This lecture is being recorded

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

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http://www.cs.cmu.edu/~prs/wirelessS22/

Announcements

- Last regular lecture of the semester
  - We still have survey presentations, project 2 presentations, final Q&A
- Upcoming deadlines:
  - Next Wed: P2 CP1
  - The week after next: draft survey presentations (on Mon or Wed)
  - HW 4: out at the end of next week

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

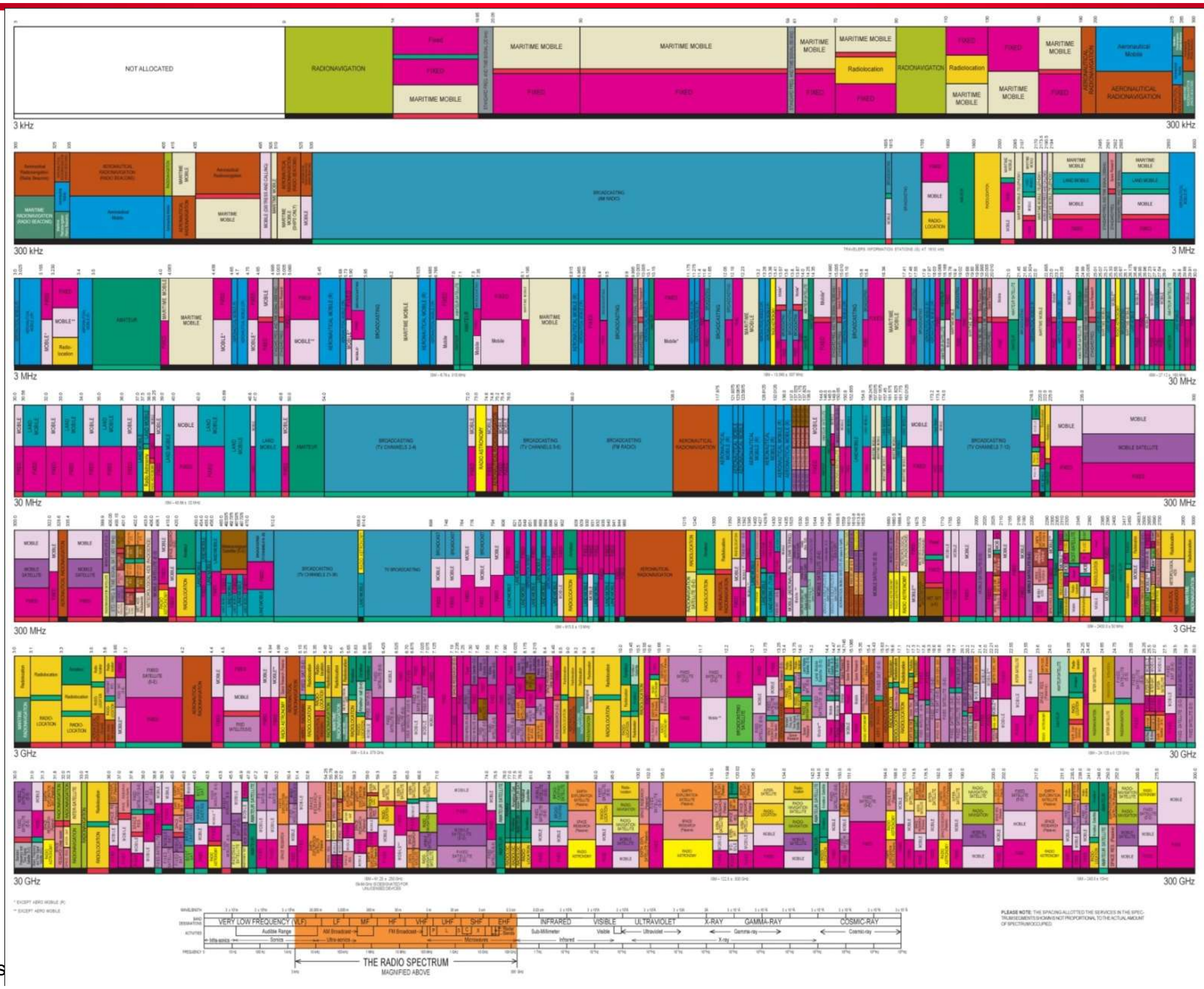
- 300 GHz is huge amount of spectrum!
  - Spectrum can also be reused in space
- Not quite that easy:
  - Most of it is hard or expensive to use!
  - Noise and interference limits efficiency
  - Most of the spectrum has already been allocated
- FCC controls who can use the spectrum and how
  - Need a 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) for federal government communications

