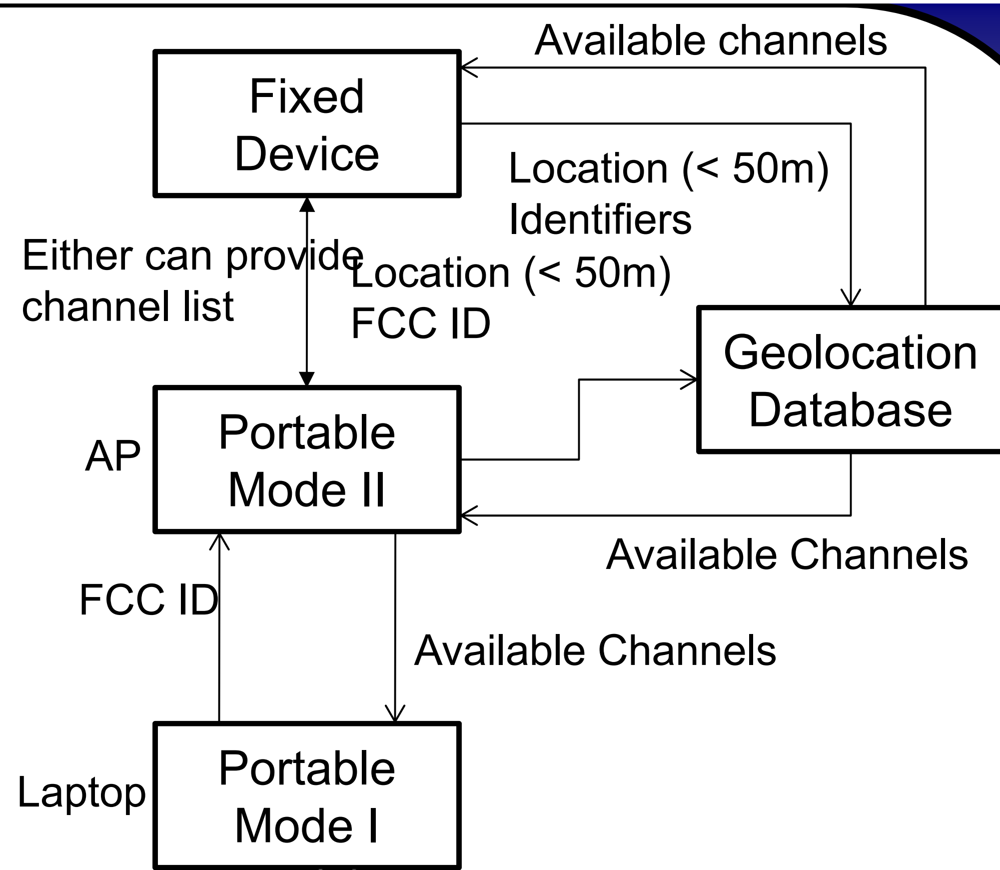
  - Above: no TVBD devices in 608-614 (adjacent to chan 37) in 13 metros (LMR conflict)
    - Channels 36,38 reserved for wireless mics

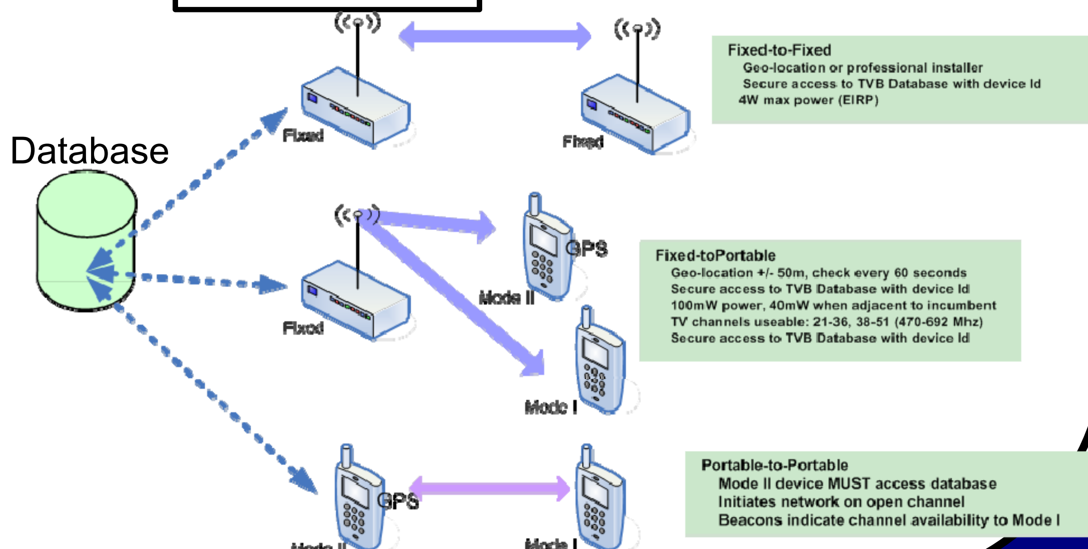
- Protected users:
  - TV (including low power), TV translators, TV boosters, licensed mics, registered mics for major events, PLMRS/CMRS, MVPD receive sites, radio astronomy

Diagram from: Marvell, WinnForum TVWS Workshop Dec 2010

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





Lower Diagram from: Marvell, WinnForum TVWS Workshop Dec 2010

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
  - http://www.cisco.com/en/US/netsol/ns1070/index.html
- 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."

CleanAir Spectrum Monitor

Other self-healing access points

	Time to Self-Heal						
Interferer Distance from AP	**Cisco**	**Aruba AP 125**	**Aruba AP105**	**Motorola**	**HP**	**Trapeze**	**Meru**
Close (10ft)	30 sec	Never	Never	Never	Never	47 min	Never
Medium (50ft)	41 sec	2:10	Never	Never	Never	Never	Never
Far (100ft)	48 sec	2:22	Never	Never	Never	Never	Never
Notes:		At the close location, noise remained at -87dBm	Noise varied at each location but never remained above the change 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%.

