

18-759: Wireless Networks

Lecture 24: Dynamic Spectrum Access

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<http://www.cs.cmu.edu/~prs/wirelessF18/>

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Overview

- Spectrum use background
- Concepts and approaches
- DSA technologies
- Case study: TV white spaces

- Some material based on slides by Ian Akyildiz, Raj Jain

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Spectrum Availability

- 300 GHz is huge amount of spectrum!
 - Spectrum can also be reused in space
- Not quite that easy:
 - Most of it is hard or expensive to use!
 - Noise and interference limits efficiency
 - Most of the spectrum is allocated by FCC
- FCC controls who can use the spectrum and how it can be used.
 - Need a license for most of the spectrum
 - Limits on power, placement of transmitters, coding, ..
 - Need to optimize benefit: guarantee emergency services, simplify communication, return on capital investment, ...
 - National Telecommunications and Information Agency (NTIA) for federal government communications

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Spectrum Allocation

<http://www.ntia.doc.gov/osmhome/allochrt.html>

- Most bands are (statically) allocated
- Industrial, Scientific, and Medical (ISM) bands are "unlicensed"
 - But still subject to various constraints on the operator, e.g. 1 W output
 - 433-868 MHz (Europe)
 - 902-928 MHz (US)
 - 2.4000-2.4835 GHz
 - Unlicensed National Information Infrastructure (UNII) band is 5.725-5.875 GHz

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Spectrum Allocation in US



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Different Ways of Controlling Access to Bands

- Licensed spectrum: users need a license to use that part of the spectrum
 - Cellular, radio/TV broadcast, federal agencies, ...
 - License typically provides exclusive use, i.e. license holder has full control over use of spectrum band
 - Commercial entities often pay for the license, e.g. through an auction
- Unlicensed spectrum: no user license required
 - Various constraints are placed on the radio to improve coexistence between users
 - E.g. transmit power, modulation, MAC, ...
 - Devices must be licensed

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New Spectrum is Scarce

- Suppose you need to find X MHz for a new technology or service
- All easy to use frequencies have been allocated
- Difficult to reallocate existing bands for new uses
 - Need to move current users somewhere
 - Significant investment in infrastructure

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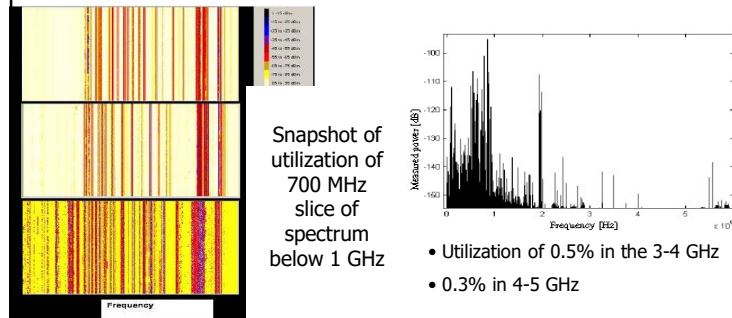
But Allocated Spectrum is not Used Effectively

- Many bands only used in certain regions
 - E.g. big cities, airports, etc.
- Some bands have low utilization or are only used at certain times
 - Driven by events, seasonal, ..
 - Wrong predictions about demand and use
- Some bands are used inefficiently
 - Use outdated technology
 - Expensive to replace
- Static allocation is fundamentally inefficient
 - This is not an unusual problem!
 - But context is unique

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Examples of Low Utilization



- According to FCC spatial and temporal utilization of assigned spectrum ranges from 15% to 85%

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Dynamic Spectrum Access

- Make allocation "more dynamic"
 - Can better adjust to allocation to needs
- Main concern: avoid interference to "incumbents"
 - Often have major investment in infrastructure
 - Interference can be fatal, e.g. first responders, businesses, ...
- Many models are possible:
 - License holder leases spectrum to third party
 - Allow secondary users that need to coexist with primary users – many models
- DSA makes use of "cognitive radios"
 - Radio parameters can be adapted at runtime based on its environments and goals
 - Can opportunistically operate in best available spectrum

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Overview

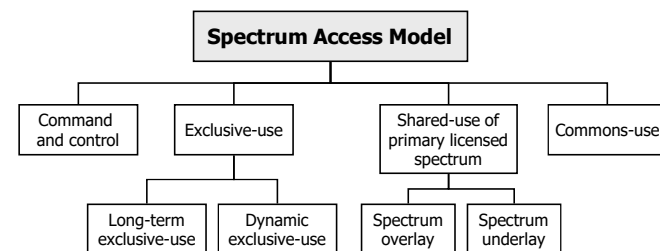
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Dynamic Spectrum Access (DSA)

