18-452/750
Wireless Networks and Applications
Lecture 24:
Dynamic Spectrum Access

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http://www.cs.cmu.edu/~prs/wirelessS24/

Announcements

- **Last regular lecture of the semester**
  - **We still have survey presentations, project 2 presentations, final Q&A**
- **P2 checkpoint 1 meetings are this week**
  - **If you have not signed up yet, please do so asap:** https://docs.google.com/spreadsheets/d/18akKRFlqXQBjYEj2Torf9-OO0ffQYjBenG6kgyZrNDs/edit?usp=sharing

Overview

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

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

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
  - A lot of the spectrum has already been allocated
- FCC controls who can use the spectrum and how
  - Need a license for most of the spectrum
  - Limits on power, placement transmitters, modulation, ..
  - Allocation tries to "optimize benefits for society"
  - National Telecommunications and Information Agency (NTIA) is in charge of federal government communications

Spectrum Allocation

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

- **Most bands are (statically) allocated and can be used only by users with a license**
- **Some bands do not require a license**
- **Exampe: Industrial, Scientific, and Medical (ISM) bands"But they are 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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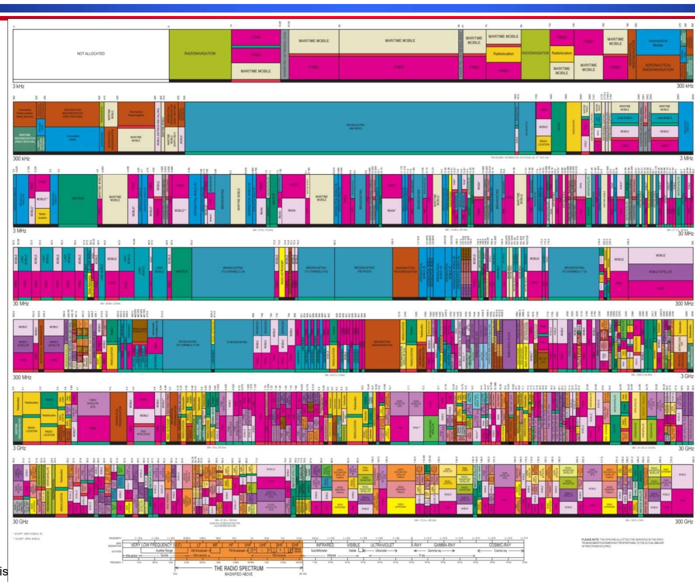
Spectrum Allocation in US



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Different Ways of Controlling Access to Bands

- Licensed spectrum: users need a license to use the spectrum band
  - 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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Licensed versus Unlicensed Spectrum: Protocol Implications

- In a licensed band, the license holder has full control over the spectrum use
  - This simplifies optimizing spectrum use
  - Can control transmitters so ..
    - Interference is limited
    - Bandwidth use of devices matches target values
    - Limit transmit paper, e.g., better frequency reuse, …
- In unlicensed bands, protocols must be designed to deal with many challenges
  - Diverse transmit ranges, interference, ..
  - Diverse protocols that do not coordinate, …

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New Spectrum is Scarce

- Suppose you need to find X MHz for a new technology or service
  - E.g., request from congress for more mobile broadband spectrum
- All easy-to-use frequencies have been allocated
- Difficult to reallocate existing bands
  - Need to move current users somewhere
  - Significant investment in infrastructure
  - However, some bands do get re-allocated
- Exception: higher frequency bands that become viable because of technology advances

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But Allocated Spectrum is not Used Effectively

- Many bands are 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! Other examples?
  - But the context is unique

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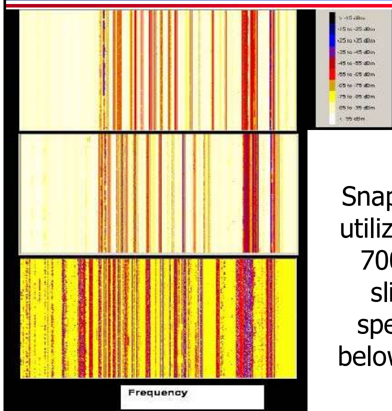
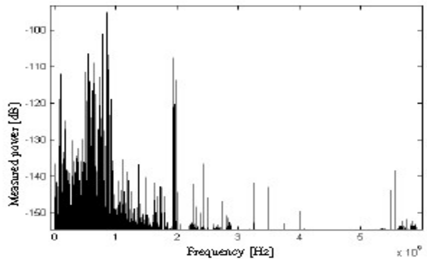
Examples of Low Utilization



Snapshot of utilization of 700 MHz slice of spectrum below 1 GHz



- Utilization of 0.5% in the 3-4 GHz
- 0.3% in 4-5 GHz

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

How do increase spectrum utilization?