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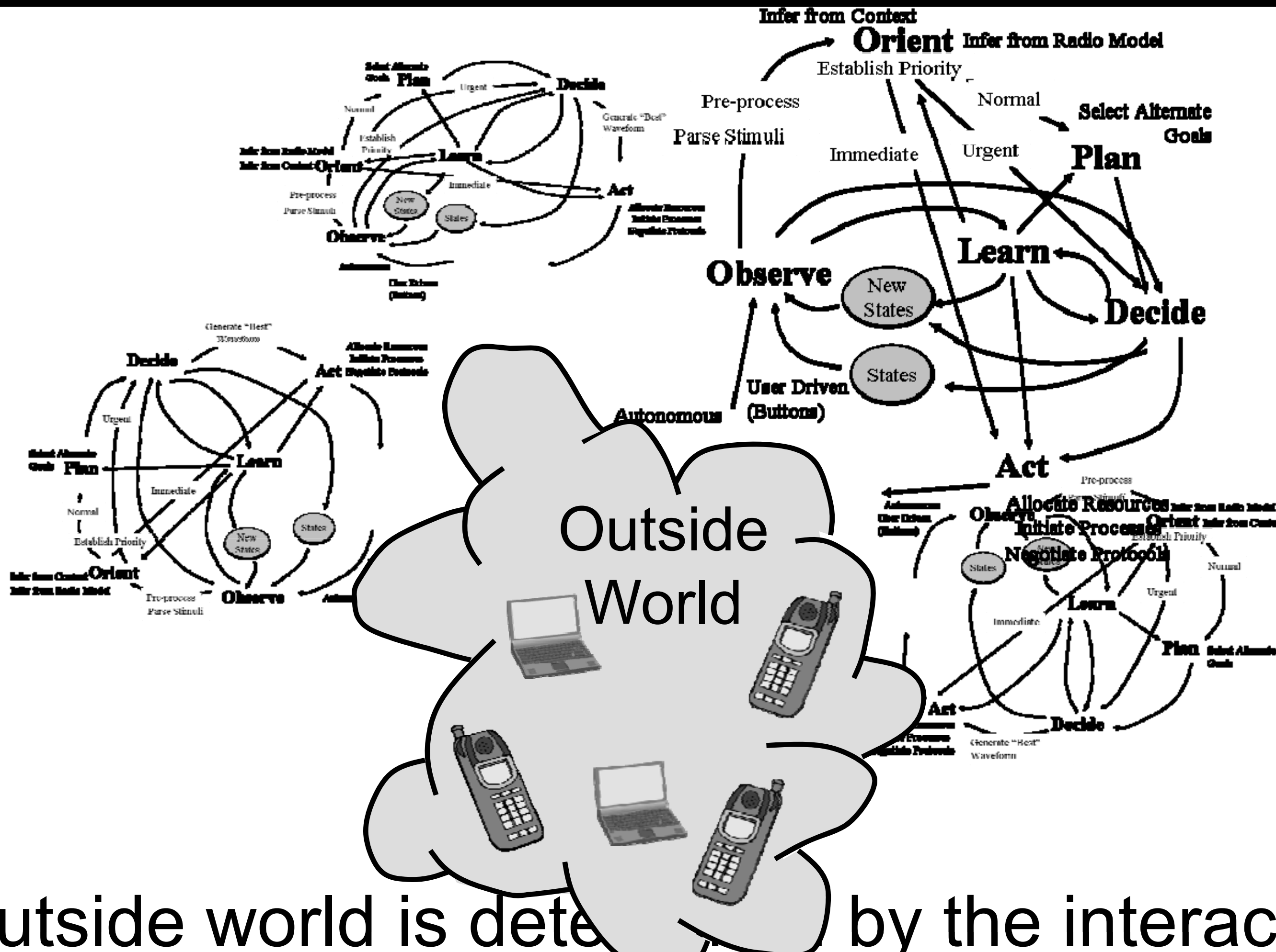
The Cognition Cycle and Interactive Processes



- Outside world is dete by the interaction of numerous cognitive radios

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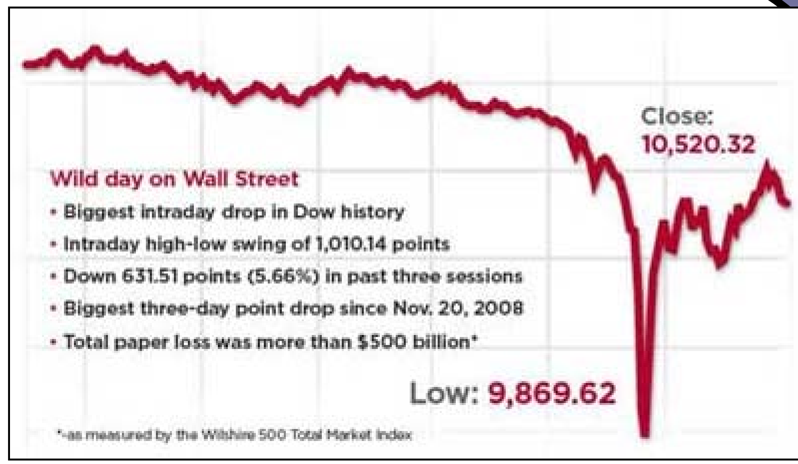
8

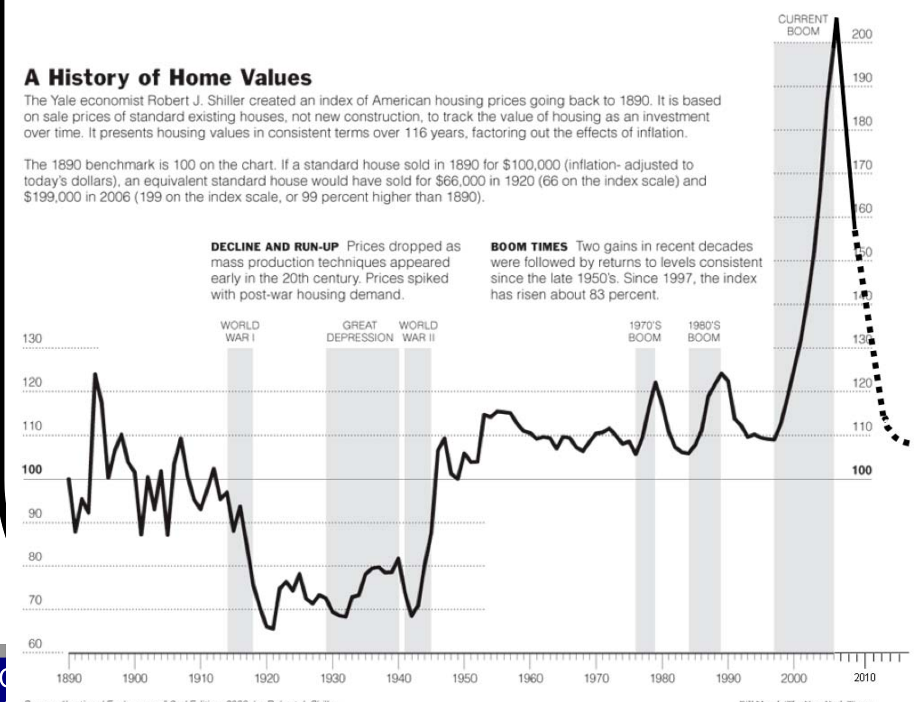
Issues Can Occur When Multiple Intelligences Interact

- 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



http://www.legitreviews.com/images/reviews/news/dow_drop.jpg

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



http://www.nytimes.com/imagepages/2006/08/26/weekinreview/27leon_graph2.html

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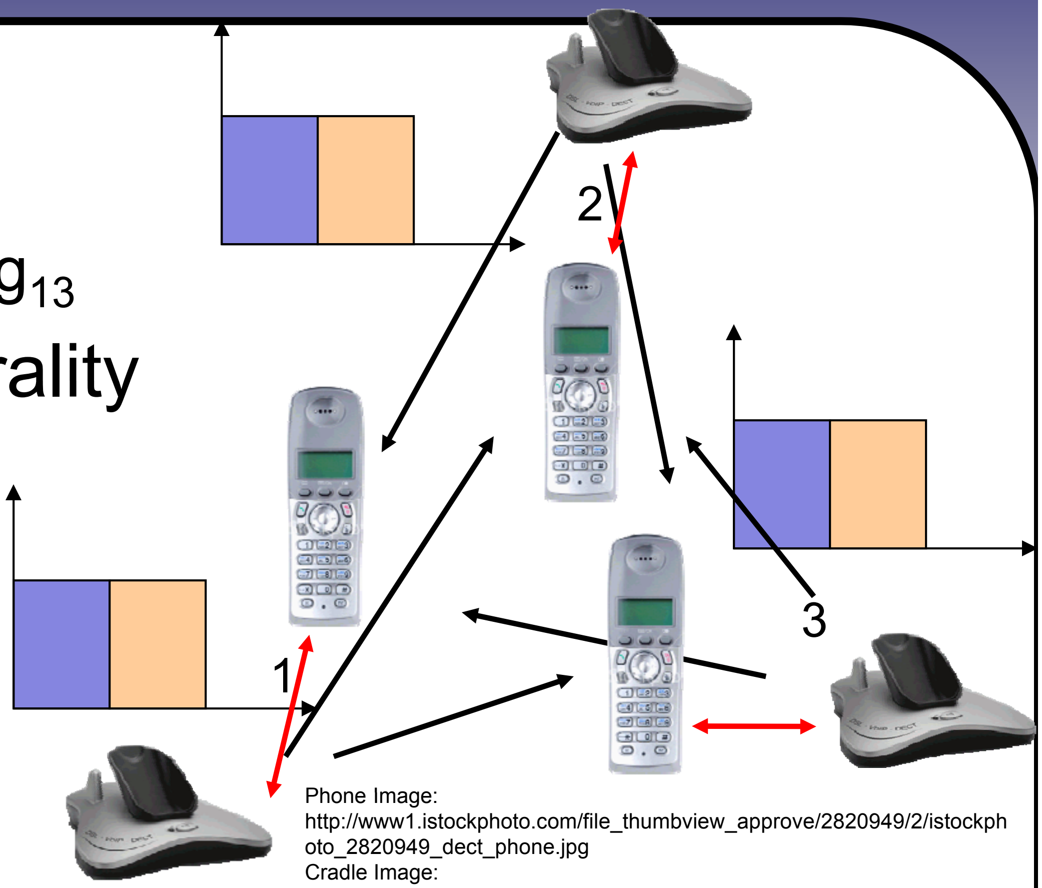
In heavily loaded networks, a single adaptation can spawn an infinite adaptation process