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**

Spectrum Allocation in US



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

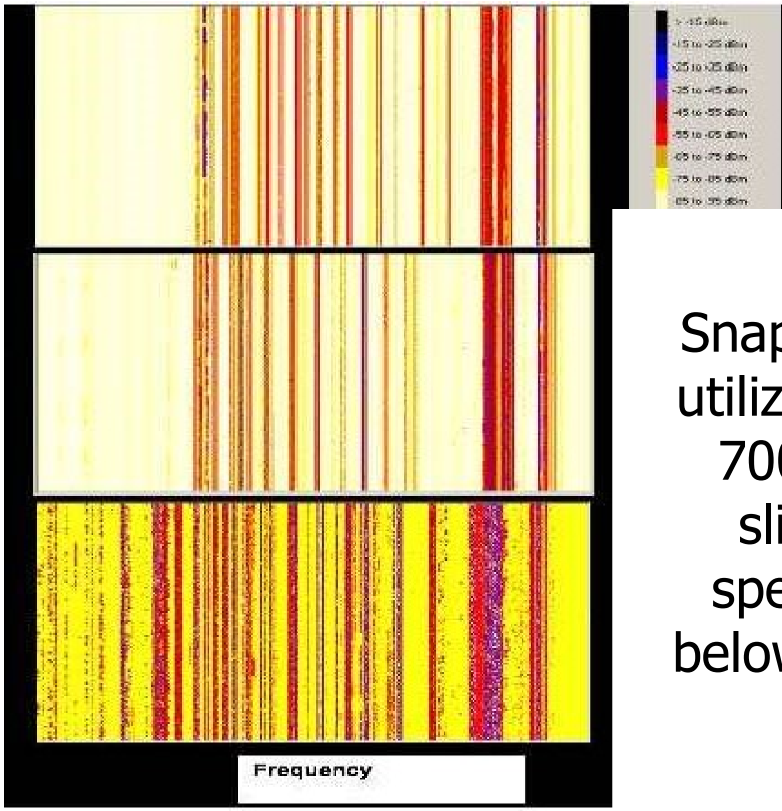
New Spectrum is Scarce

- 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
  - Need to move current users somewhere
  - Significant investment in infrastructure
  - However, some bands do get allocated
- Exception: higher frequency bands that become viable because of technology advances

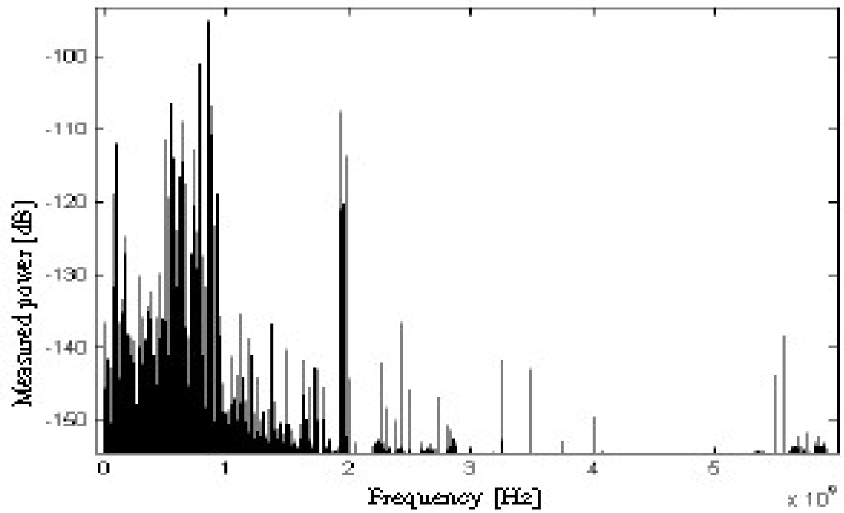
But Allocated Spectrum is not Used Effectively