Dynamic Spectrum Access

- **Make allocation "more dynamic"**
  - **Can better adjust the allocation to (local) needs**
- **Main concern: avoid interference to "incumbents"**
  - **Often have major investment in infrastructure**
  - **Interference can be fatal, e.g. first responders, business, …**
- **Many models are possible:**
  - **License holder leases spectrum to third party**
  - **Allow secondary users to coexist with primary users – many models**
- **DSA requires protocols and radios that can sense the presence of primary users**
  - **Protocols must adapt to local conditions**

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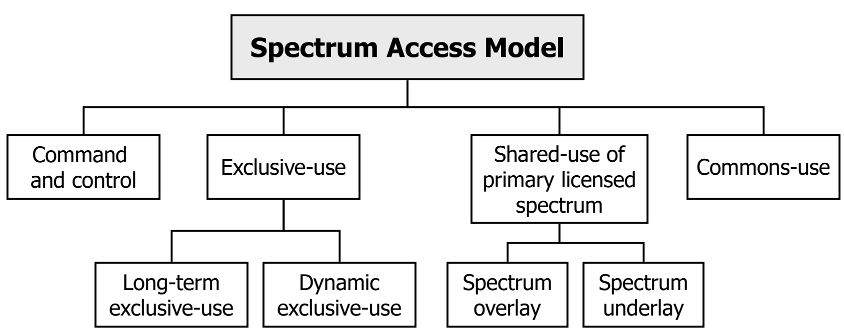
Dynamic Spectrum Access (DSA)

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



Exclusive-Use Model

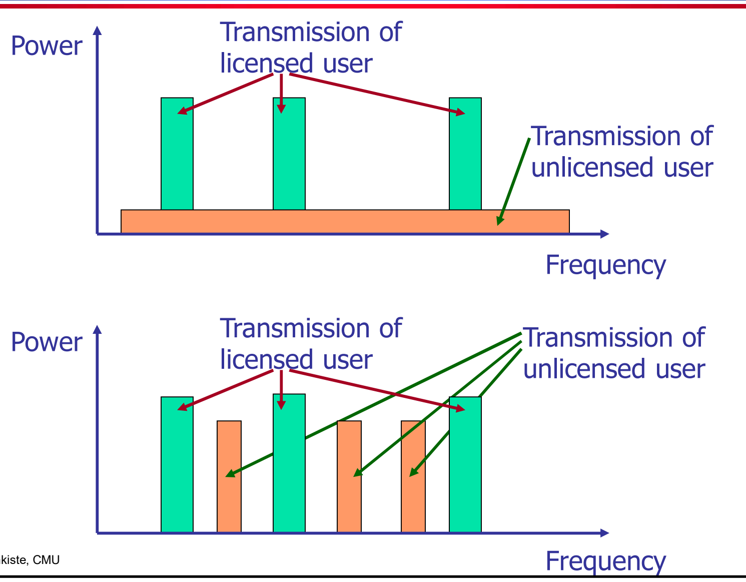
Exclusively owned and used by single owner

- **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**

Shared Use of Primary Licensed Spectrum



Spectrum Underlay

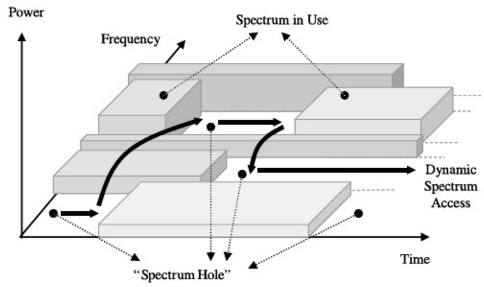
- Spectrum underlay approach constraints the transmission power of secondary users so that they operate below the interference temperature limit of primary users.
- One possible approach: transmit signals in a very wide frequency band (e.g., UWB communications)
  - Can still achieve a high data rate with very low transmit power/hertz
- It is based on the worst-case assumption that primary users transmit all the time
  - Must be conservative
  - Detecting primary users is hard!