- 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,…



Phone Image:
http://www1.istockphoto.com/file_thumbview_approve/2820949/2/istockphoto_2820949_dect_phone.jpg
Cradle Image:
http://www.skypejournal.com/blog/archives/images/AVM_7170_D.jpg

Interference Characterization

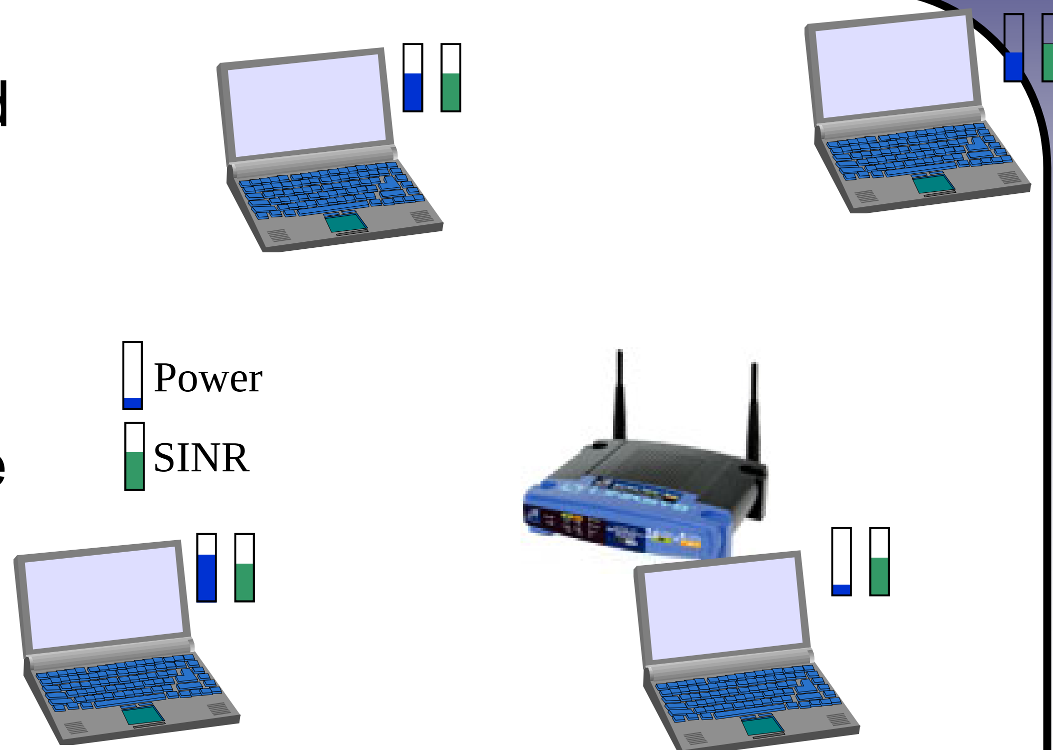
Chan.	(0,0,0)	(0,0,1)	(0,1,0)	(0,1,1)	(1,0,0)	(1,0,1)	(1,1,0)	(1,1,1)
Interf.	(1.5,1.5,1.5)	(0.5,1,0)	(1,0,0.5)	(0,0.5,1)	(0,0.5,1)	(1,0,0.5)	(0.5,1,0)	(1.5,1.5,1.5)
	0	1	2	3	4	5	6	7

Generalized Insights from the DECT Example

- If # links / clusters > # channels, decentralized channel choices will have a non-zero looping probability
- As # links / clusters $\rightarrow\infty$, looping probability goes to 1
  - 2 channels $p(loop) \geq 1-(3/4)^{{}^{n}C_{3}}$
  - k channels $p(loop) \geq 1-\left(1-2^{-k+1}\right)^{{}^{n}C_{k+1}}$
- 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
- 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

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12

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* $\tilde{u}_i\left(a^k\right) = \delta^k u_i\left(a^k\right)$
  - Expected value over all future stages

$$\widehat{u}_i\left(\left(a^k\right)\right) = \sum_{k=0}^{\infty} \delta^k u_i\left(a^k\right)$$

Stage 1

Γ	N	W
n	(9.6,9.6)	(3.2,21)
w	(21,3.2)	(7,7)

Stage 2

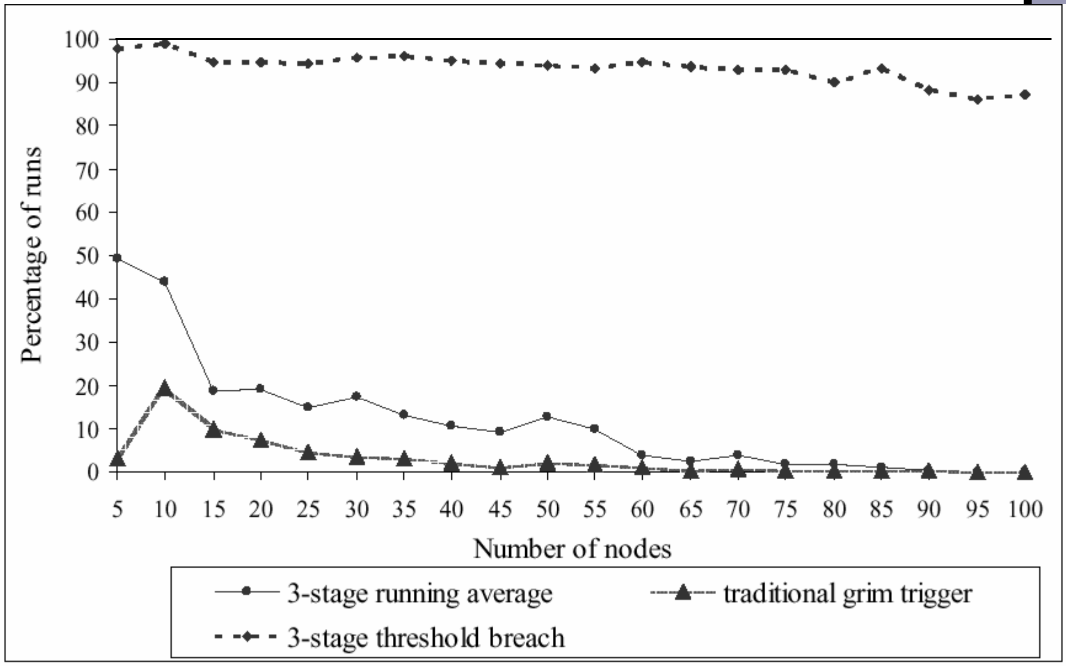
Γ	N	W
n	(9.6,9.6)	(3.2,21)
w	(21,3.2)	(7,7)

Stage *k*

Γ	N	W
n	(9.6,9.6)	(3.2,21)
w	(21,3.2)	(7,7)