- **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**

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

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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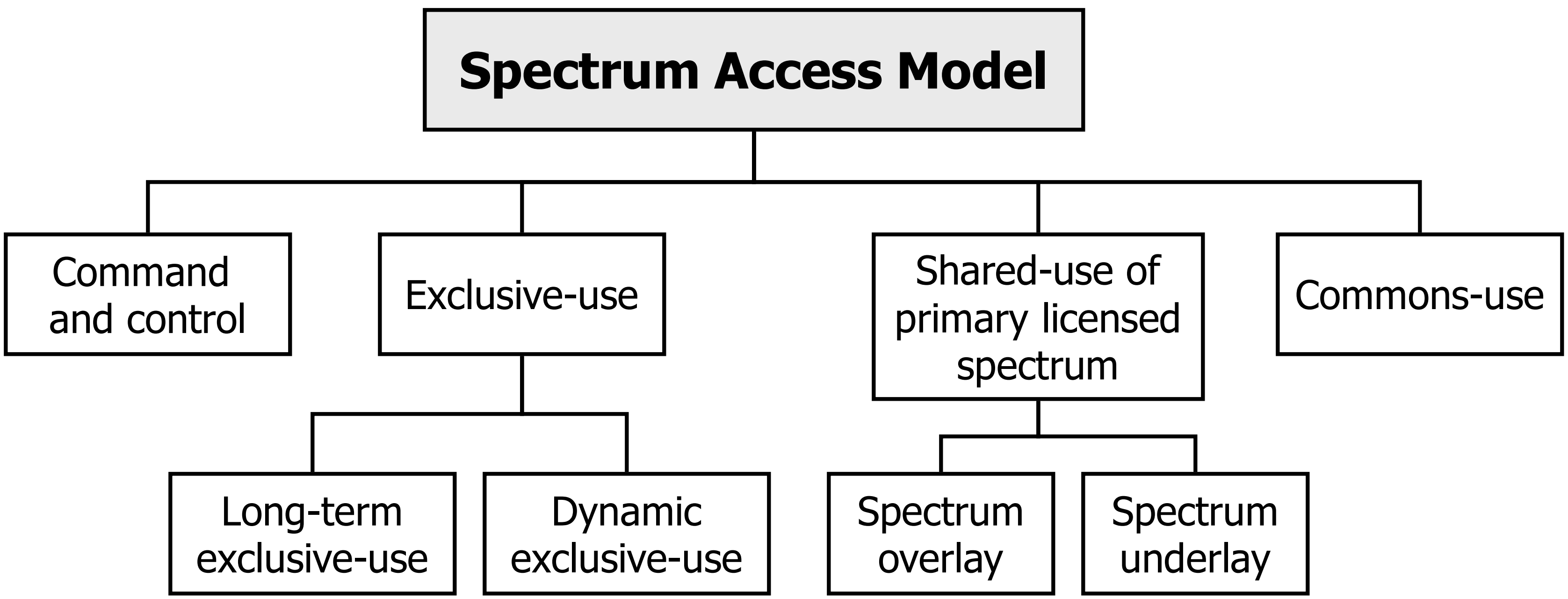
Dynamic Spectrum Access (DSA)

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



Exclusive-Use Model

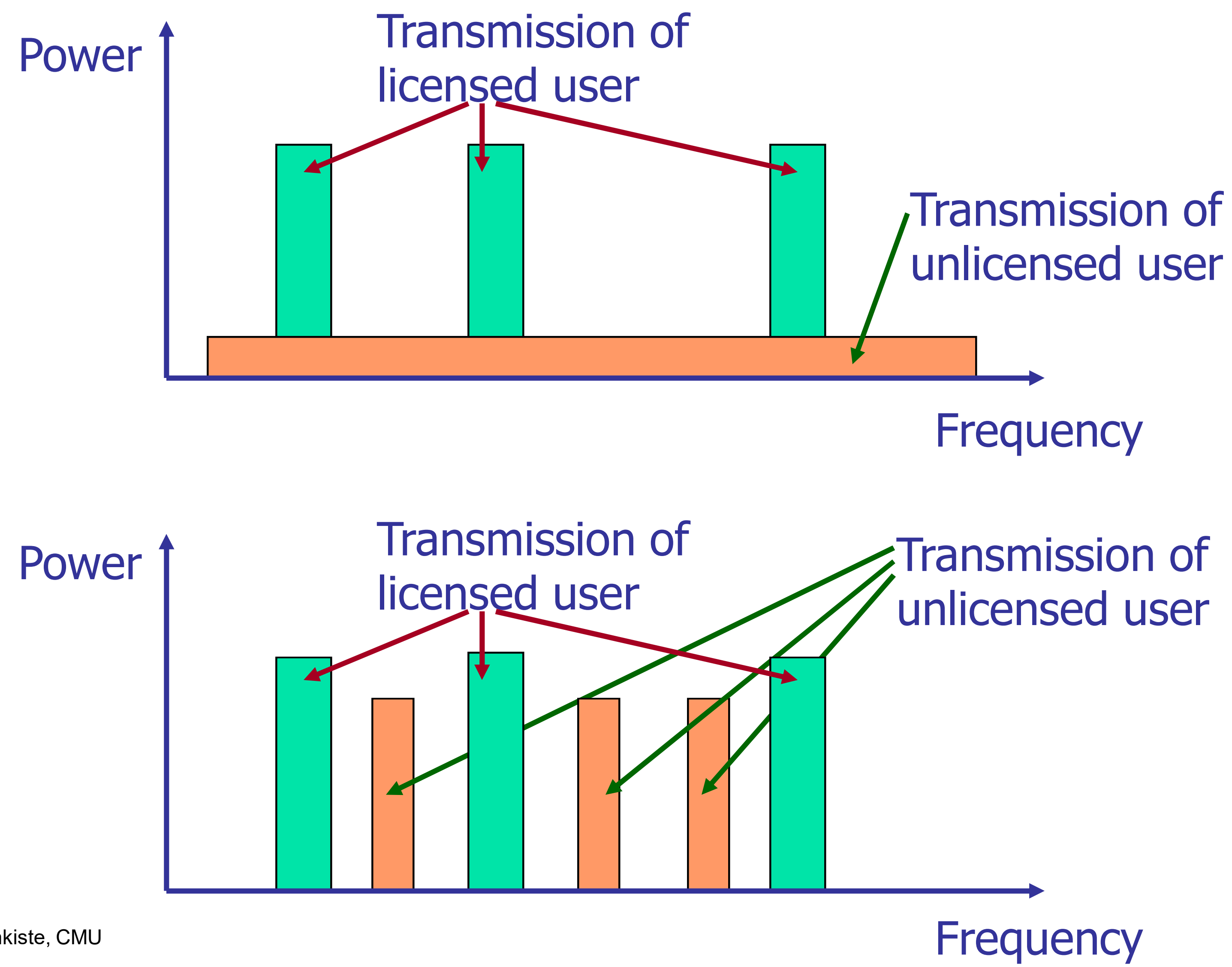
Exclusively owned and used by single owner

