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Cognitive Radios: Present and Future Directions

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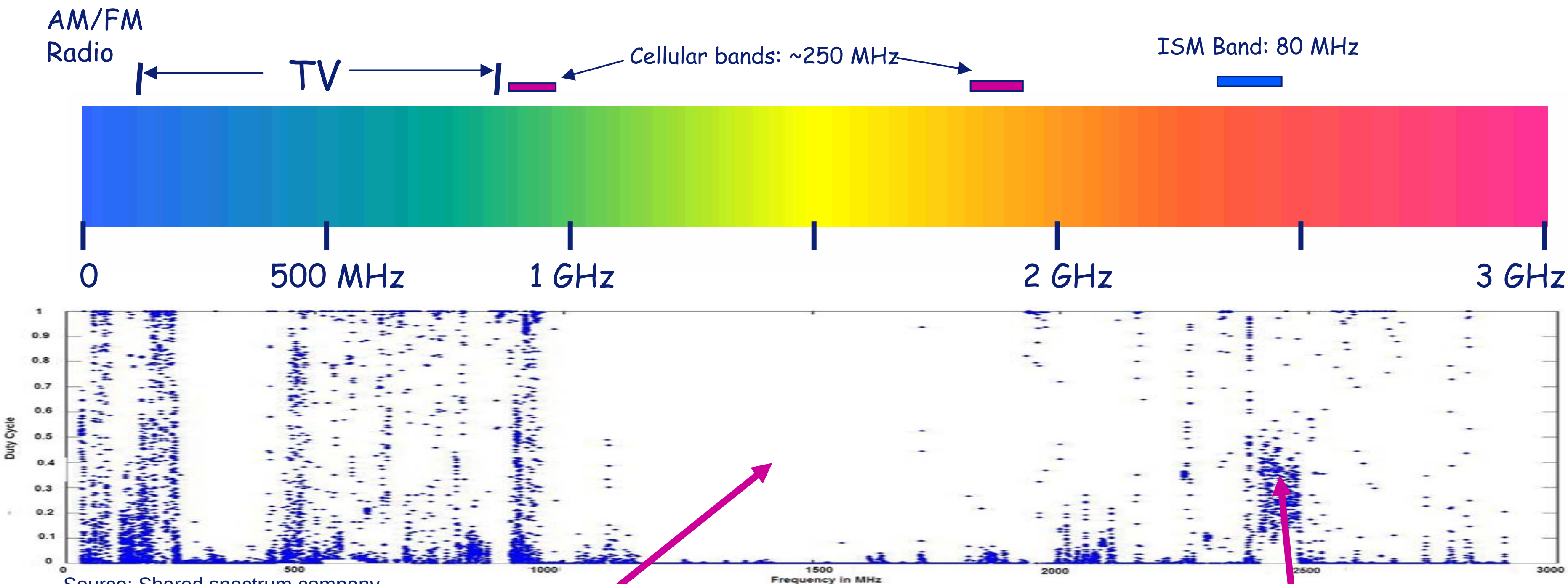
Motivation

Wireless industry ($12 Billion) from a small part of the spectrum



Source: Shared spectrum company

Most (85%-90%) of the spectrum is unused.

Evidence of overcrowding

*Cognitive Radios (CRs) can opportunistically use spectrum white space and increase usage by **10x***

Outline

- Spectrum usage today and tomorrow
- Cognitive radios demystified
- Application scenarios
- The IEEE 802.22 standard
  - Spectrum Sensing, PHY, and MAC
- Conclusions and future directions

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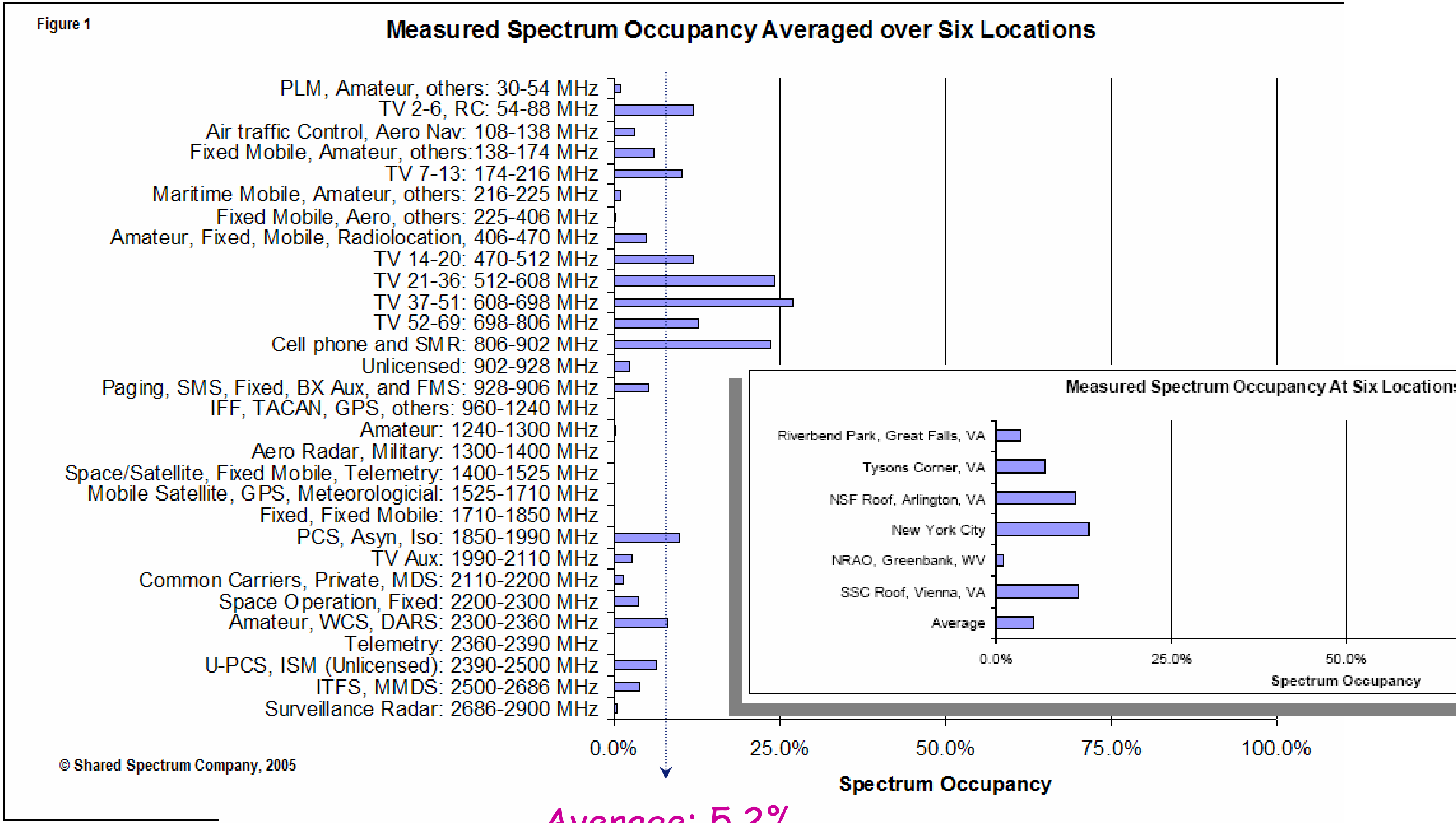
Spectrum usage today

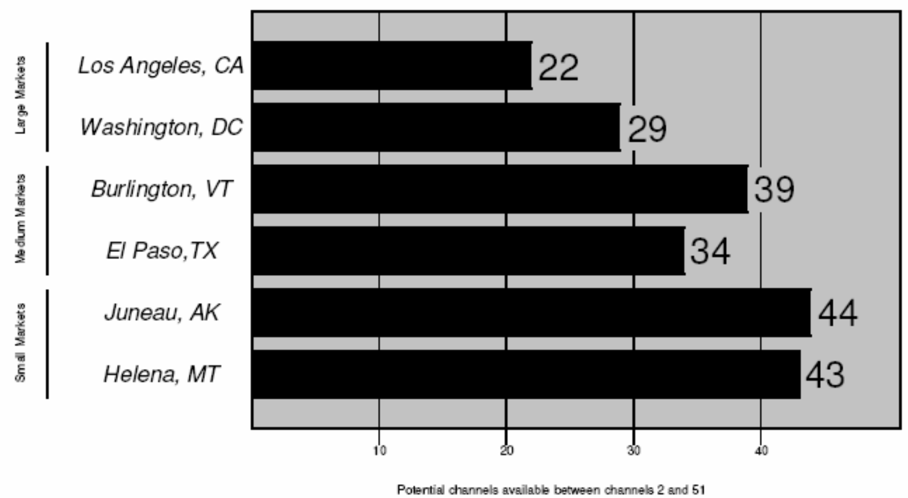


Average: 5.2%
(Average in New York City: 13.1%)