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



V. Srivastava, L. DaSilva, "Equilibria for Node Participation in Ad Hoc Networks – An Imperfect Monitoring Approach," ICC 06, June 2006, vol 8, pp. 3850-3855

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

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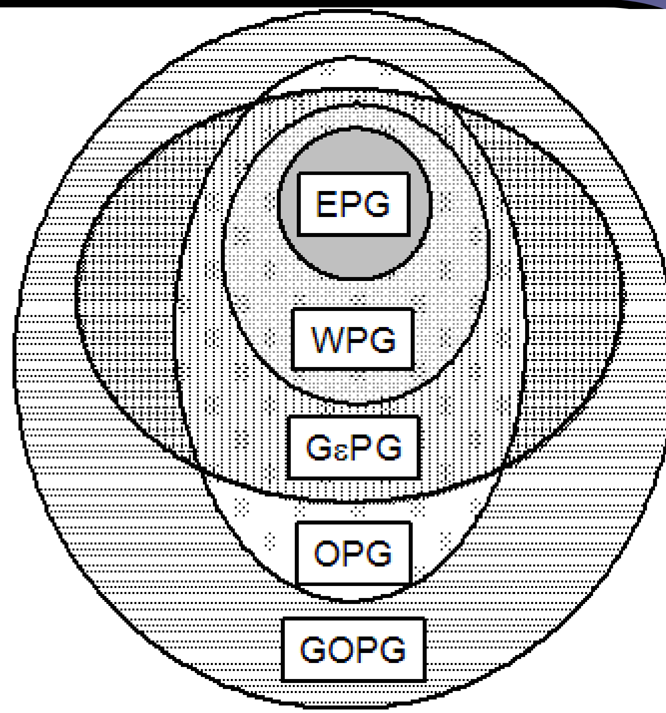
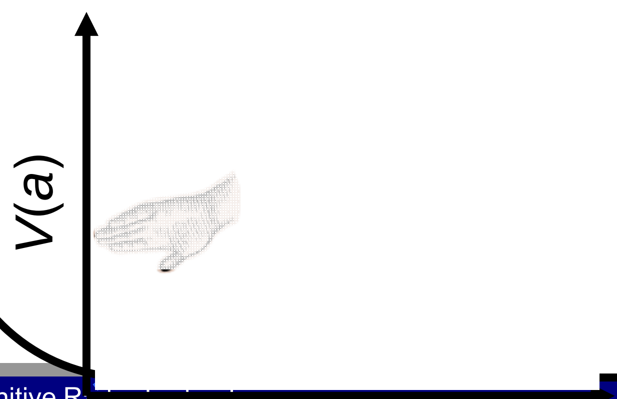
Potential Games

- 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.