- Dynamic spectrum access allows different wireless users and different types of services to utilize radio spectrum



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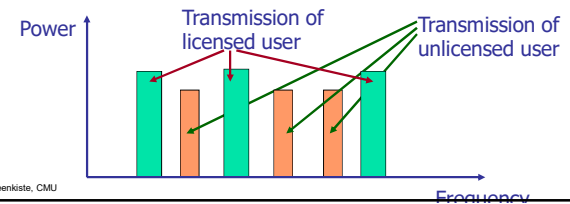
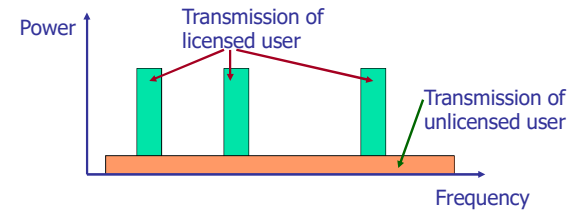
Exclusive-Use Model

Exclusively owned and used by single owner

- Long-term exclusive-use
 - E.g., cellular service licenses
 - Wireless technology can change (GSM, CDMA, OFDMA)
 - Owner and duration of license do not change
- Dynamic exclusive-use (micro-licenses)
 - Non-real-time secondary market
 - Multi-operator sharing homogeneous bands
 - dynamically change spatio-temporal allocation along with the amount of spectrum among multiple operators
 - different technology can be used
 - Multi-operator sharing heterogeneous services

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Shared-Use of Primary Licensed Spectrum Model



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Spectrum Underlay

- Spectrum underlay approach constraints the transmission power of secondary users so that they operate below the interference temperature limit of primary users.
- One possible approach is to transmit the signals in a very wide frequency band (e.g., UWB communications) so that high data rate is achieved with extremely low transmission power.
- It is based on the worst-case assumption that primary users transmit all the time; hence does not exploit spectrum white space.

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Spectrum Overlay

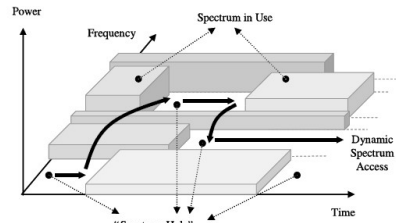
- Spectrum overlay approach does not necessarily impose any severe restriction on the transmission power by secondary users – allows secondary users to identify and exploit the spectrum holes defined in space, time, and frequency (*Opportunistic Spectrum Access*).
- Compatible with the existing spectrum allocation – legacy systems can continue to operate without being affected by the secondary users.
- Regulatory policies define basic etiquettes for secondary users to ensure compatibility with legacy systems.

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Example

- Use of temporally unused spectrum, which is referred to as **spectrum hole** or **white space**.



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Overview

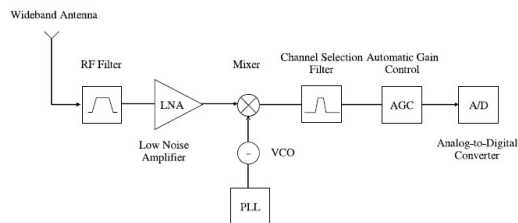
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Cognitive Radio - Architecture

- The novel characteristic of CR transceiver is a wideband sensing capability of the **RF front-end**.
 - RF hardware should be capable of tuning to any part of a large range of frequency spectrum.



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Cognitive Radio - Reconfigurability

- The capability of adjusting operating parameters for the transmission on the fly without any modifications on the hardware components.
 - **Operating frequency**
 - **Modulation**
 - Reconfigure the modulation scheme adaptive to the users requirements and channel conditions.
 - **Transmission power**
 - If higher power operation is not necessary, the CR reduces the transmitter power to a lower level to allow more users to share the spectrum and to decrease the interference
 - **Communication technology**

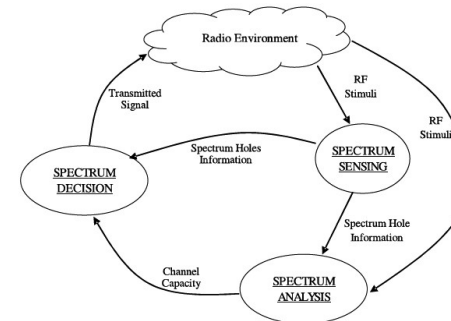
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Main Function in DSA