Trend: TV bands for unlicensed use

- FCC has issued an NPRM on opening TV bands for unlicensed use
  - TV bands only sparsely used today (see graphic)
- Fewer and fewer US households rely on over-the-air TV (from FCC report)
  - 33% in 1994
  - 15% in 2004
  - Among these, on average only a few channels watched
  - 0% in 2015??
- TV bands very suitable for long range, low power wireless networks

Potential Channels Available for Unlicensed Access*



Source: New America Foundation

Table 1: How U.S. TV Households Receive Televis 4[1]

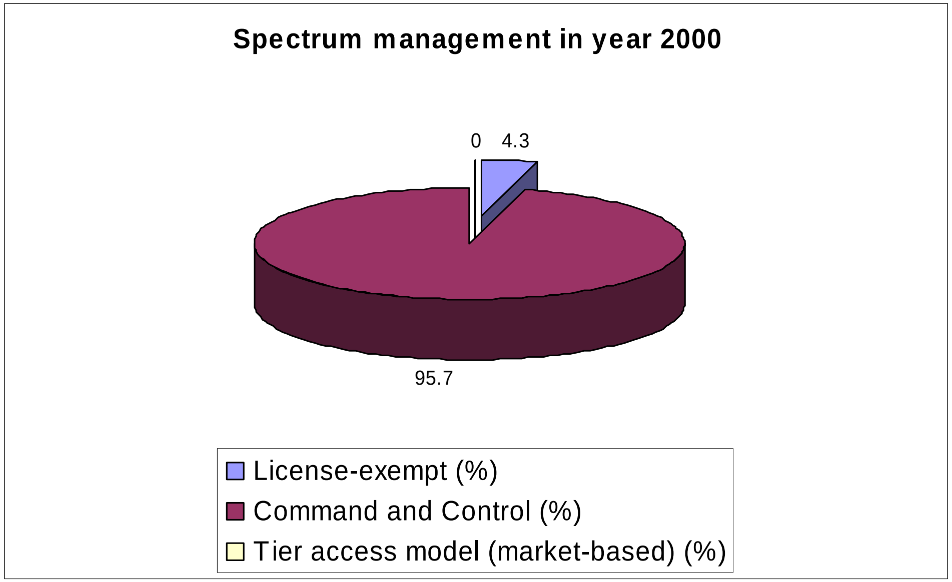
TV Households in the United States	Dec. 1994 (Millions)	Dec. 1994 (Share of All TV Households)	June 2004 (Millions)	15%	Change (%)
Over the Air Only	31.5	33%	16.1	85%	-48.9%
Total MVPD Subscribers*	63.9	67%	92.3		44.4%
Cable	59.7		66.1		
DBS	0.6		23.2		
Other	3.6		3.0		

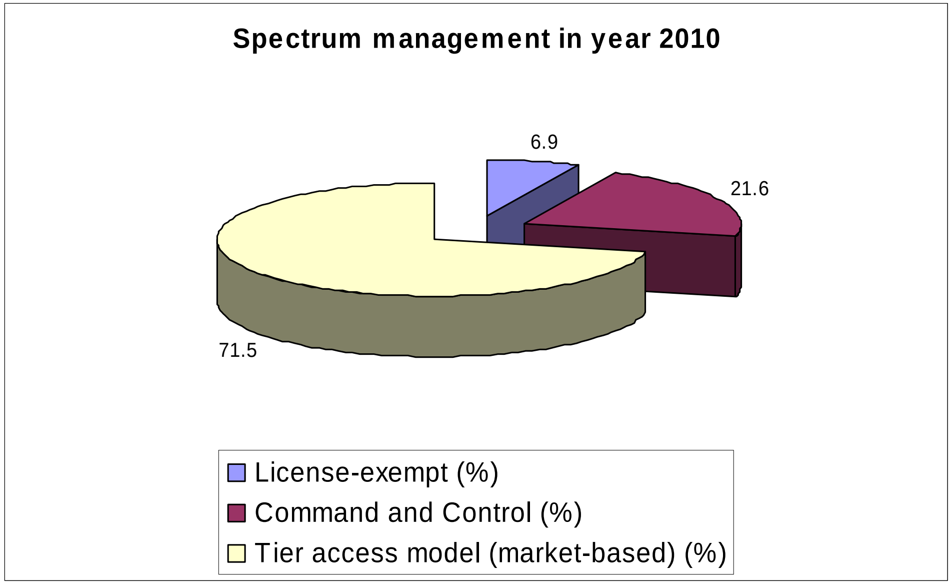
**MVPD = Multichannel Video Programming Distributors are Cable, DBS, and other services*

Source: **FCC.** Reported by New America Foundation

Spectrum usage tomorrow

- More "open spectrum", and hence more opportunities
- Opening up the TV bands is only the first step





Source: Ofcom

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Characteristics of cognitive/agile radios

Cognitive/agile radio =

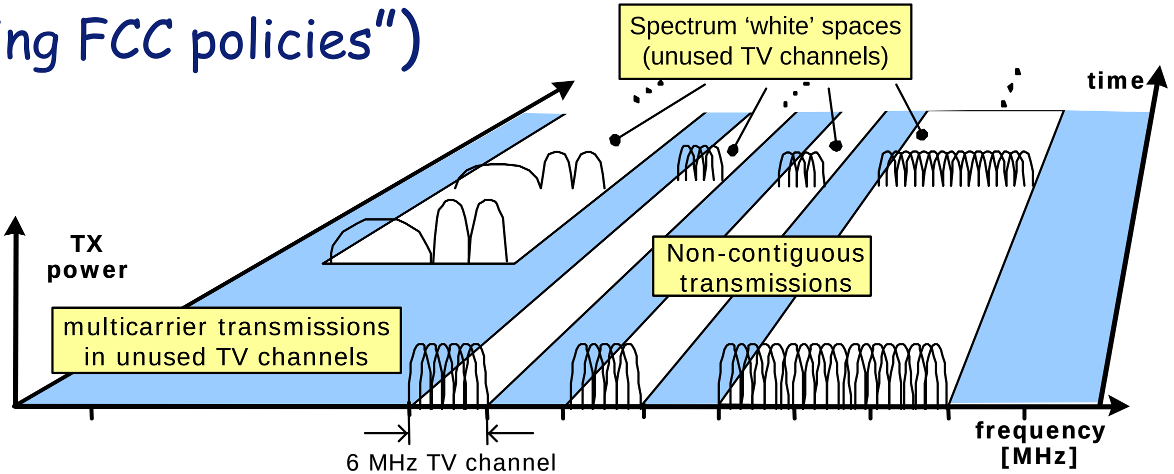
flexible re-configurable radio

("quickly adapts transmission characteristics")

+

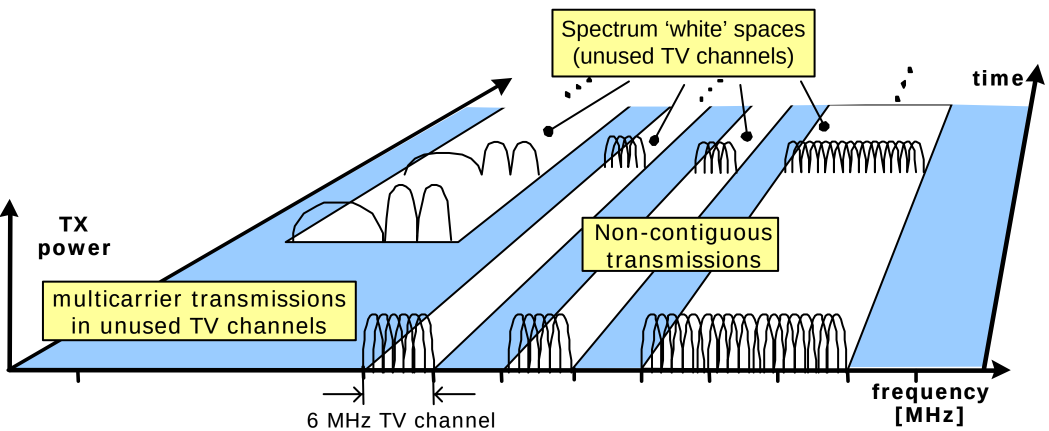
smart

("aware of spectrum usage in vicinity,
makes intelligent decisions on that basis, and
reacts to evolving FCC policies")

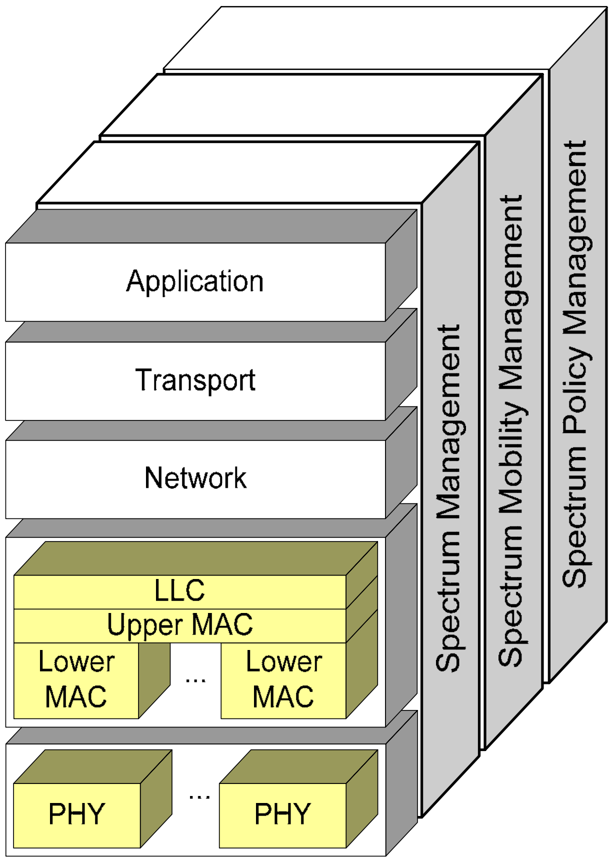


Architecture of a cognitive radio

- Requirement



- Architecture



Key goals of a cognitive radio

- The key goals of a CR is to enable:
  - Dynamic Spectrum Access (DSA)
    - Defined with respect to primary users
  - Dynamic Spectrum Sharing (DSS)
    - Defined with respect to other secondary users
  - Dynamic Spectrum Multi-Channel (DSM)
    - Must be spectrum-agile and provide (simultaneous) operation over multiple (non-)contiguous channels

- A number of architectural components are needed as to achieve these goals

Key goals of a cognitive radio (cont.)