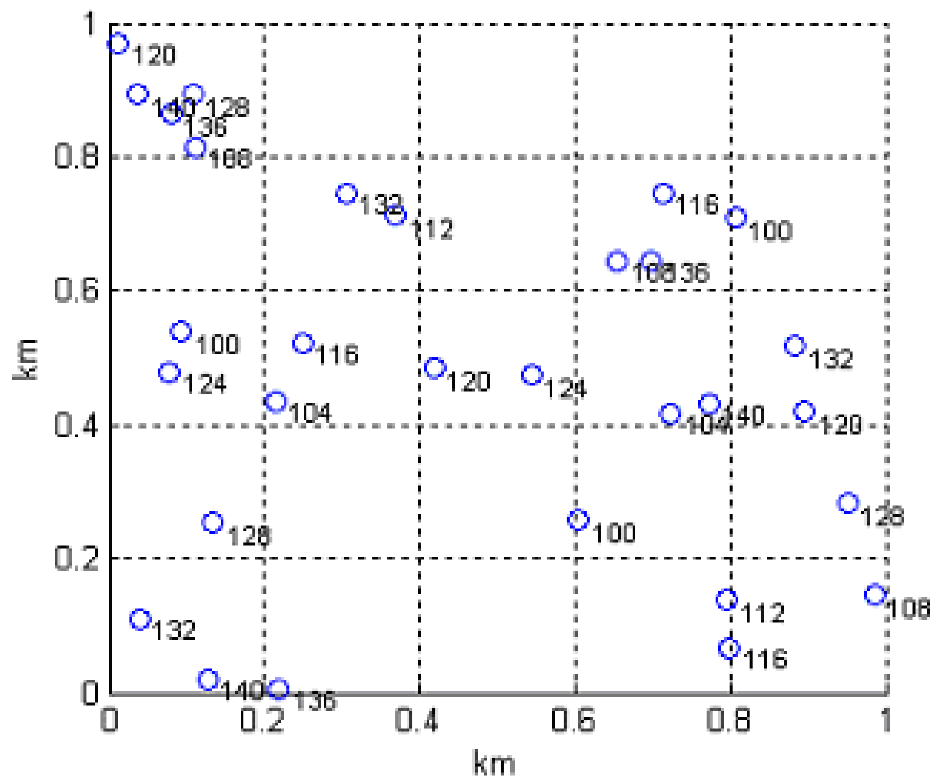


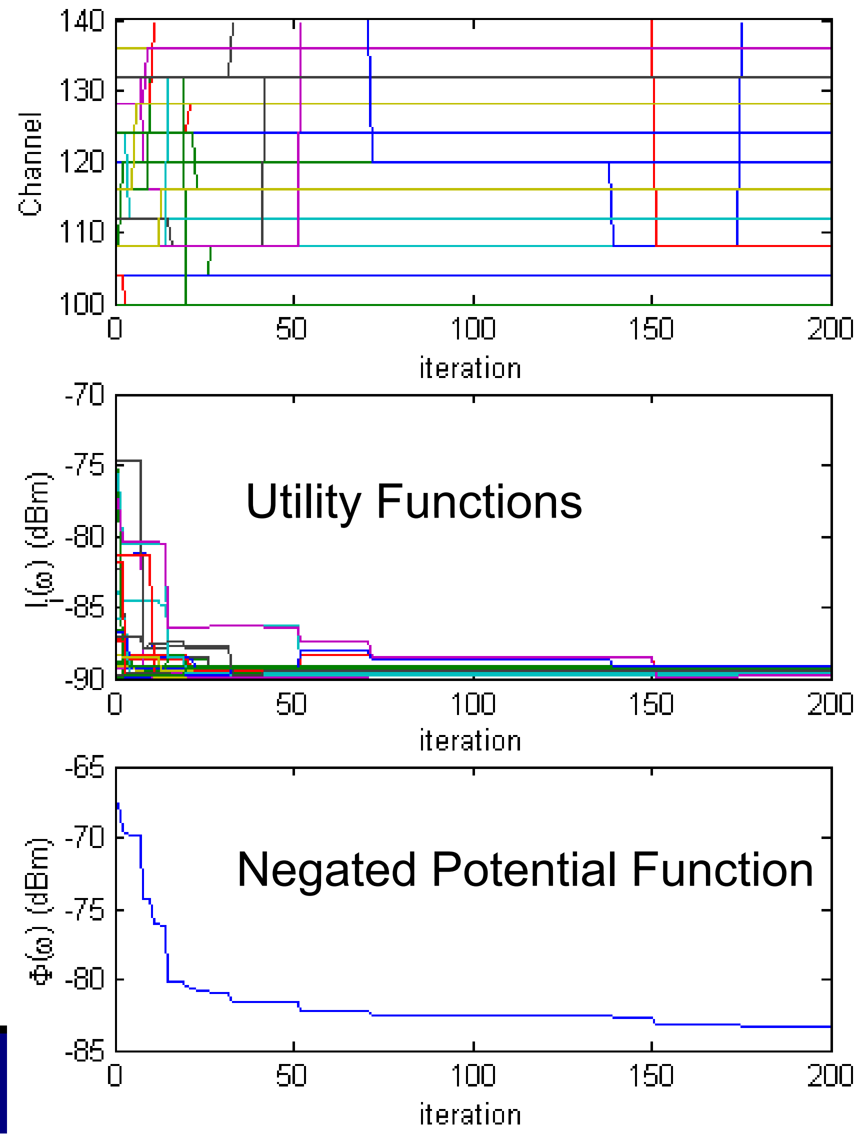


Potential Game	Relationship ($\forall i \in N, \forall a \in A$)
Exact (EPG)	$u_i(b_i,a_{-i}) - u_i(a_i,a_{-i}) = V(b_i,a_{-i}) - V(a_i,a_{-i})$
Weighted (WPG)	$u_i(b_i,a_{-i}) - u_i(a_i,a_{-i}) = \alpha_i\left[V(b_i,a_{-i}) - V(a_i,a_{-i})\right]$
Ordinal (OPG)	$u_i(b_i,a_{-i}) - u_i(a_i,a_{-i}) > 0 \Leftrightarrow V(b_i,a_{-i}) - V(a_i,a_{-i}) > 0$
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)	$u_i(b_i,a_{-i}) > u_i(a_i,a_{-i}) + \varepsilon_1 \Rightarrow V(b_i,a_{-i}) > V(a_i,a_{-i}) + \varepsilon_2$

A Dynamic Frequency Selection Algorithm

Final channels by access node





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”

	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)

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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

$$\text{Ⓐ} = \frac{\text{Performance of Centralized Algorithm Solution}}{\text{Performance of Distributed Algorithm Solution}}$$

$$\text{Ⓐ} \geq \mathbf{1}$$

- 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

Γ	N	W
n	(9.6,9.6)	(3.2,21)
w	(21,3.2)	(7,7)

$$\text{Ⓐ} = \frac{9.6}{7}$$

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

	a_2	b_2
a_1	1,1	-5,5
b_1	5,-5	-1,-1

	a_2	b_2
a_1	1,1	-5,5
b_1	5,-5	3, 3

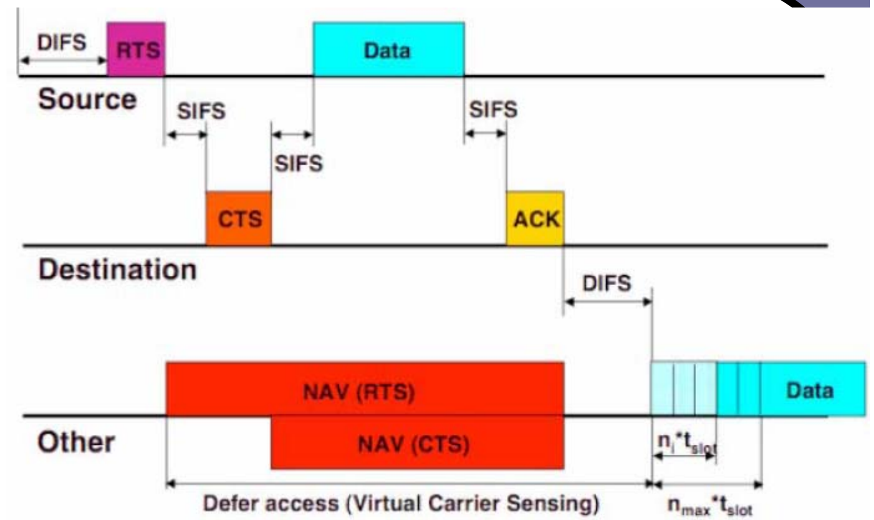
May have to leave some resources on the table for sensing or other applications

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

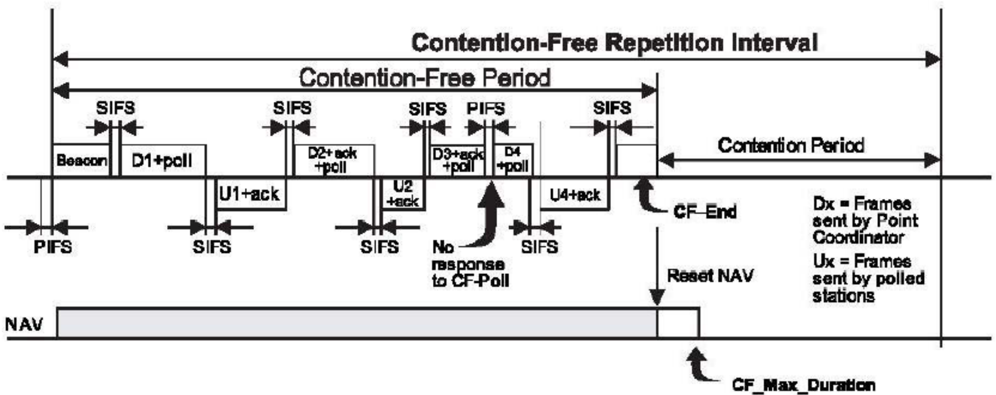


- Network allocation vector
  - Acts as virtual carrier sense
  - Duration given in RTS/CTS fields
- DIFS = DCF Interframe Space
- SIFS = Short Interframe Space

Example of a Polite Etiquette

Point Coordination Function (PCF)

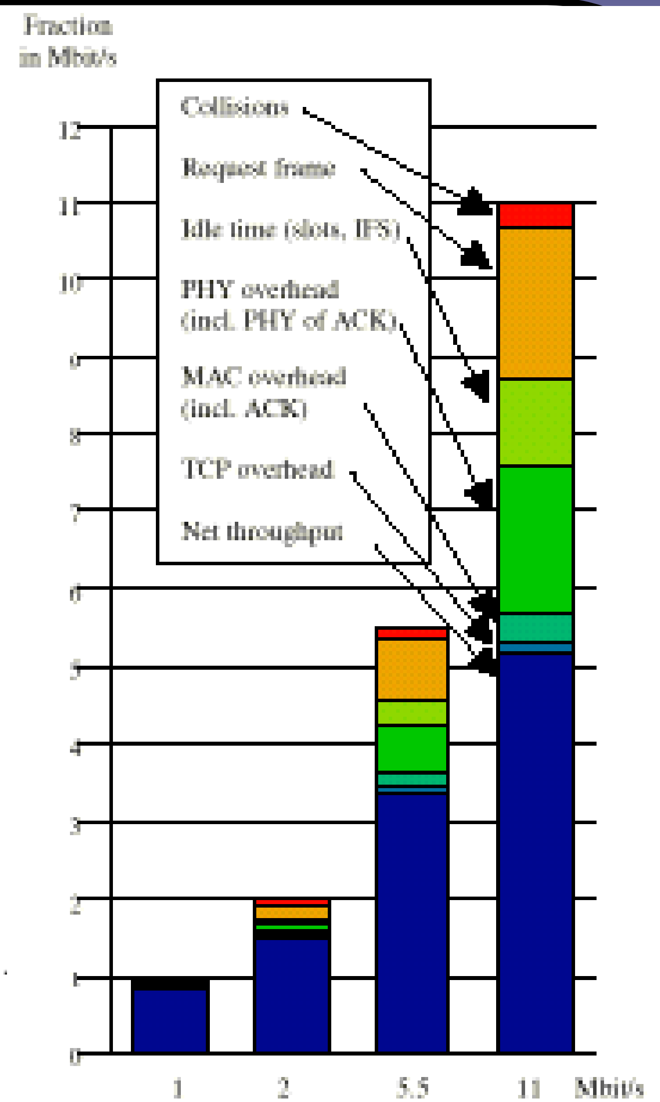
- Intended to provide service more appropriate for real-time applications
  – Not widely utilized initially