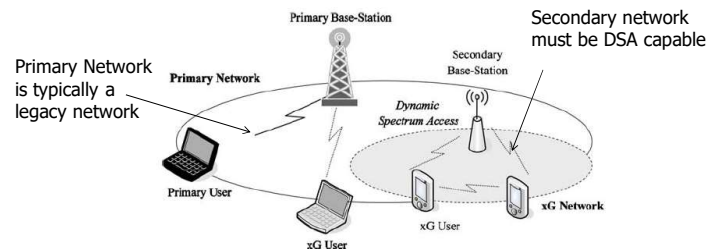
- **Spectrum sensing**
 - Detecting unused spectrum and sharing the spectrum without harmful interference with other users
- **Spectrum management**
 - Capturing the best available spectrum to meet user communication requirements
- **Spectrum mobility**
 - Maintaining seamless communication requirements during the transition to better spectrum
- **Spectrum sharing**
 - Providing the fair spectrum scheduling method among coexisting users

DSA– Cognitive Cycle



Example of DSA

- DSA networks is deployed to exploit the spectrum holes through cognitive communication techniques

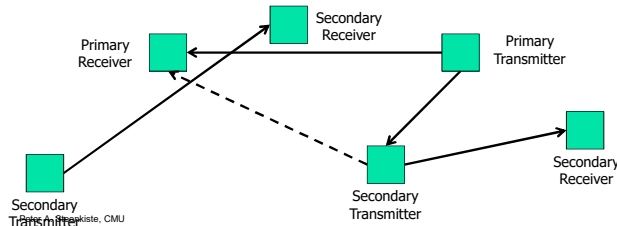


Network Applications

- **Leased network**
 - The primary network can provide a leased network by
 - allowing opportunistic access to its licensed spectrum with the agreement with a third party without sacrificing the service quality of the primary users.
 - e.g., Mobile Virtual Network Operator (MVNO)
- **Cognitive mesh network**
 - Networks have the ability to add temporary or permanent spectrum to the infrastructure links used for relaying in case of high traffic load.
- **Emergency network**
- **Military network**

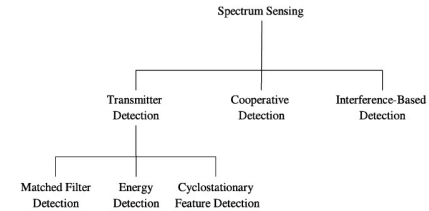
Spectrum Sensing

- Secondary user monitors the spectrum
 - Must detect primary users that are receiving data within its communication range
- In practice, it is difficult for a cognitive radio to have a direct measurement of a channel between a primary receiver and a transmitter.



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Classification of Spectrum Sensing Techniques



- Transmitter detection approach: the detection of the weak signal from a primary transmitter through the local observation:

Basic hypothesis
$$x(t) = \begin{cases} n(t) & H_0, \\ hs(t) + n(t) & H_1, \end{cases}$$

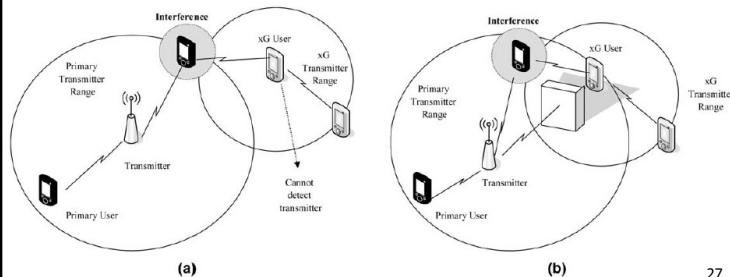
$n(t)$ the AWGN
 $hs(t)$ transmitted signal of the primary users
 h the amplitude gain of the channel

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Transmitter Detection Problem

- Transmitter detection problem
 - Receiver uncertainty (a)
 - Shadowing uncertainty (b)
- Even more difficult if receiver does not transmit



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Sensing Techniques

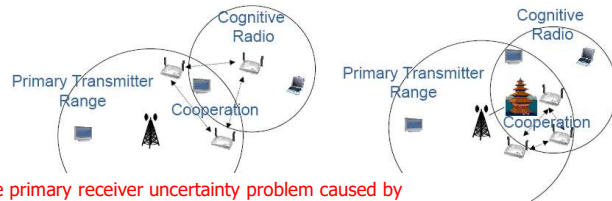
- **Energy detection** senses for energy in the time of frequency domain
 - Can be very difficult, e.g. receive only devices
- **Matched filter** can be used if a priori knowledge of primary user signal is available
 - E.g., modulation type, shaping signal, ...
 - Optimal because it maximizes SNR in AWGN channel
- **Cyclostationary detectors** look for signals with periodic properties
 - Modulated signals have a mean and autocorrelation that exhibit periodicity.
 - These features are detected by analyzing a spectral correlation function.