- 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

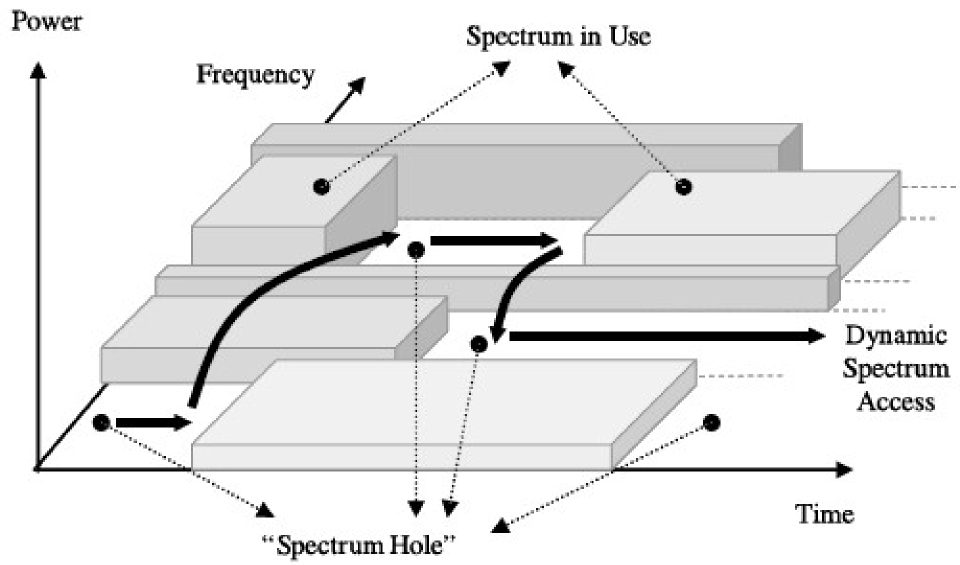
- Spectrum underlay approach constraints the transmission power of secondary users so that they operate below the interference temperature limit of primary users.
- One possible approach is to transmit the signals in a very wide frequency band (e.g., UWB communications) so that high data rate is achieved 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".

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.