Spectrum Overlay

- A spectrum overlay allows secondary users to identify and exploit the spectrum holes defined in space, time, and frequency
  - *"Opportunistic Spectrum Access"*
  - approach does not necessarily impose any restriction on the transmission power by secondary users
- 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.

High Level View

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



- How realistic is this?
  - Have we seen examples in the course?
  - Units for Frequency and Time axis? Impact on radio?

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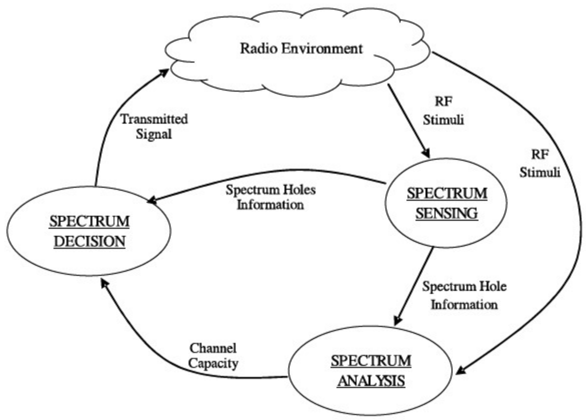
DSA– Cognitive Cycle



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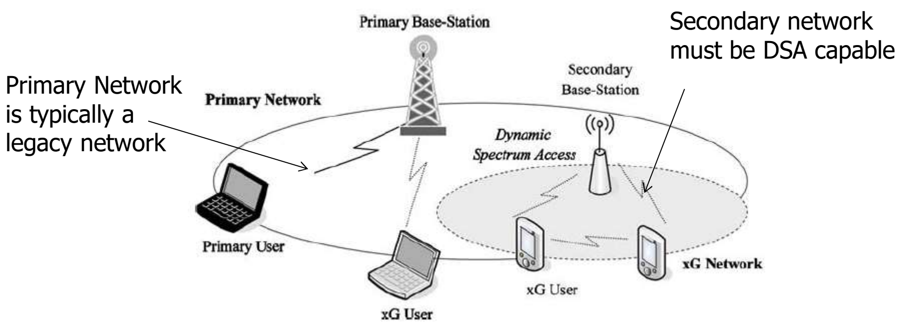
Example of DSA

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



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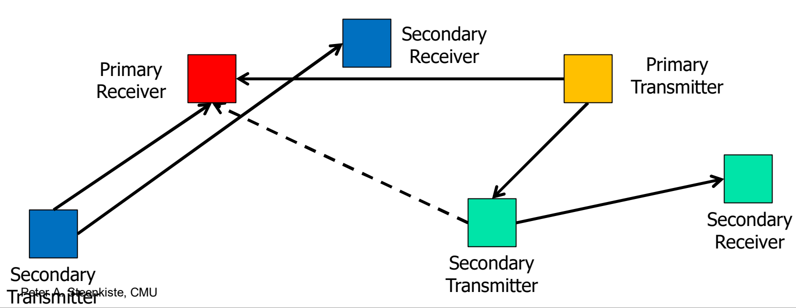
Main Function in DSA

- **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**

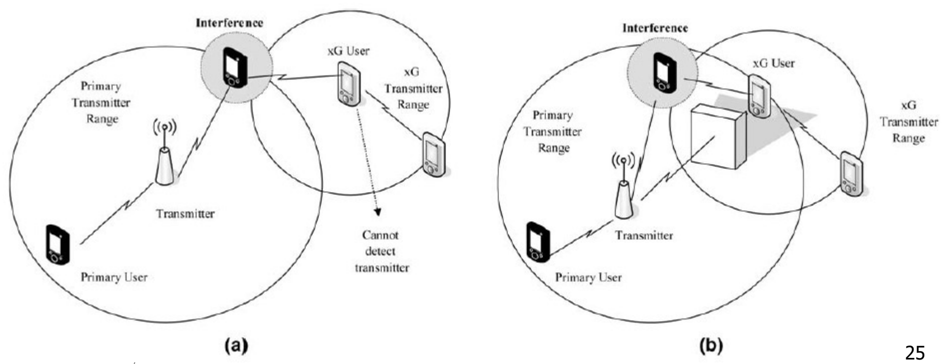
Spectrum Sensing

- **Secondary user monitors the spectrum**
  - **Must detect primary users that are receiving data within its communication range**
- **This is very hard!**
  - **Remember the hidden terminal problem!**
  - **Some receivers never transmit!**