Layer	Sublayer	DSA	DSA	DSS	DSS	DSM	DSM
Application		QoS requirements	User utility/Policy	QoS requirements	User utility/policy	QoS requirements	Multi-layer management
Transport		Spectrum handoff	Delay/Jitter/Loss	Inter-system and inter-flow communication	Delay/Jitter/Loss	Delay/Jitter/Loss	Multi-flow management
Transport				Spectrum Handoff			
Network		Spectrum aware routing	Policy	Load (node & radio resource) balancing	Interference aware routing	Multi-channel assignment	Multi-channel and multi-path routing
Network		Delay tolerant networking (DARPA DTN)	Topology management for distributed sensing				
Link	**LLC**	Radio environment characterization	Centralized (e.g., broker) or distributed (e.g., opportunistic)	Policy	Interference aware dynamic frequency selection	Multi-channel assignment	
Link	**LLC**	Policy	Interference temperature	Power control	Channel assignment		
Link	**LLC**	Power control	Dynamic frequency selection (if channel vacation)	Centralized (e.g., broker) or distributed (e.g., opportunistic)			
Link	**MAC**	Coordination of quiet periods	Spectrum sensing management	Space, time, and code division multiple access	(Non)-Coordinated resource sharing	(Non-) contiguous multi-channel operation	Inter-channel synchronization
Link	**MAC**	Directionality		Fairness	Directionality	Real-time and dynamic resource allocation	Multi-channel access
Physical		Spectrum sensing algorithms	Low SNR signal detection	Adaptive modulation and coding	Multiple antenna beamforming and beamnulling	Wideband antennas	ADC
Physical		Wideband or narrowband sensing	Multiple antenna beamforming and beamnulling	Waveform shaping	Spreading	Multicarrier modulation	Programmable filters
Physical		Beacon detection				Multiple antennas	Bandwidth (RF, BB) scalability

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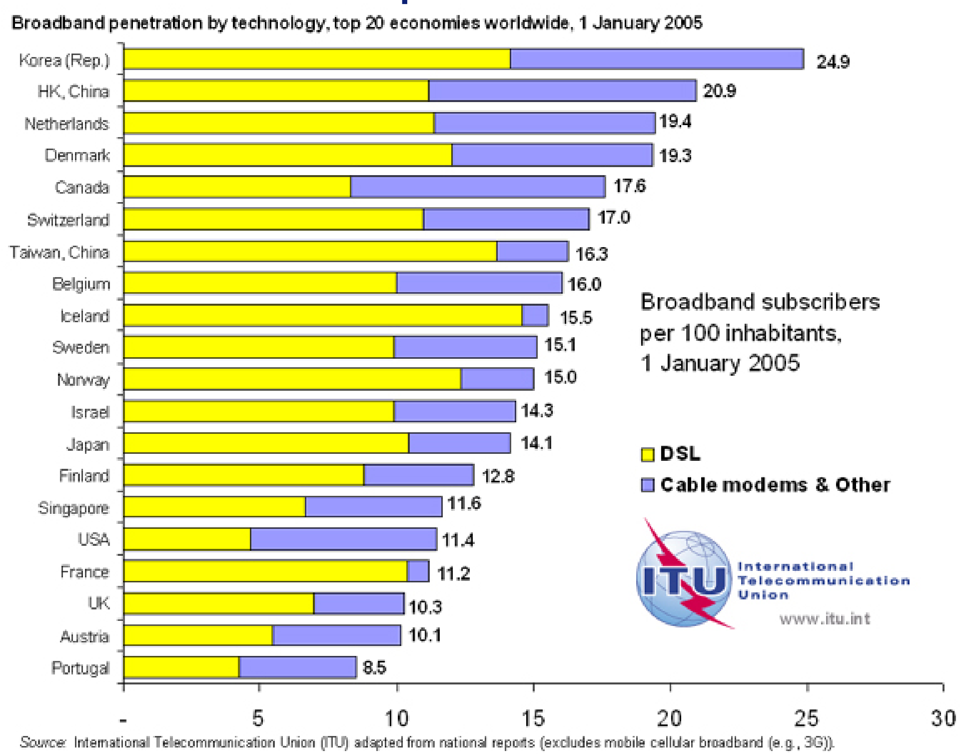
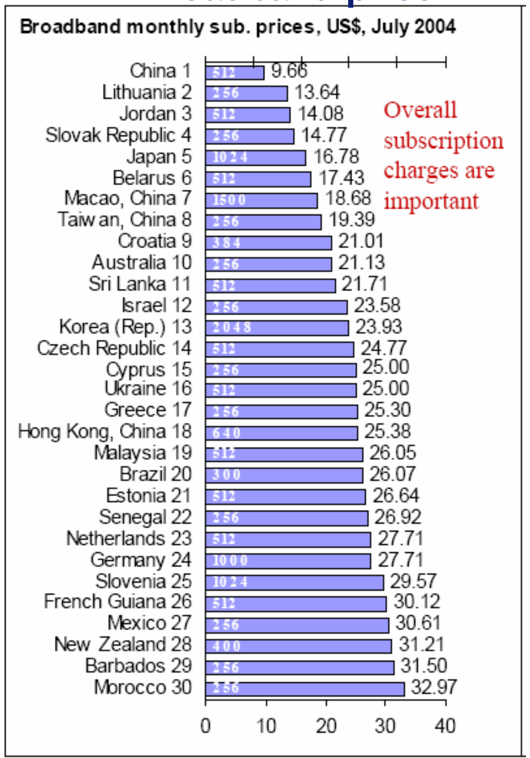
Wireless broadband (last-mile) access

- Although internet access is widespread, broadband is not
  - According to ITU, US is #16
  - High subscription charges
- Hurdles for broadband penetration
  - High infrastructure costs due to population density distribution
  - Lack of competition, bundling DSL/Cable services