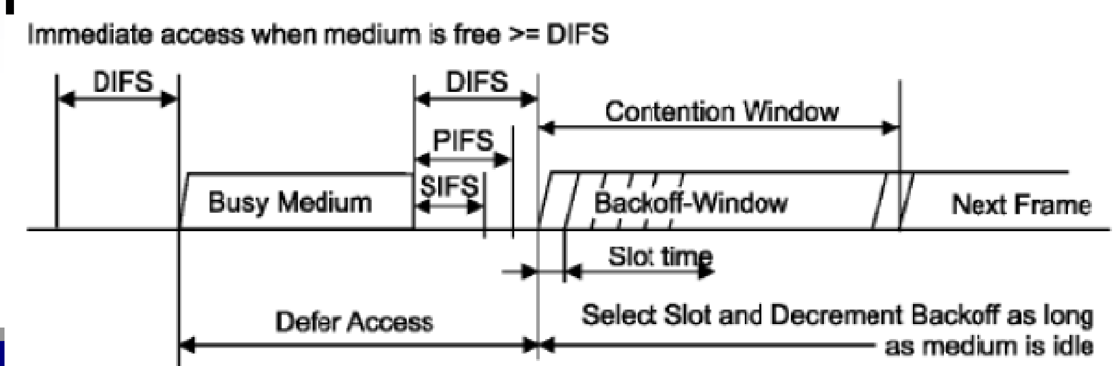


- Basic steps
  – Access node (AN) implementing PCF "wins" the channel by cheating (SIFS < PIFS < DIFS)
  – AN announces contention free period in Beacon (realized in NAV) to lock out DCF
  – Polls each client in its polling list
    - Frames separated by PIFS
    - If client fails to respond within 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 come close to PHY raw rate





http://www.ittc.ku.edu/~frost/EECS_563/Slides/Lecture4.pdf

wireless.ictp.trieste.it/school_2002/lectures/ermanno/System_Performance.ppt

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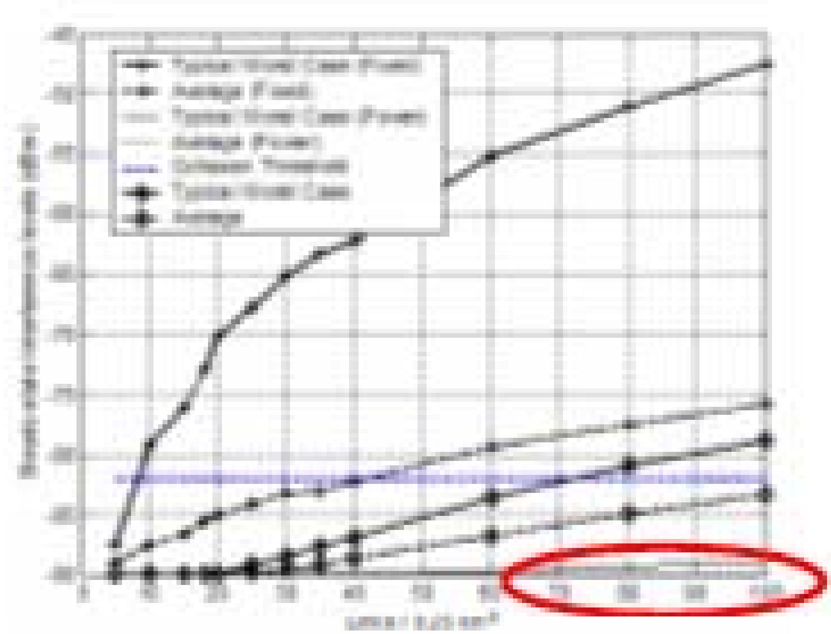
802.11h

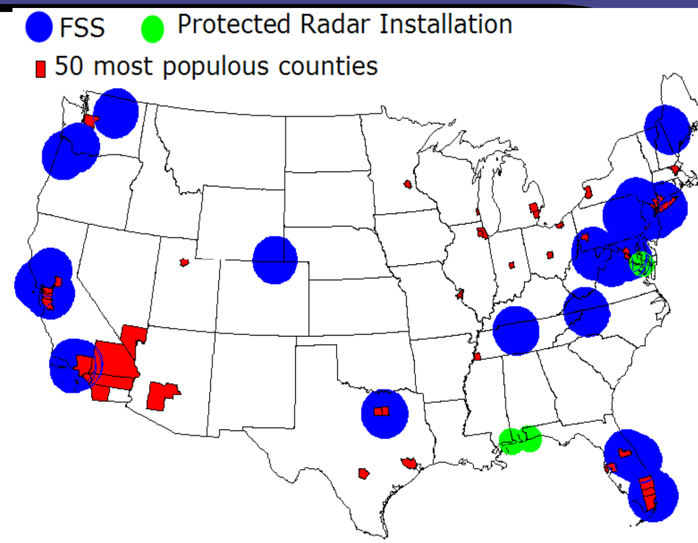
- Dynamic Frequency Selection (DFS)
  - Avoid radars
    - Listens and discontinues use of a channel if a radar is present
  - Uniform channel utilization
- Transmit Power Control (TPC)
  - Interference reduction
  - Range control
  - Power consumption Savings
  - Bounded by local regulatory conditions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

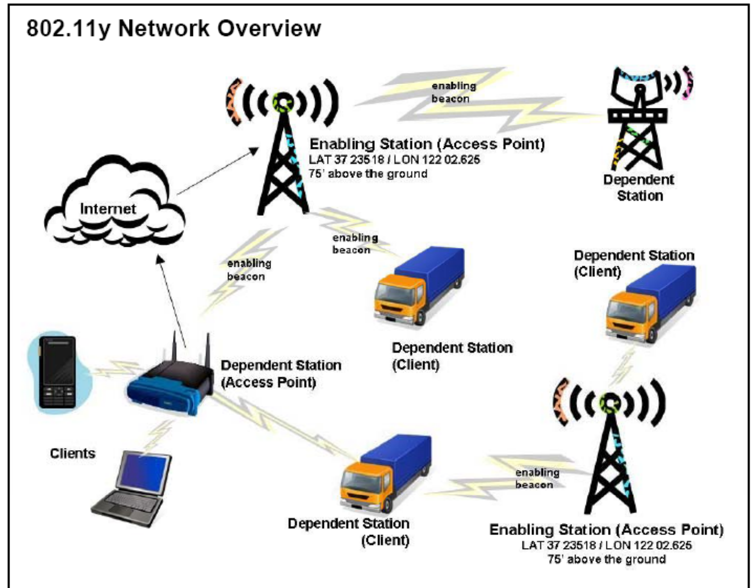


802.11y

- 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

Source: IEEE 802.11-06/0YYYr0



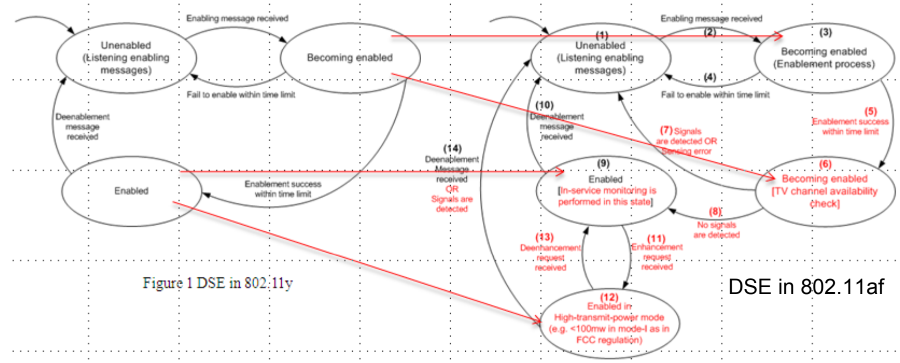


WiFi Alliance, "A New Regulatory and Technical Environment for Wireless Broadband: A Primer on the IEEE 802.11y Amendment,"