Transmitter Detection Problem

- The general transmitter detection problem
  - Receiver uncertainty (a)
  - Shadowing uncertainty (b)



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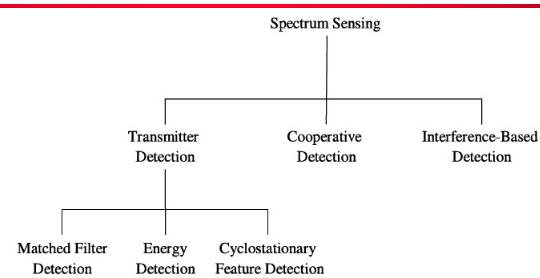
Classification of Spectrum Sensing Techniques



- Transmitter detection approach: the detection of the weak signal from a primary transmitter through the local observations
- Basic hypothesis

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

noise

transmitted signal of the primary users

Channel attenuation

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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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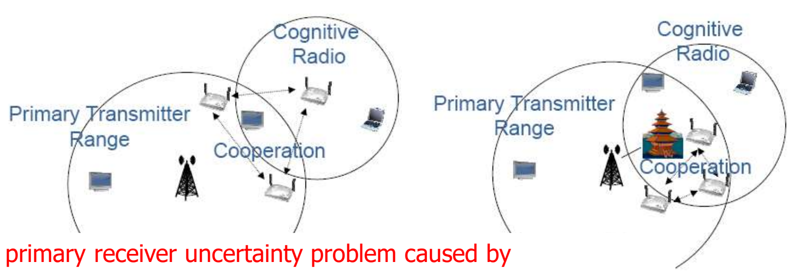
Cooperative Spectrum Sensing

- Cooperative spectrum sensing methods where information from multiple secondary users is combined for primary user detection.
  - Allows for addressing multi-path fading and shadowing effects - 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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Overview

- Spectrum use background
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- DSA technologies
- Use cases: TV white spaces and CBRS

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Supporting Secondary Users

- How can secondary users avoid interfering with the primary user of a frequency band?
  - They cannot explicitly coordinate
  - Primary users do not change infrastructure
- Let us look at two examples
  - TV white spaces
  - Citizens Broadcast radio Service (CBRS)

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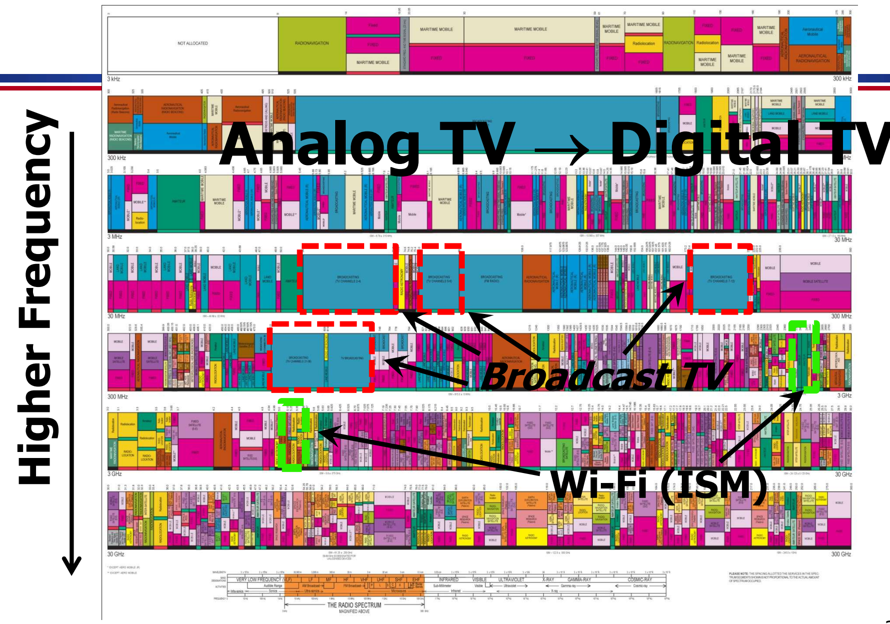