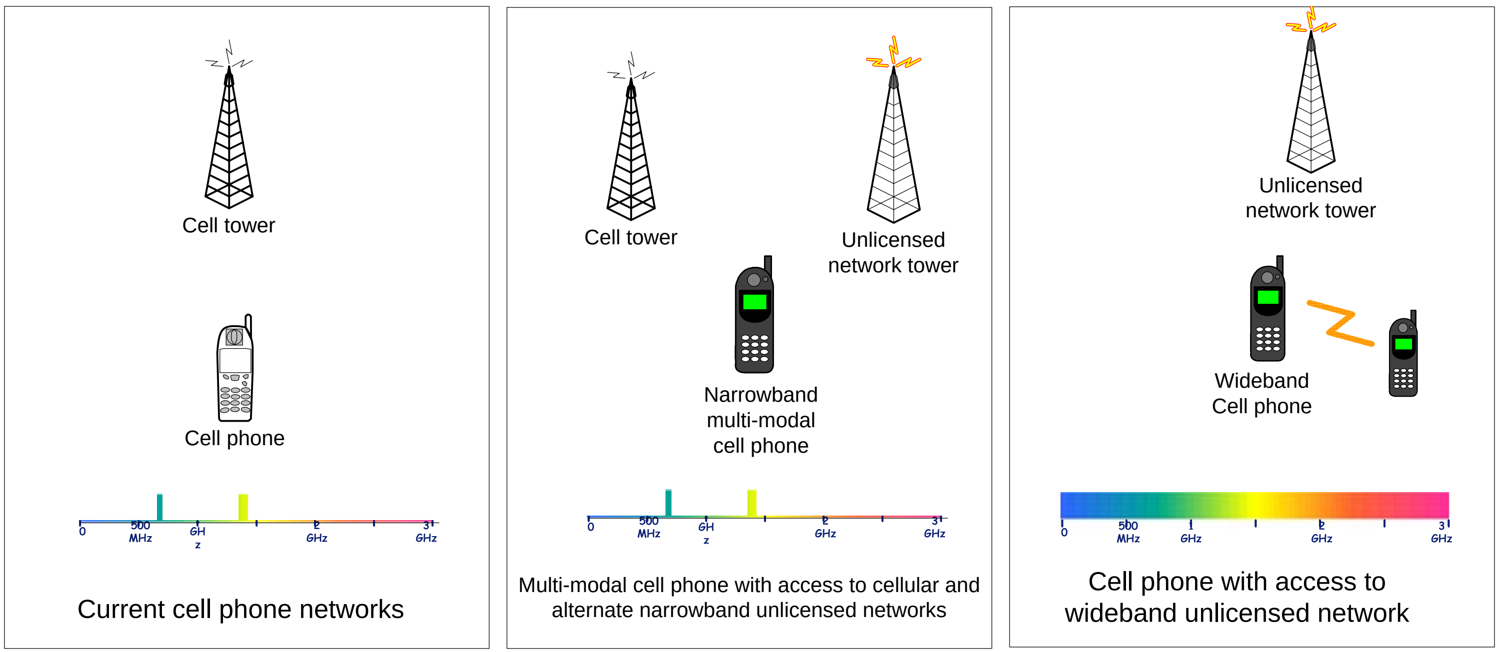
Broadband penetration



Broadband price



Application: Cellular service augmented with Agile Radio last-mile



Current *Near future* *Future?*

Yellow coverage by cellular service, blue by unlicensed last-mile service. The right panel (future) shows cell phones with wideband.

IEEE 802.22 WRAN WG Website - Microsoft Internet Explorer

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Address http://www.ieee802.org/22/ Go Links News Philips Agile Radio Traffic & Weather IEEExplore

IEEE 802 LAN/MAN Standards Committee
802.22 WG on WRANs (Wireless Regional Area Networks)

Documentation Requirements

Meeting

802.18 RR-TAG

802.19 Coexistence TAG

802.20 Wireless Mobility

802.21 Handover/Interoperability

802.22 WRAN Homepage

802.22 e-mail reflector

Webmaster: Carl Stevenson

Introduction

IEEE 802.22, the Working Group on Wireless Regional Area Networks ("WRANs") is the newest Working Group in the IEEE 802 LMSC.

Its charter, under the PAR approved by the IEEE-SA Standards Board is to develop a standard for a cognitive radio-based PHY/MAC/air_interface for use by license-exempt devices on a non-interfering basis in spectrum that is allocated to the TV Broadcast Service.

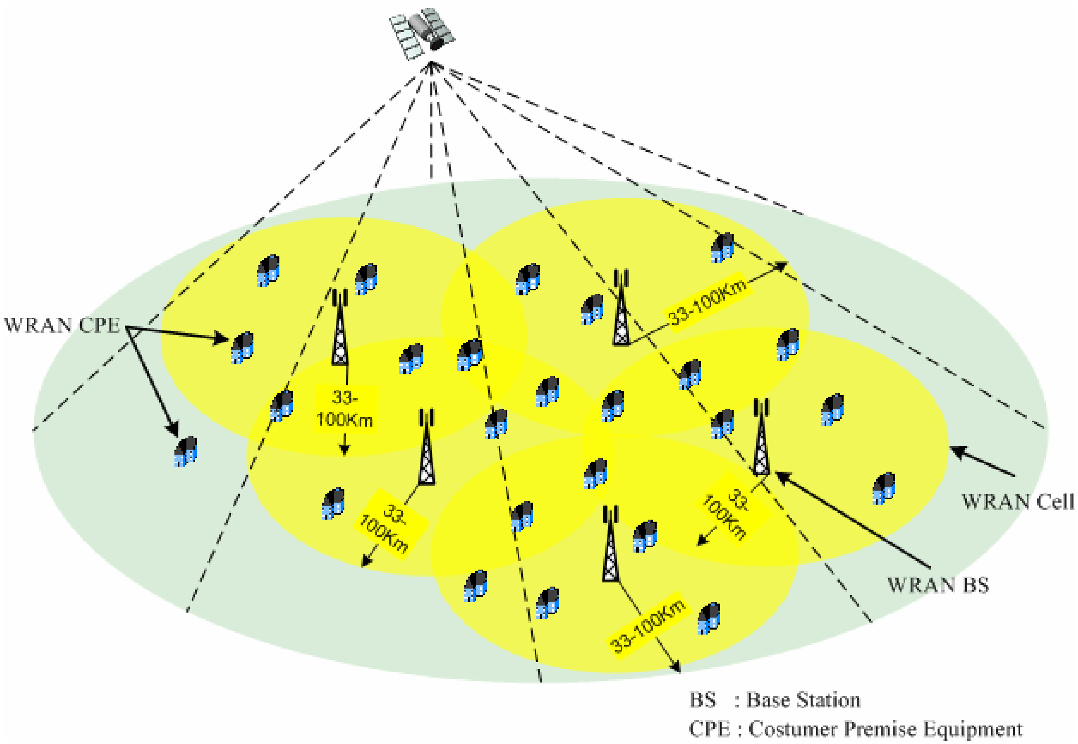
The IEEE 802.22 WG held its first meeting at the November 2004 IEEE 802 plenary in San Antonio, TX, where the PAR was reviewed, IEEE Patent Policies were explained, WG Policies and Procedures were approved, the WG elected officers, and a decision was made to hold the WG interims in conjunction with the joint wireless interim meetings of 802.11, 802.15, 802.18, 802.19, 802.20, and 802.21 (and 802.16 when they choose to join the other wireless WGs).

Since then, we've had an interim meeting session in Monterey, CA, in January 2005.

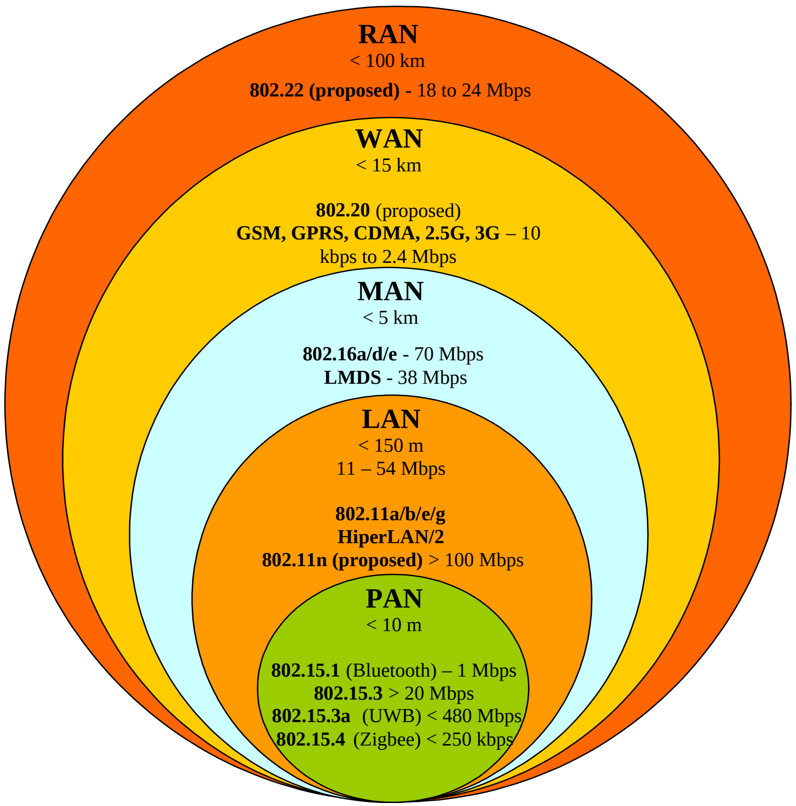
The next face-to-face meeting will be in conjunction with the IEEE 802 plenary in Atlanta, GA, in March.