High Level View

- Use of temporally unused spectrum, which is referred to as 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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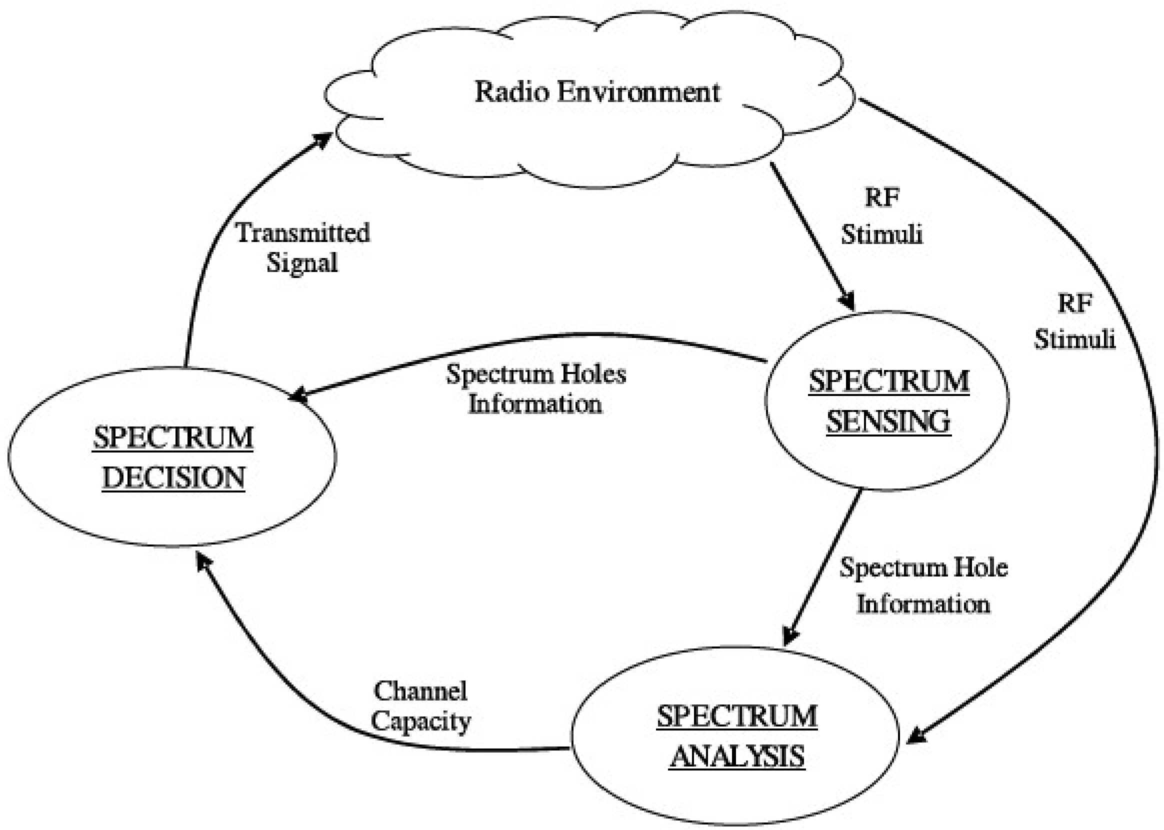
DSA– Cognitive Cycle