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Cooperated Spectrum Sensing

- Cooperated spectrum sensing methods where information from multiple secondary users are incorporated for primary user detection.
 - allow to mitigate the multi-path fading and shadowing effects, which improves the detection probability in a heavily shadowed environment.



The primary receiver uncertainty problem caused by the lack of the primary receiver location knowledge is unsolved.

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Spectrum Analysis

- The available spectrum holes show different characteristics which vary over time.
- Spectrum analysis enables the characterization of different spectrum bands,
 - which can be exploited to get the spectrum band appropriate to the user requirements.
- In order to describe the dynamic nature of DSA networks, each spectrum hole should be characterized considering
 - not only time-varying radio environment and
 - but also the primary user activity and the spectrum band information.

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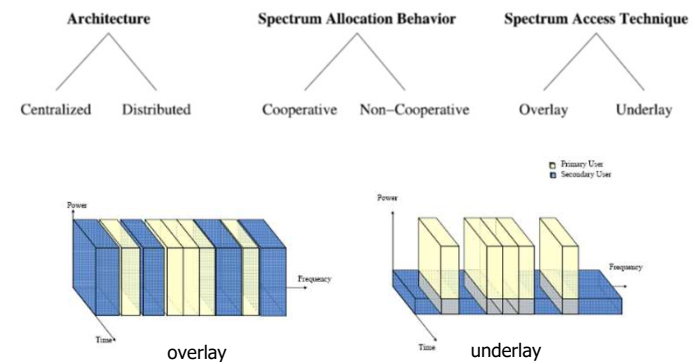
Spectrum Sharing Process

- Spectrum sensing
- Spectrum allocation
 - The allocation not only depends on spectrum availability, but it is also determined based on internal (and possible external) policies.
- Spectrum access
 - The access should be coordinated in order to prevent multiple users colliding in overlapping portions of the spectrum.
- Transmitter-receiver handshake
- Spectrum mobility

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Classification of Spectrum Sharing



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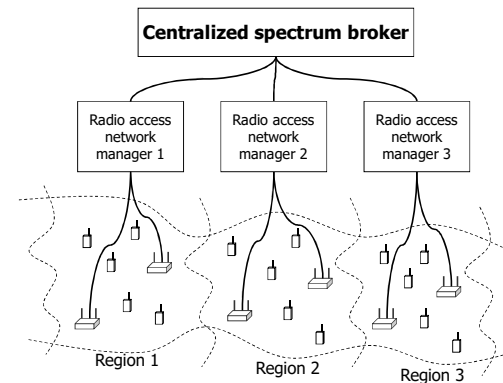
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Cooperative/Centralized DSA

- A centralized server maintains a database of spectrum availability and access information (based on information received from secondary users, e.g., through a dedicated control channel).
- Spectrum management is simpler and coordinated and enables efficient spectrum sharing.

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Cooperative/Centralized DSA



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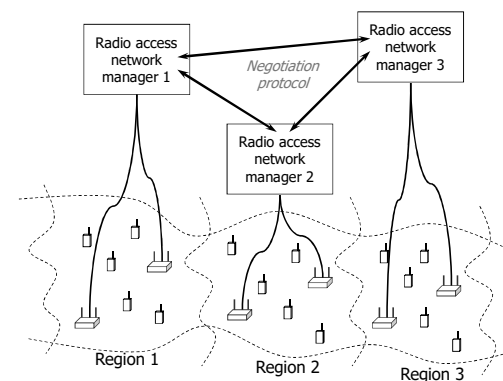
Cooperative/Distributed DSA

- Cooperative/distributed strategy relies on cooperative local actions throughout the network (to achieve a performance close to the global optimal performance).
- May suffer due to hidden node problem and large control overheads
- In both centralized and distributed strategies, the primary user may or may not cooperate.