Meeting documents will be posted, on a per meeting basis, on this website, as soon as possible after the conclusion of meetings, and will be available via an index under the

IEEE 802.22 WRAN



Exemplary 802.22 deployment configuration



802.22 wireless RAN classification as compared to other popular wireless standards

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IEEE 802.22

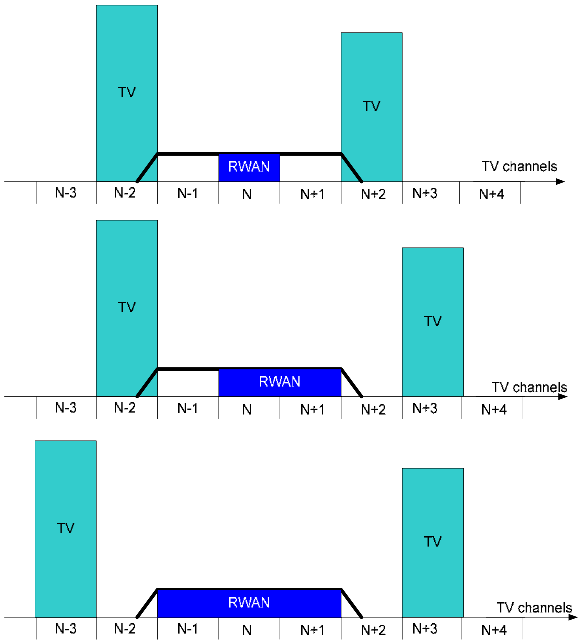
- IEEE 802.22 is the first worldwide cognitive radio based standard
  - Wireless broadband access
  - Reuse of TV broadcast bands on a non-interfering basis
- Draft standard version 0.1 is out
  - Version 1.0 is scheduled to be released in January/2007
  - Expected to become an official IEEE standard in January/2008
- Coexistence is key requirement
  - Primary sharing (e.g., NTSC, DTV)
  - Secondary sharing (e.g., with 802.22 itself)

Coexistence

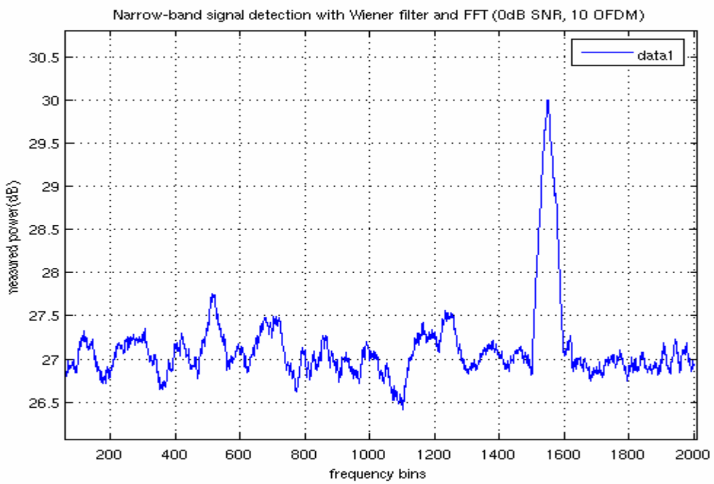
- Two primary types
  - With incumbents (TV service and Part 74 devices)
  - With other overlapping similar networks
    - Self-Coexistence
- Measurements and Channel Management are key
  - Flexibility and efficiency is very important
- Coexistence is achieved by a joint application of:
  - PHY
    - Spectrum sensing, suitable modulation, coding, etc.
  - MAC
    - Spectrum management (frequency and power)
    - "Interference-free" traffic scheduling (time)

PHY Layer

- Some PHY issues
  - Quick and robust detection
  - Dynamic bonding of contiguous TV channels
  - Flexible modulation scheme
    - Spectrum sharing using (Spread) OFDMA



- DTV detection
  - Based on energy, matched filter, and feature detection
- Wireless microphones
  - Based on spectral estimation and statistics of the estimated signal



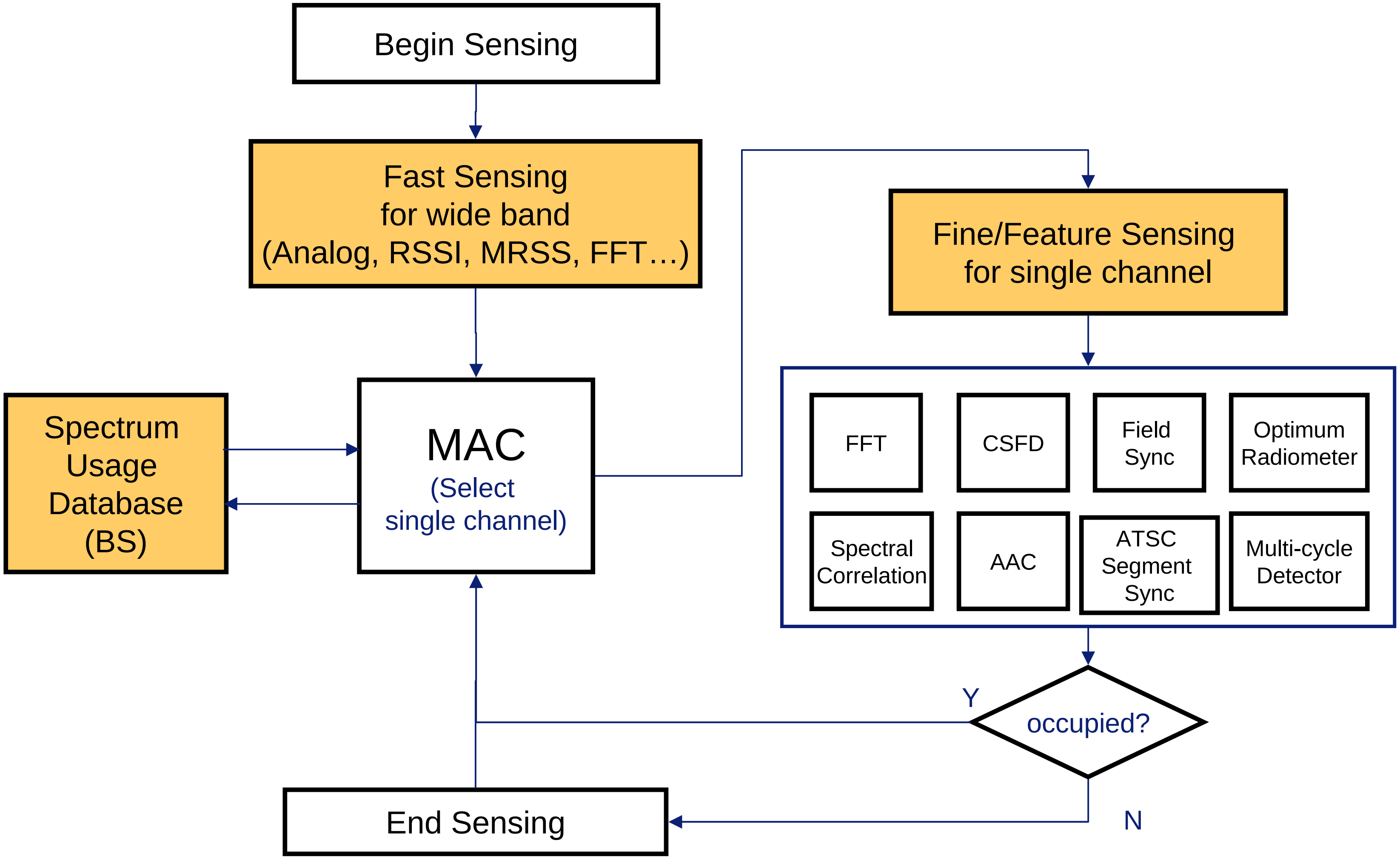
PHY Layer: Sensing

- Key incumbent sensing requirements

Parameter	Value for Wireless Microphones	Value for TV Broadcasting
Channel Detection Time	≤ 2 sec	≤ 2 sec
Channel Move Time (In-service monitoring)	2 sec	2 sec
Channel Closing Transmission Time	100 msec	100 msec
Incumbent Detection Threshold	-107 dBm (over 200KHz)	-116 dBm (over 6MHz)

- Need to detect weak signals (negative SNR)