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TV White Spaces

- 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 "not used" by licensed devices at a given location
- FCC regulation allows access by unlicensed devices subject to many rules

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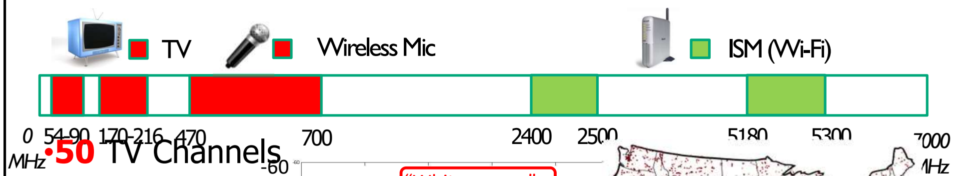
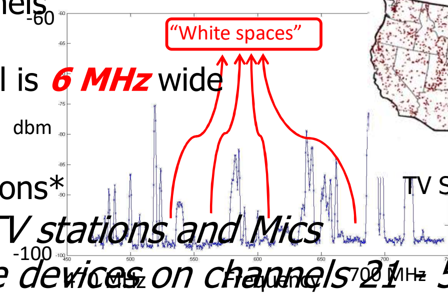
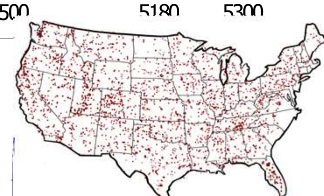
What are TV White Spaces?



- **50** TV Channels
- Each channel is ***6 MHz*** wide
- FCC Regulations*
  - *Sense TV stations and Mics*
  - *Portable devices on channels 21 - 51*

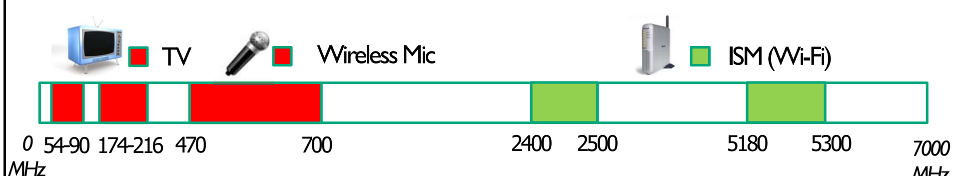




TV Stations in America

White Spaces are *Unoccupied* TV Channels

The Promise of White Spaces



Up to 3x of 802.11g

More Spectrum

Longer Range

***at least* 3 - 4x of Wi-Fi**

Potential Applications

- Rural wireless broadband
- City-wide mesh
- ……..
- ……..

Challenges of Using TV White Spaces

- How do we avoid interfering with primary users?
  - Over the air TV broadcast
  - Wireless microphones
- Both use unidirectional communication!
  - One can only the sense the transmitter!
- Solutions considered by FCC
  - Require sensing by white space devices
    - Either individual nodes or a controller (e.g., AP)
  - Geolocation database that lists registered primary users