802.11af

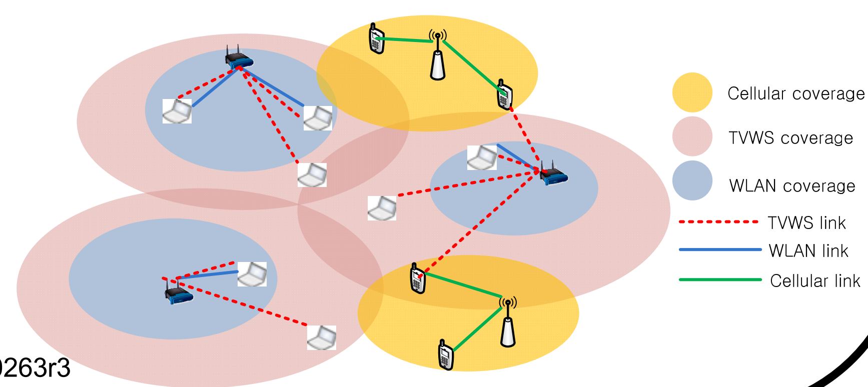
- Builds on 802.11y
  - DFS, TPC, quiet periods, policy enabling
  - Hope to be done in two years
  - Maybe only 15 pages…
  - Started in January 2010
- Multiband support
- Looking for techniques to speed up channel sensing
- Sharing MAP information

Building on 802.11y (Engagement State machi



IEEE 802.11-10/0261r0

Multi-band Concept



IEEE 802.11-10/0263r3

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

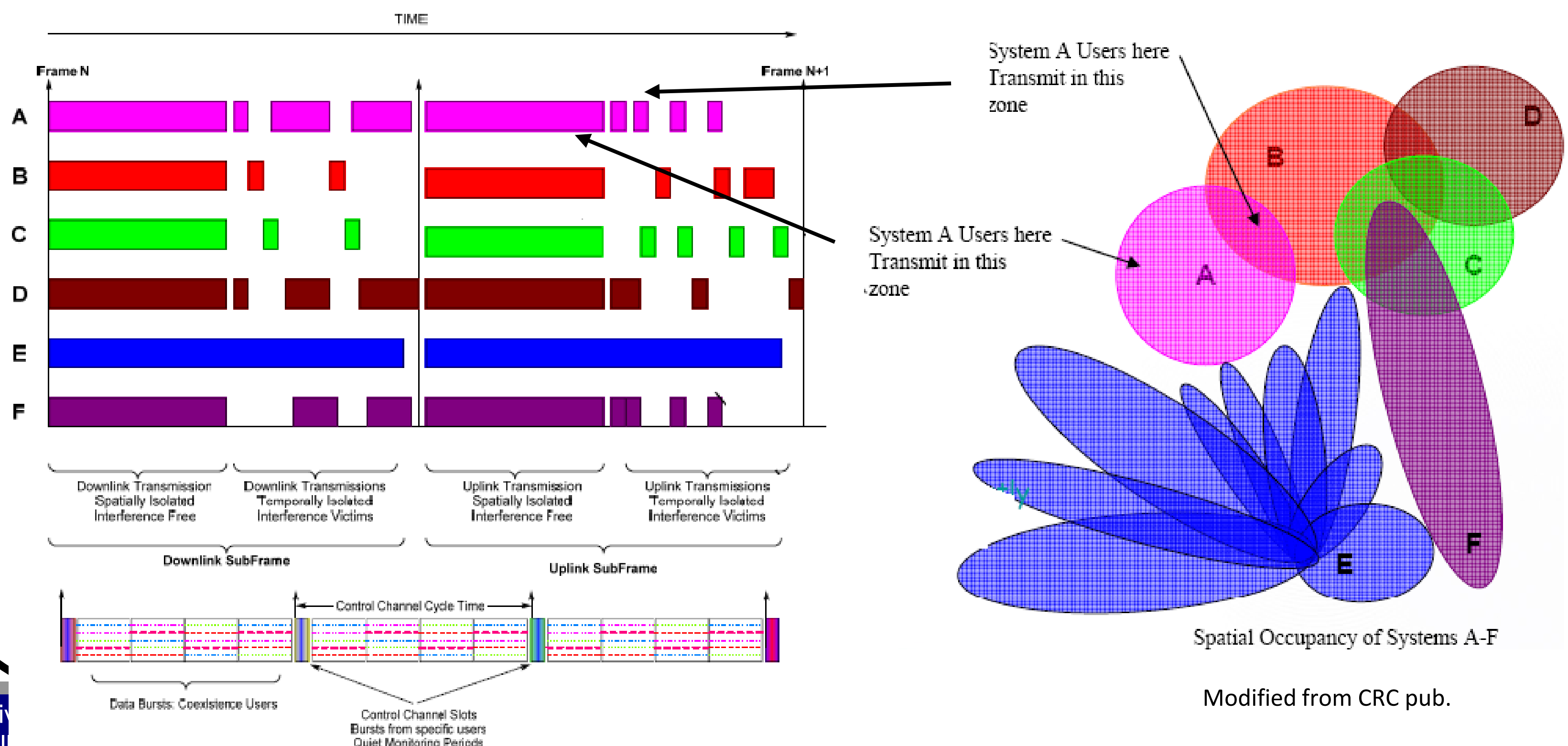
Cognitive Techniques in 802.16h

non-collaborative mechanism	*(CXCC:) dynamic frequency selection (DFS) *6.4.2.2*
	*(CXCC:) GPS timing recovery (GPS/UTC) *15.2.1*
	Extended quiet periods (EQP) *6.4.3.3*
	Adaptive EQP *6.4.3.4*
	Listen before talk *6.4.3.5*
	Uncoordinated Coexistence Protocol (UCP) *6.4.2.4*
collaborative mechanism	IP network message (CXP message) *15.5.2*
	coexistence proxy (CXPRX) *15.1.6*
	*(CXCC:) coexistence signaling (CSI/ radio signature) *15.3.1*
	*(CXCC:) coexistence messaging (CMI/CCD) *15.3.2*
	sub frame sharing (master sub frame) *15.4.2*
	channel reallocation (ACS) *15.4.1*
	Subframe Reallocation (ASFA) *15.4.2.2*
	credit token *15.4.2.5*

From: M. Goldhamer, "Main concepts of IEEE P802.16h / D1," Document Number: IEEE C802.16h-06/121r1, November 13-16, 2006.

Scheduling in 802.16h

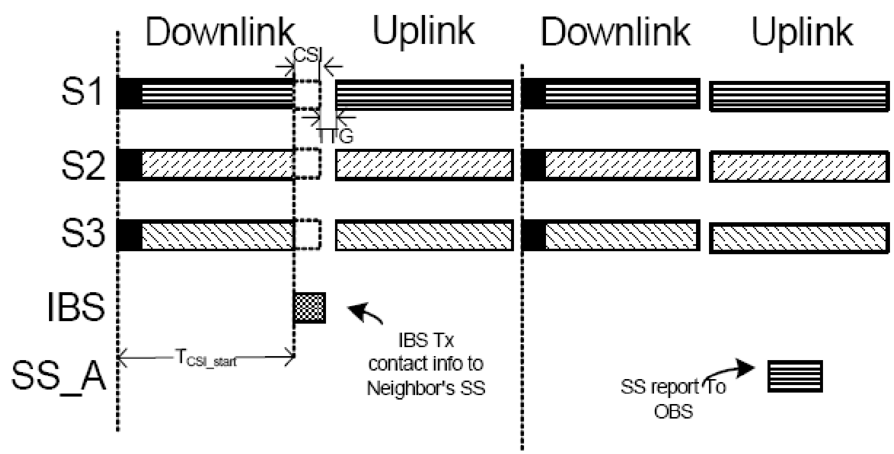
- Coordinate on times to deconflict users
  - “Interference free” operation
  - Fractional Time Reuse (my term)
  - Requires significant coordination and information awareness