PHY Layer: Sensing



Experimental setup for DTV detection

8VSB_SOURCE

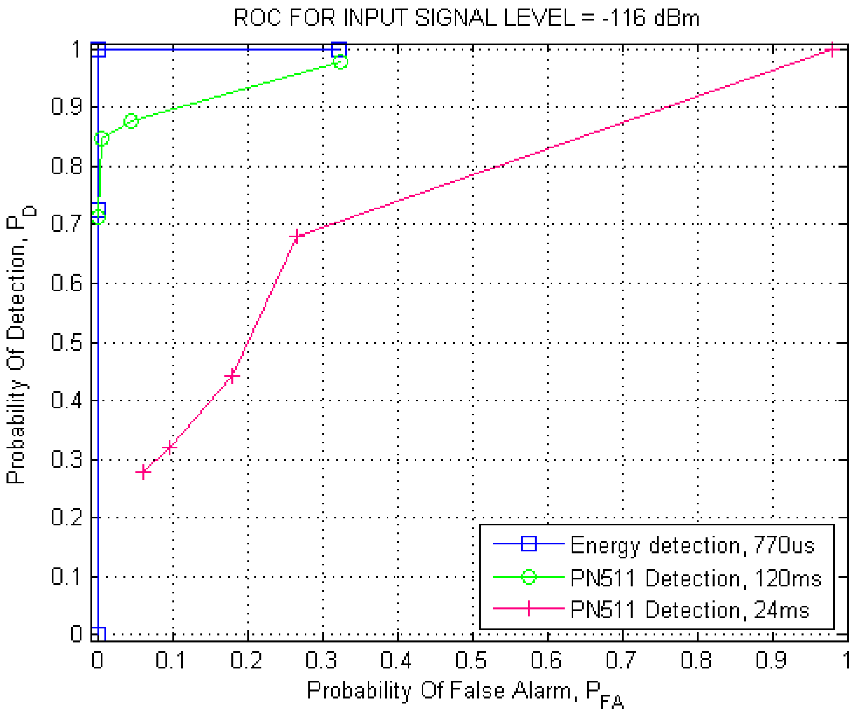
MULTIPATH SIMULATOR

ATTENUATOR

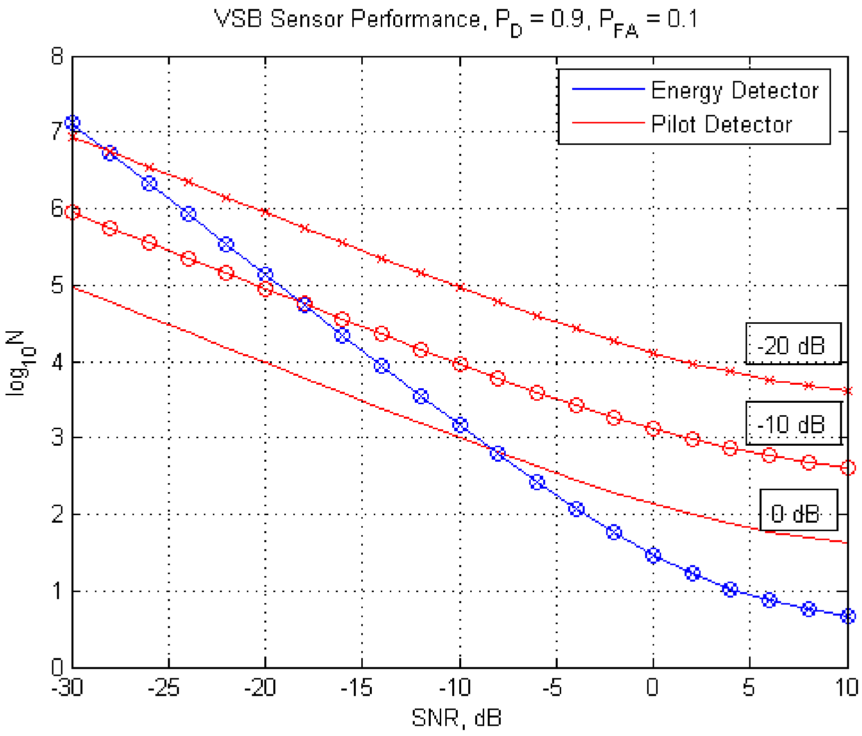
RECEIVER

Experimental results

- Energy detection vs. feature detection

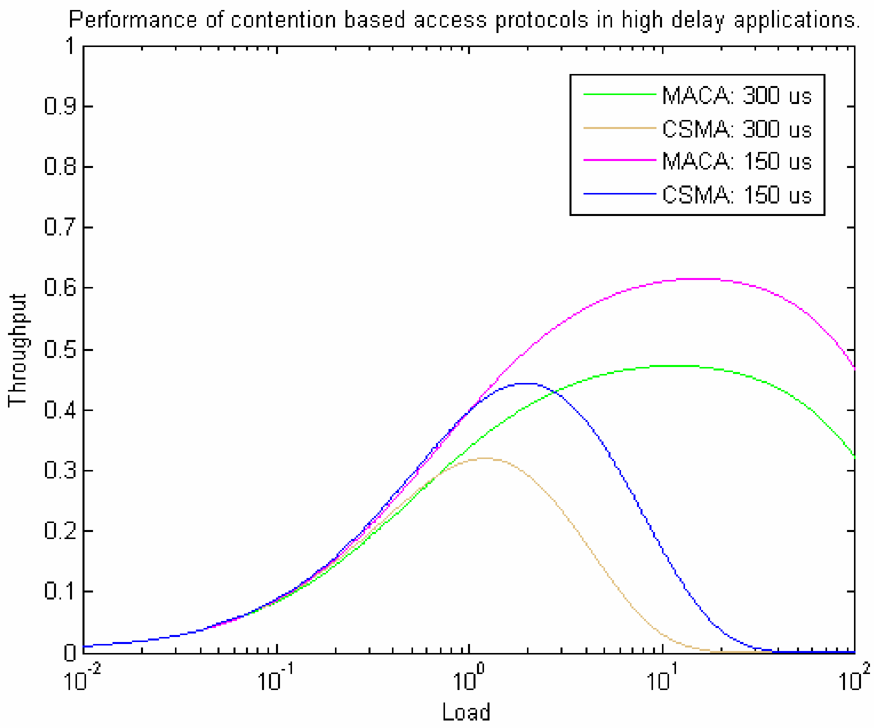


- Energy detection: full bandwidth vs. pilot



MAC Layer

- Demand assigned multiple access TDMA MAC
- Some MAC Issues
  - Data communication
    - Superframe and Frame Structures
    - Network entry and initialization
  - Coexistence
    - Incumbents
    - Self-Coexistence
    - Clustering
    - Synchronization

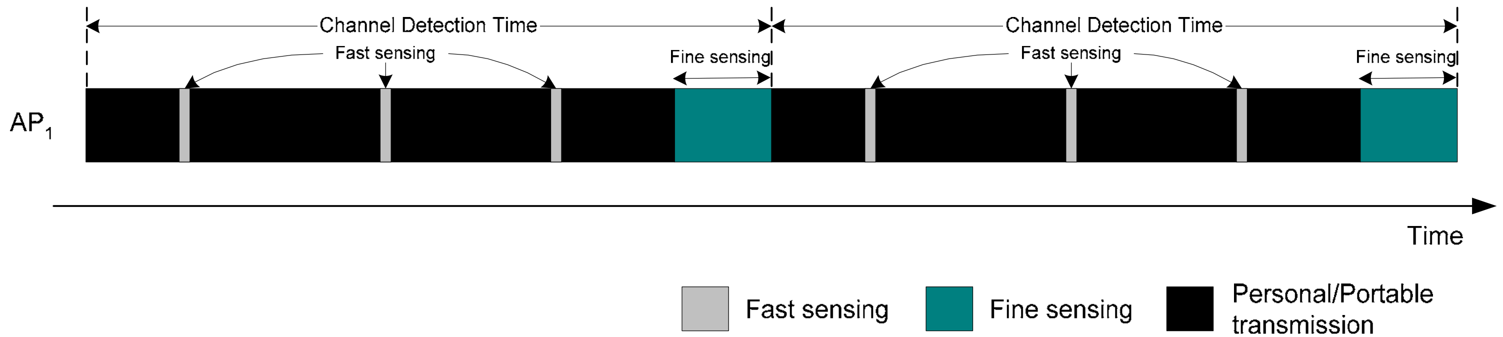


MAC Layer: Sensing

- Background
  - A potentially very large number of channels have to be periodically sensed for the presence of incumbents
  - At the same time, support to QoS traffic requires delays as low as 20ms
- Question
  - How is sensing done as to meet these requirements?
- Answer
  - Two-stage spectrum sensing (TSS) mechanism
    - Stage 1: Fast sensing (e.g., energy detection)
    - Stage 2: Only if needed, perform fine sensing (e.g., feature detection)