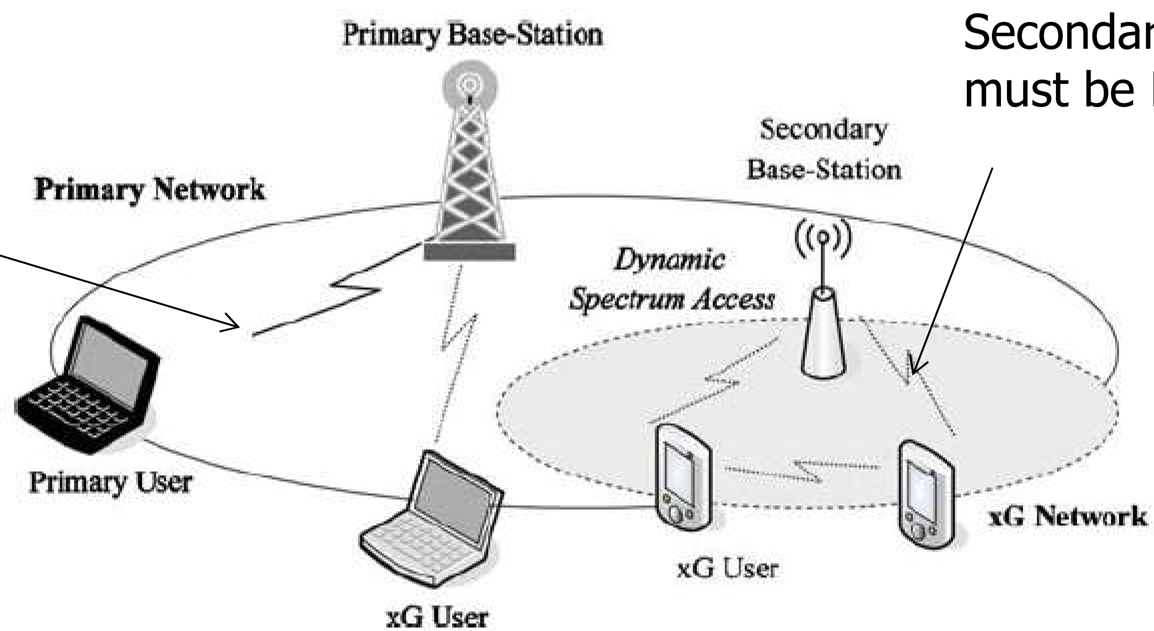


Example of DSA

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

Secondary network must be DSA capable

Primary Network is typically a legacy network

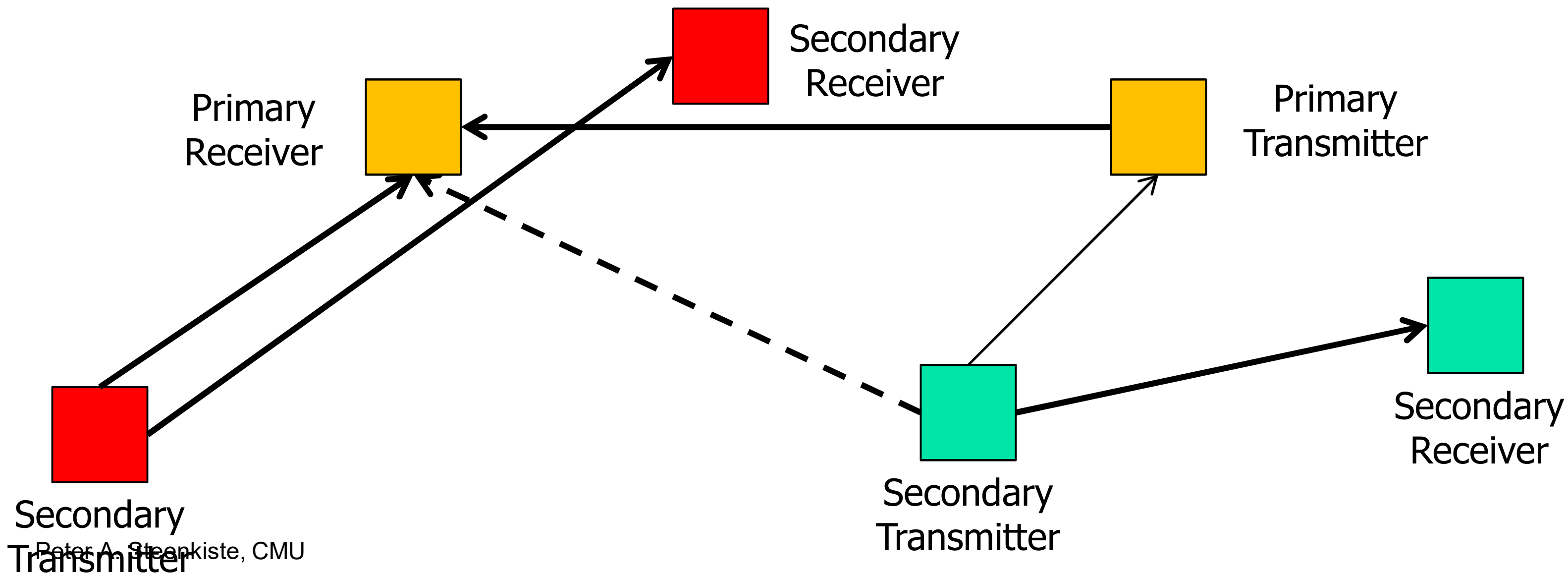


Main Function in DSA