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



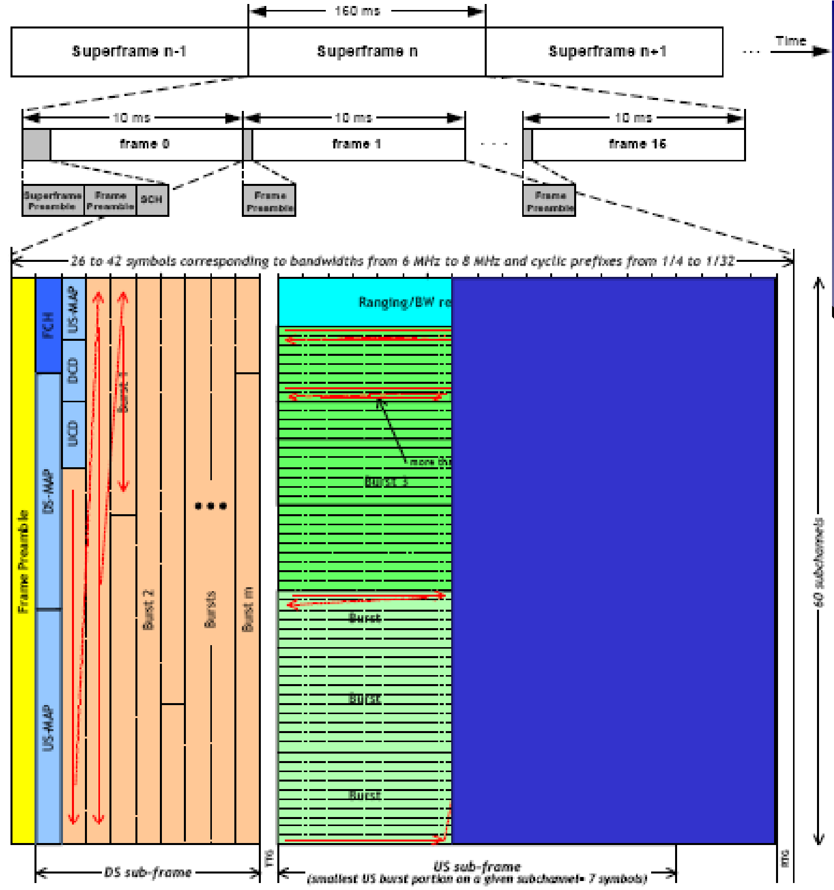
Note need for common time base

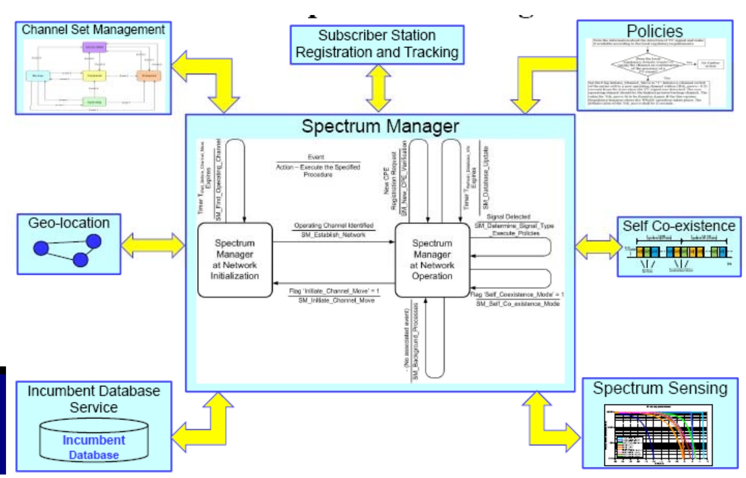
Collaboration

- 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

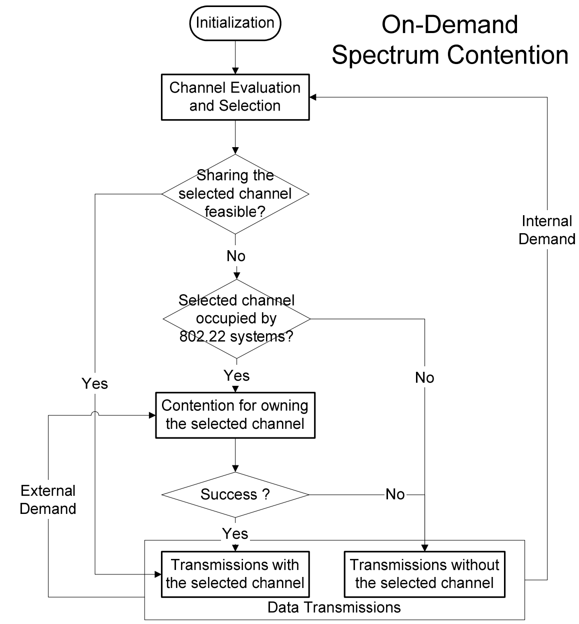


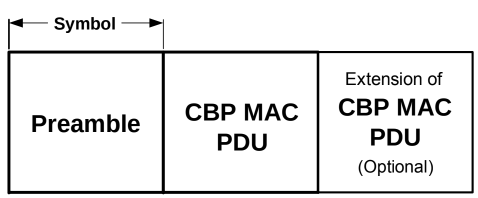


IEEE 802.22-10/0130r0

Contention / 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 **<u>every 15 min</u>**. as asked by R&O

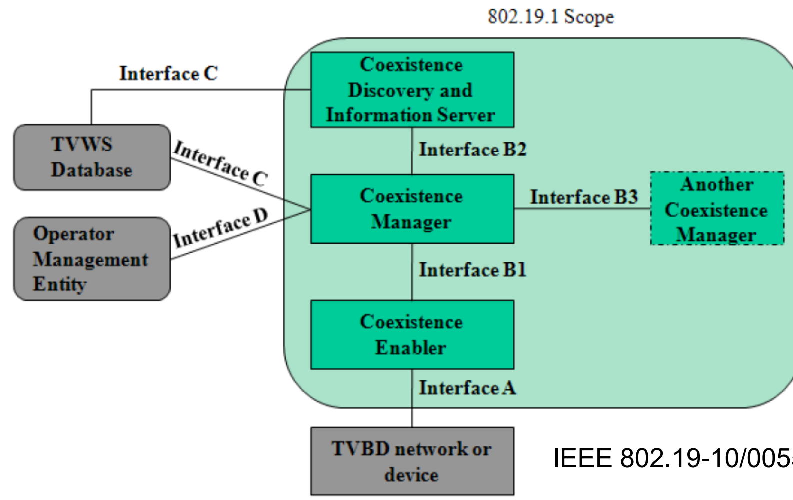




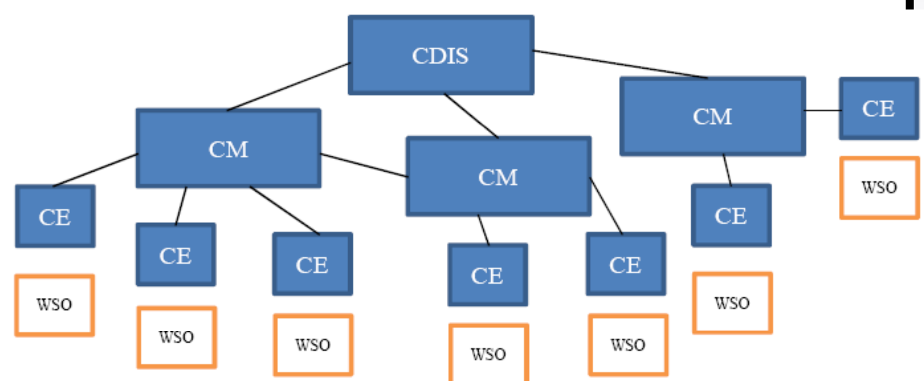
Coexistence Beacon Protocol (CBP) burst

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



IEEE 802.19-10/0055r3



IEEE 802.19-11/0144r3

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