MAC Layer: Sensing

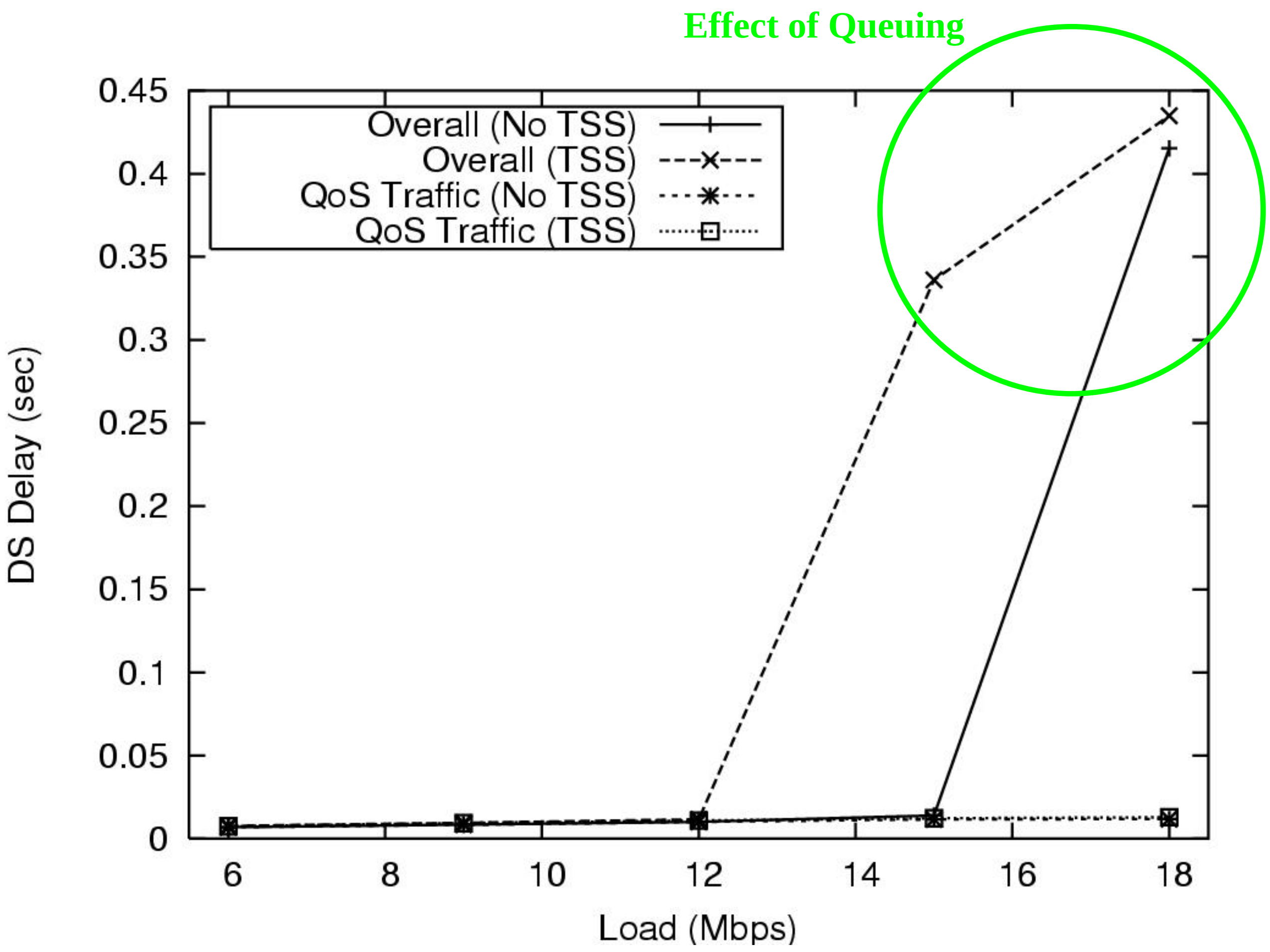
- Quiet period structure of TSS



- The fast sensing is performed in-band only
  - May or may not be scheduled
  - Consolidated reports on the fast sensing outcome is sent to moderator
  - Moderator then determines the need for the next fine sensing and how much time is required

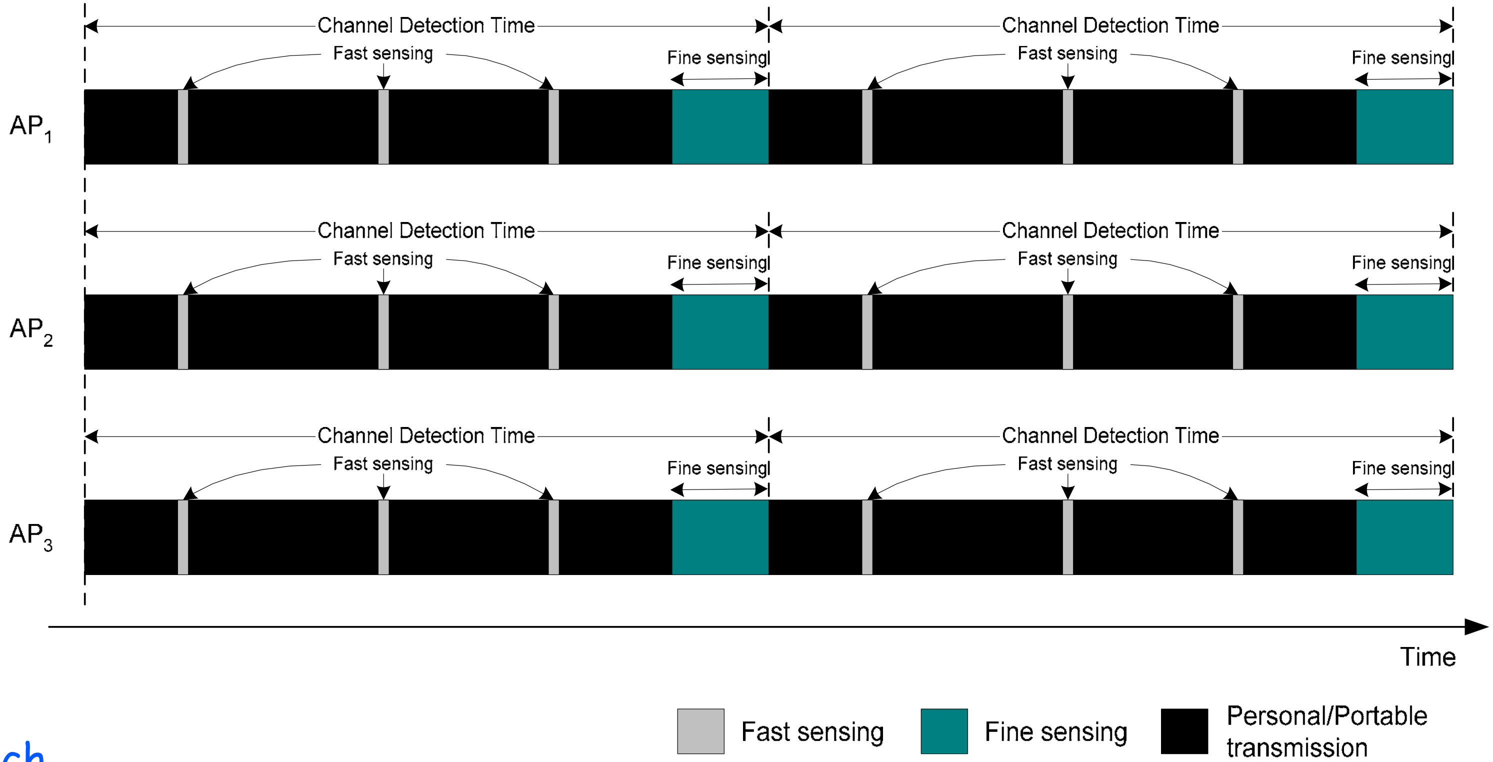
Impact on QoS

- The overall impact of TSS on downstream delay is negligible
  - QoS can still be satisfied
- A similar conclusion can be obtained for the upstream delay



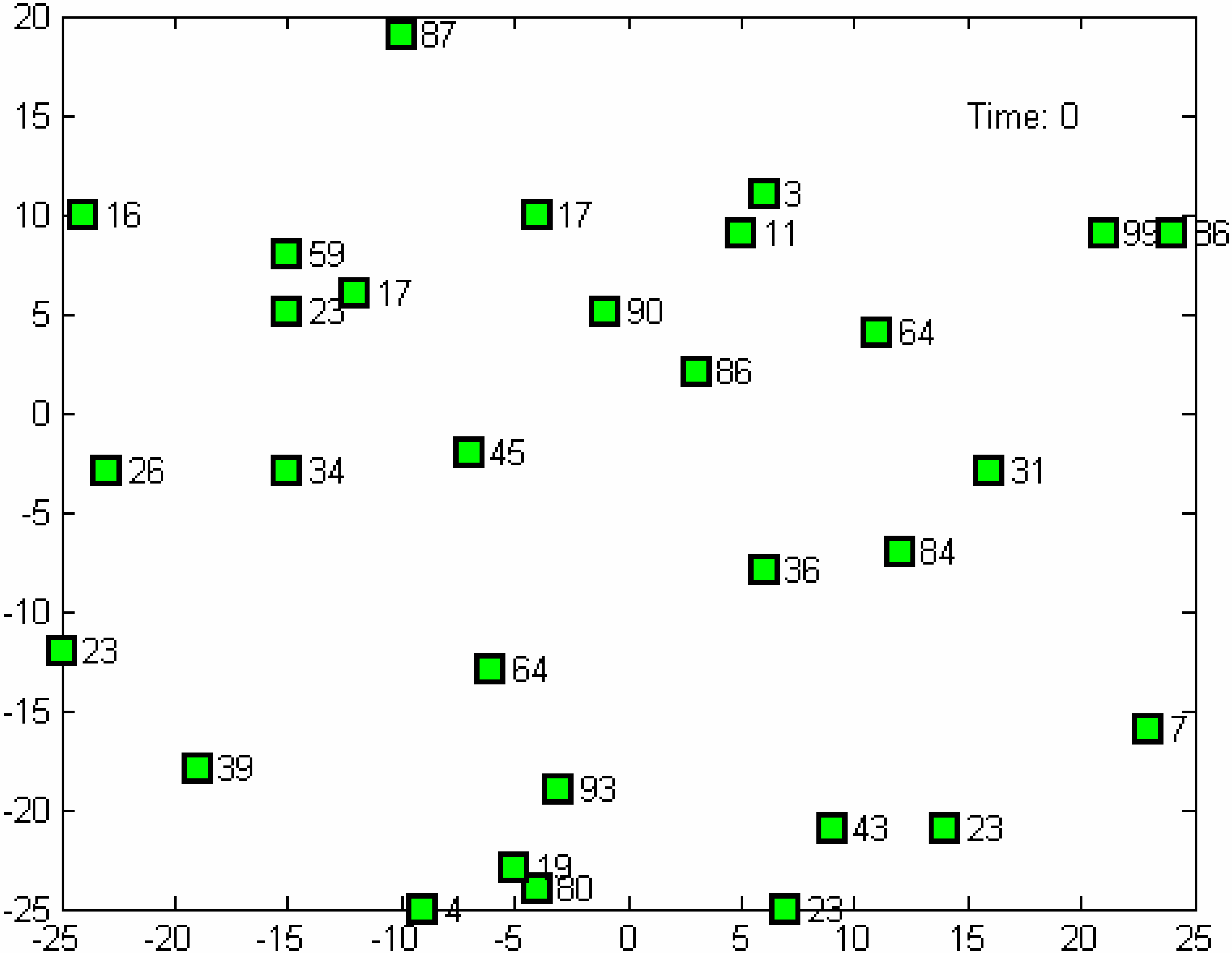
MAC Layer: Sensing with overlapping unlicensed networks