- **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

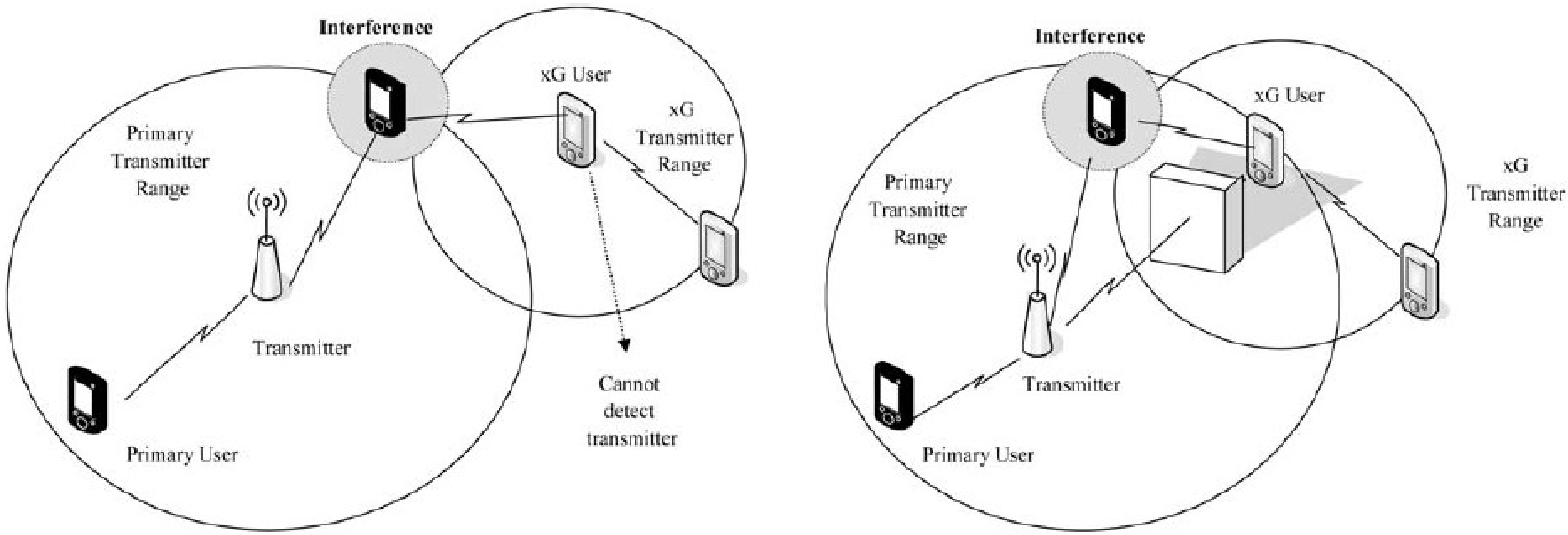
Spectrum Sensing

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



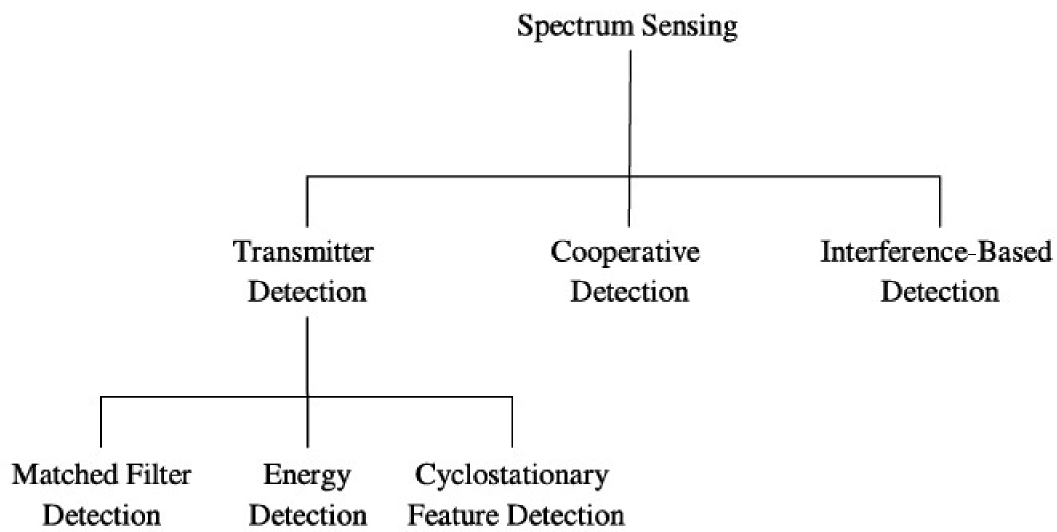
Transmitter Detection Problem

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



(a) (b)