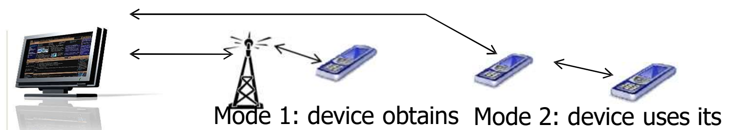
Why Using Geolocation & Database

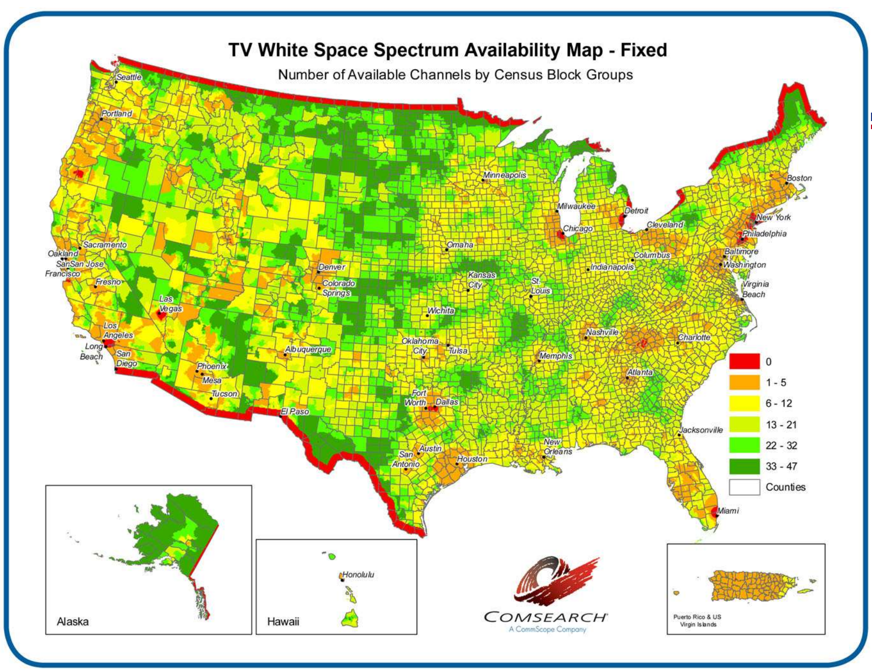
- Based on prototype test program sensing-only solutions not sufficiently developed
  - Very long scan times, poor performance in presence of strong adjacent channel signal, ..
  - Difficult to reliably detecting wireless microphones
  - Inability to determine presence of passive receive sites
- Disagreement 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 first vs. earlier deployment
- Requires geolocation capability in conjunction with a database to provide each device with a list of available channels specific to its location

TV White Space Rules

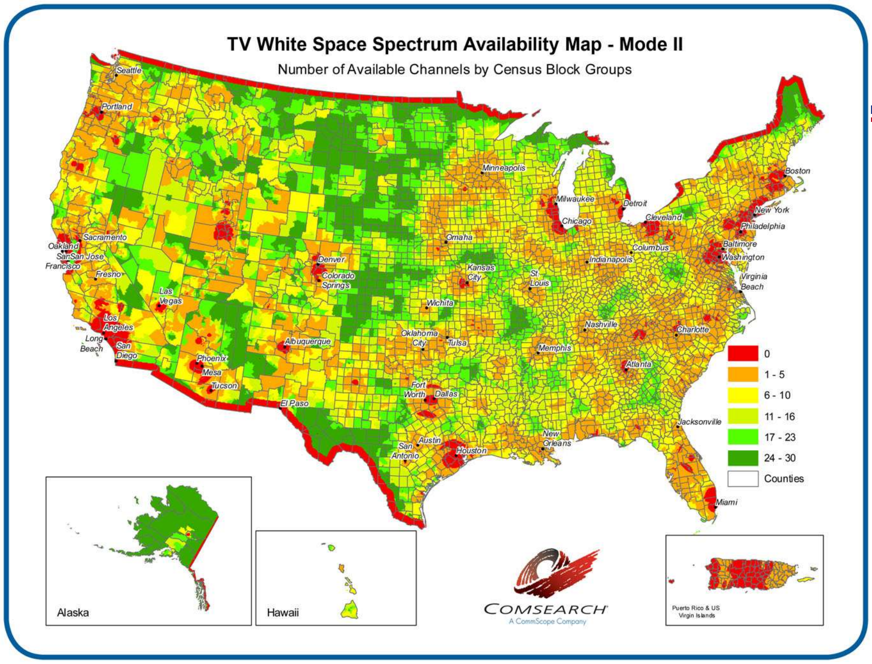
- Final rules adopted 9/2010; modified 4/2012
  - First new spectrum for unlicensed devices below 5 GHz in many years
  - Access based on geolocation & database
- Incumbent services protect by database
  - TV broadcast stations, translator and booster stations, cable TV headends, ..
  - Land mobile (in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

Example: https://usa.wavedb.com/channelsearch/tvws





Map from Jan 2010



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Map from Jan 2010

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Citizens Broadcast Radio Service CBRS

- The primary users are satellite ground stations and the US Nave – incumbents
  - Uses the 3.5-3.7 GHz
  - Spectrum is only used in certain areas
- In 2020, some of the unused spectrum was auctioned of to Priority Access Licensees (PALs)
  - Most PALs are cellular operators
- General Authorized Access (GAA) users can use the spectrum for free
  - If it is not being used by Incumbents of PALs
  - GAA users need to request access
  - A Spectrum Access System monitors spectrum use
  - Can be used for private cellular networks, …

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