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Cooperative/Distributed DSA Example



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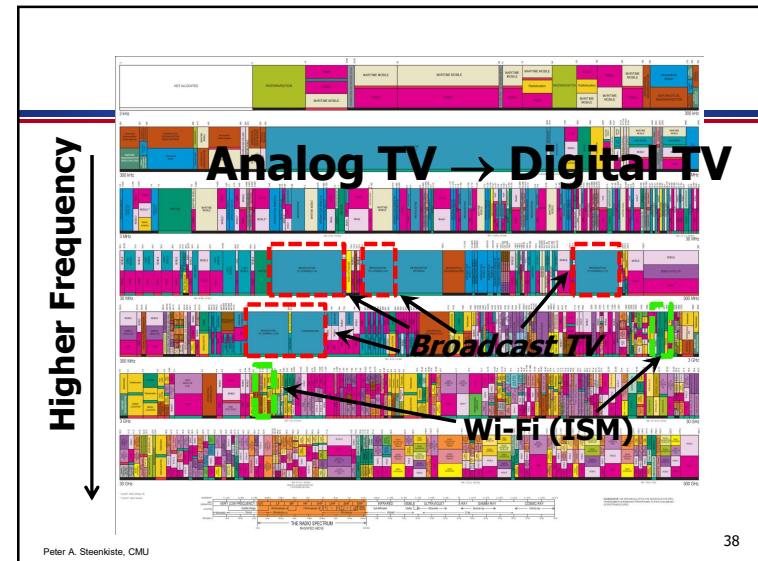
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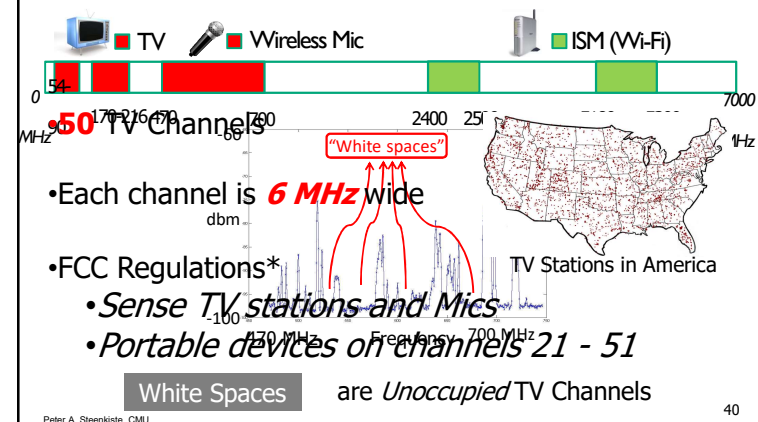
TV White Spaces

- TV channels are “allotted” to cities to serve the local area
- Other licensed and unlicensed services are also in TV bands
 - Wireless microphones
- “White Spaces” are the channels that are “unused” at any given location by licensed devices
 - FCC regulation allows access by unlicensed devices subject to many rules

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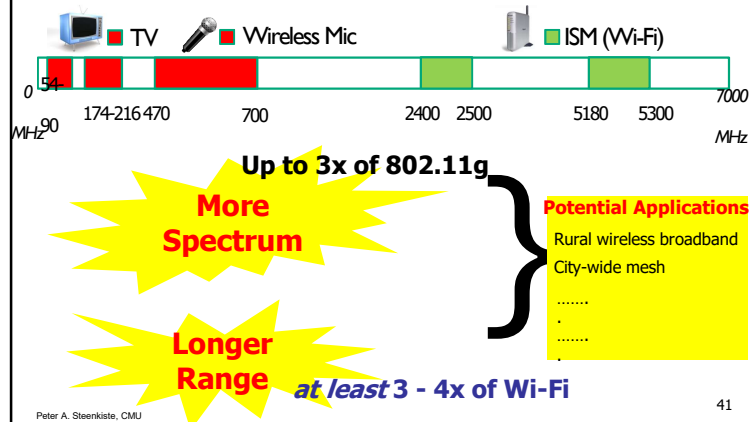
What are White Spaces?



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The Promise of White Spaces



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Use of Geolocation & Database

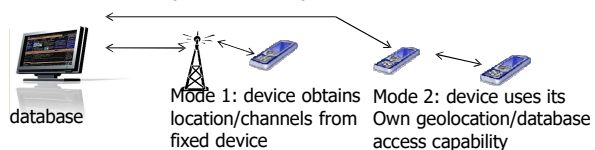
- Based on prototype test program sensing-only not sufficiently developed
 - Very long scan times, poor performance in presence of strong adjacent channel signal, ..
 - Difficult to reliably detecting wireless microphones
 - Inability to determine presence of passive receive sites
- Disagreement on technical parameters for sensing
 - What is detection threshold for determining presence of a signal? How is measurement accomplished? Type of detector
- Tradeoff between continuing to develop sensing technology vs. earlier
- Require geolocation capability in conjunction with a database to provide each device with a list of available channels specific to its location