- Quiet periods from overlapping networks are synchronized



MAC Layer: Synchronization of Overlapping Networks

- A total of 30 networks are considered
- All networks power up at the same time (worst case analysis)
- Nodes have a radio range of 20 Km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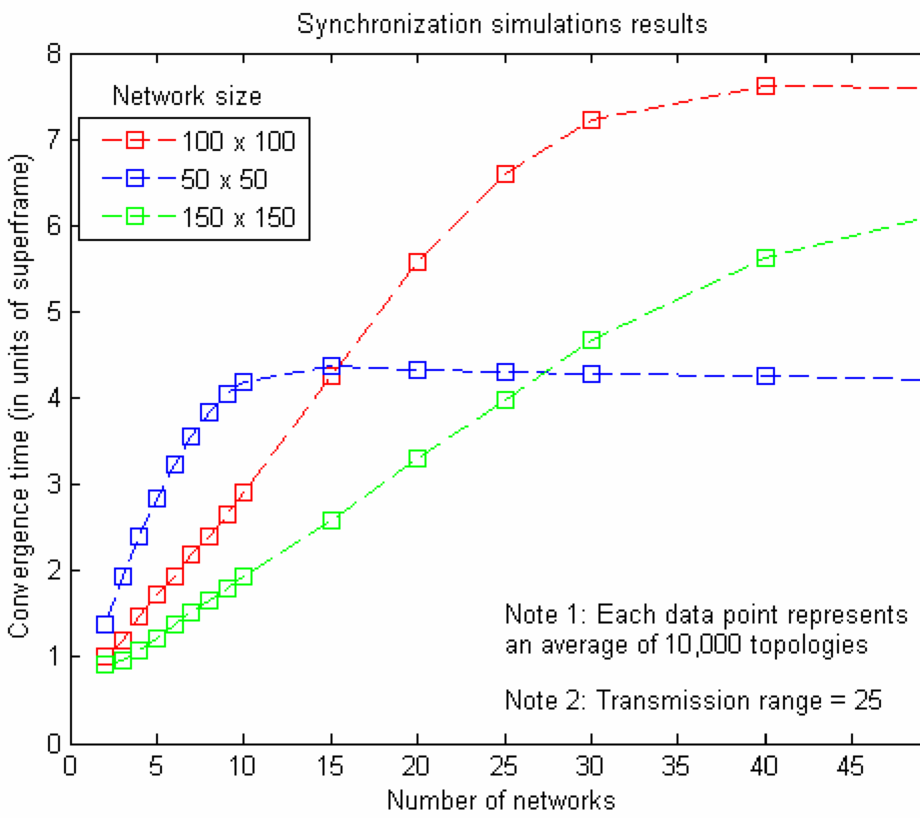
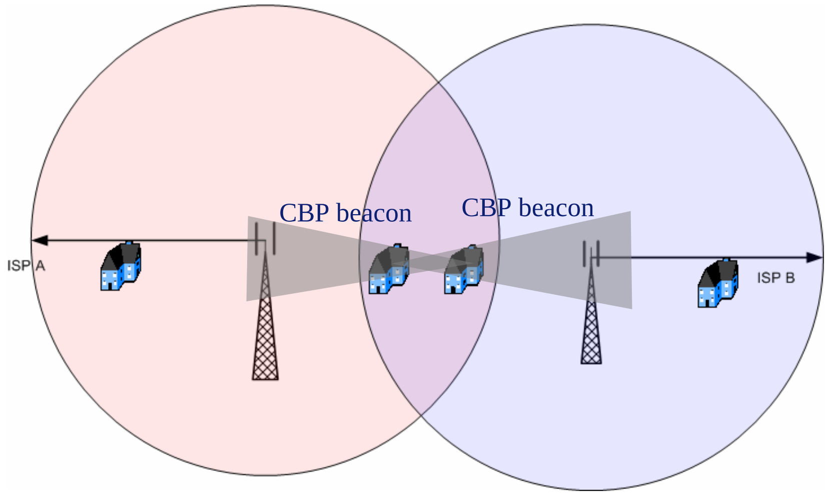
MAC Layer: Synchronization of Overlapping Networks (cont.)

- Comprehensive evaluation of the synchronization mechanism
  - Used for self-coexistence as well as for quiet periods
- Results show the quick convergence and efficiency of the algorithm



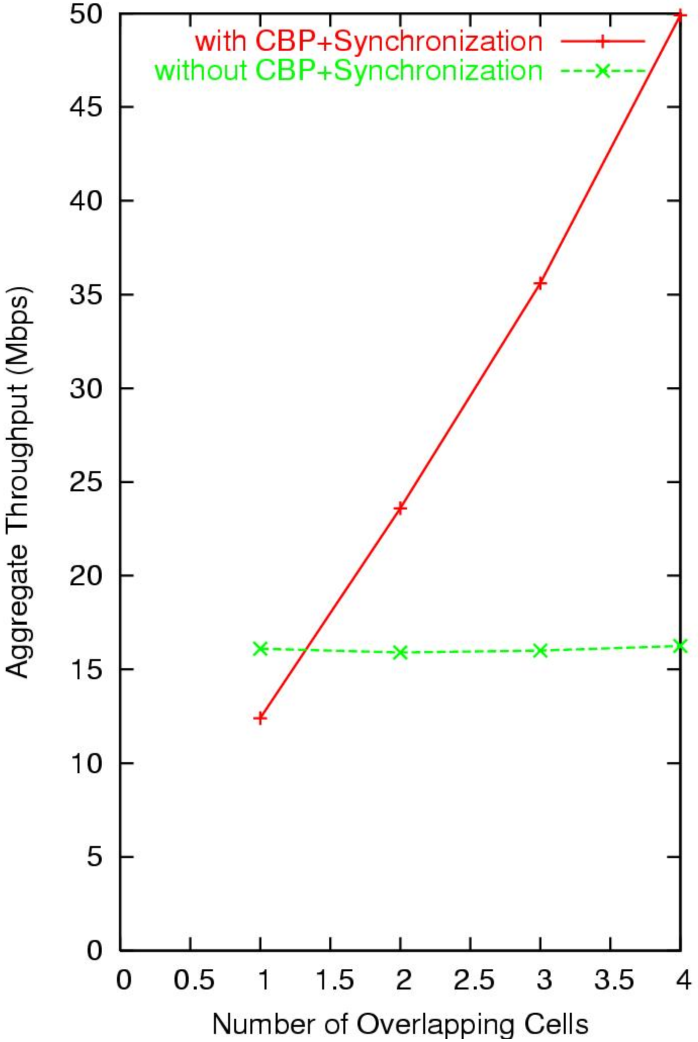
Self-Coexistence

- Coexistence Beacon Protocol (CBP)
  - CBP is executed by CPEs but under BS control
  - CPEs transmit coexistence packets with information about
    - The cell
    - This CPE's reservations with the BS
    - Resource request
    - Channels from the active and candidate sets
  - Allows better TPC and **sharing in both frequency and time**



CBP/Synchronization

- Simple scheduler
- CBP together with Synchronization can provide significant performance improvements
  - Since CBP is under control of the BS, it can be made adaptive



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Conclusions

- Spectrum-agile cognitive radios: a new paradigm in wireless communications
  - Currently, much of the spectrum allocated but unused
  - Spectrum allocation reform underway
  - Advanced (e.g., cognitive/agile) radios becoming available
- Agile radios enable new applications
  - IEEE 802.22 and Cellular applications discussed here
    - Cognitive radios techniques are being standardized faster than anticipated
  - "Spectrum is like disk-space, the more you have it, the more you will use it"
- A research topic with a number of technical challenges requiring a wide range of competencies

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Future Directions

- There are a number of open issues at all levels
- RF and Antenna design
  - E.g., ADC, filters, wideband and real-time sensing
- PHY
  - E.g., Discontinuous channel operation, spectrum sensing, adaptation/reconfiguration
- MAC
  - E.g., When/whom/for how long to sense, coexistence and sharing, multi-channel operation
- Others
  - E.g., End-to-end routing, pricing, etiquette, incentives, security, etc.

Want to know more?

- IEEE ComSoc Technical Committee on Cognitive Networks
- A number of new publication venues
  - Conferences/Workshops: DySPAN, TAPAS, CrownCom, …
  - Special Issues: IEEE J-SAC, IEEE Wireless Comm., …
- IEEE 802.22
- DARPA and NSF programs

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