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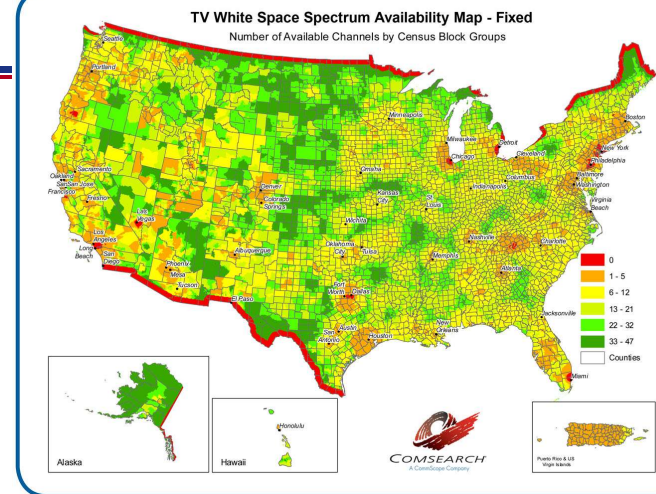
TV White Space Rules

- Final rules adopted 9/2010; modified 4/2012
 - First new spectrum for unlicensed devices below 5 GHz in many years
 - Access based on geolocation & database
 - <https://www.google.com/get/spectrumdatabase/>
- Incumbent services protect by database
 - TV broadcast stations, translator and booster stations, cable TV headends, ..
 - Land mobile (in some cities); wireless mics

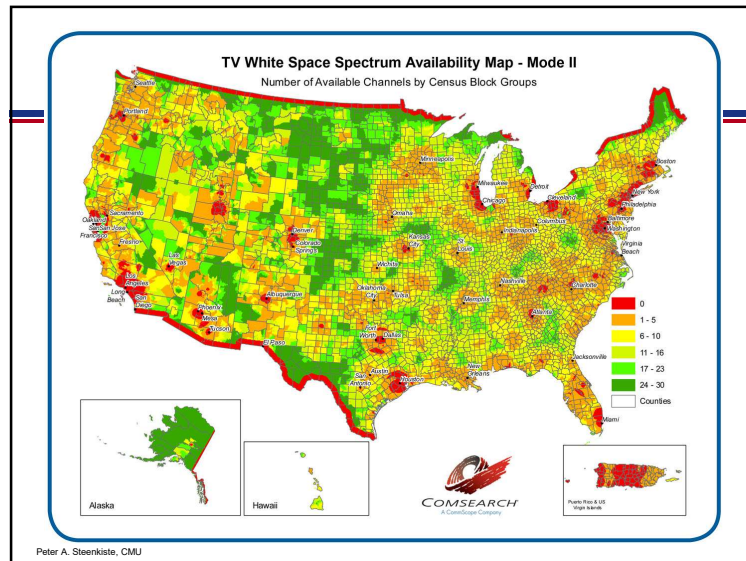


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Standards for White Spaces

- **IEEE 802.11af**: Wireless Local Area Network
- **IEEE 802.22**: Cognitive Wireless Regional Area Network
- **IEEE 802.15.4m**: Wireless Personal Area Network
- **IEEE 802.19.1**: Coexistence in white spaces
- **IETF PAWS**: Database access
- Other standards organizations:
 - ETSI BRAN: European Telecommunications Standards Institute Broadband Radio Access Networks
 - CEPT ECC SE43: European Conference of Postal and Telecommunications Administrations Electronics Communications Committee Spectrum Engineering
 - ITU-WP1B: International Telecommunication Union Working Party 1B – Spectrum Management Methodologies

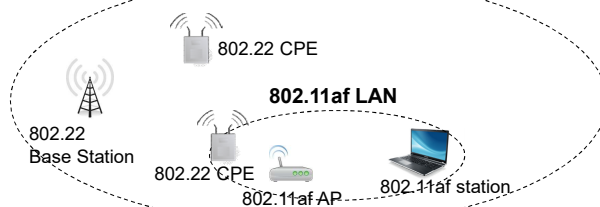
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Coexistence Problem

- Exposed Terminal: 802.11af can not transmit because 802.22 keeps the channel busy
- Hidden Terminal: 802.11af interferes with 802.22 transmissions

802.22 Regional Area Network



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