Classification of Spectrum Sensing Techniques



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

noise

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

transmitted signal of the primary users

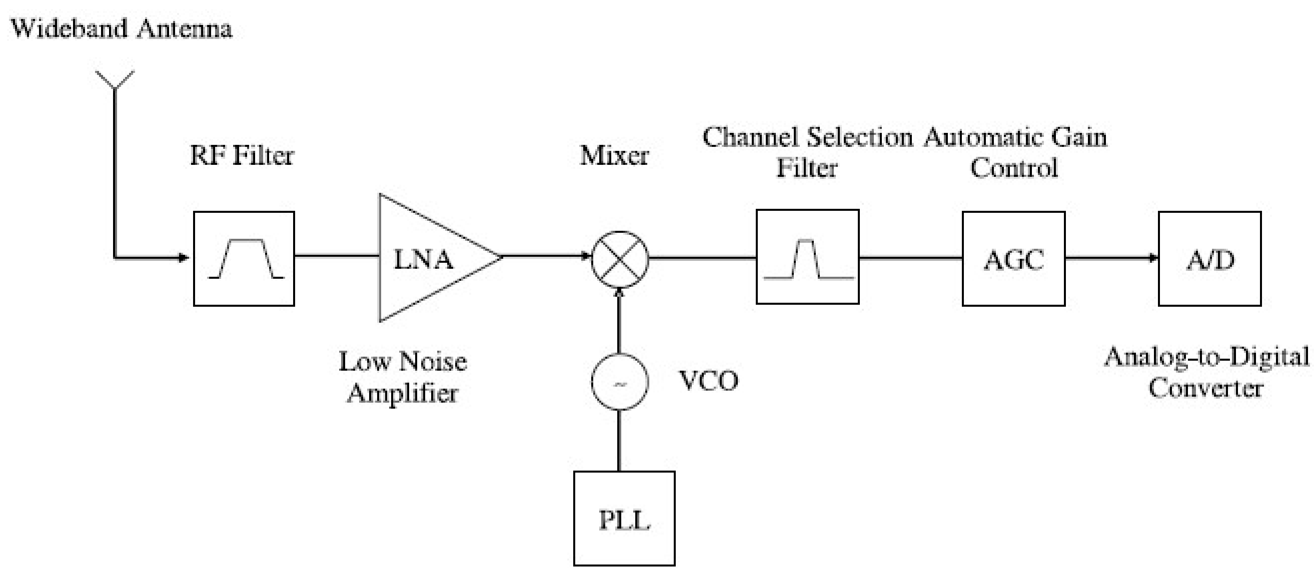
Channel attenuation

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.

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.**

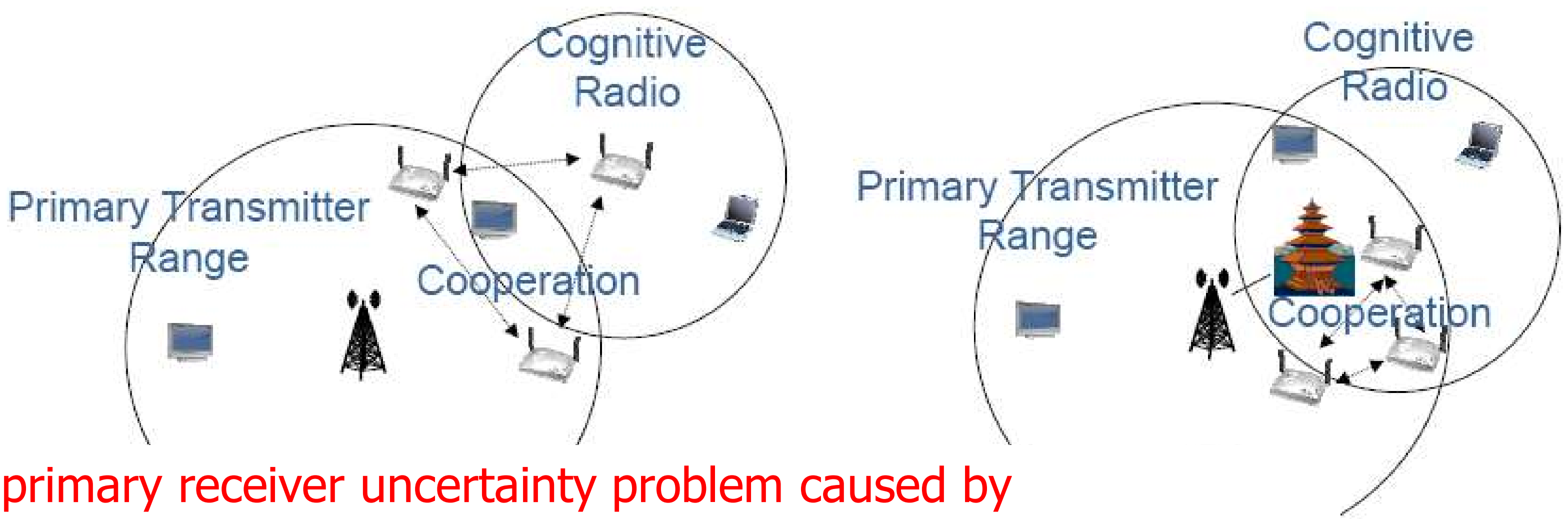


Cognitive Radio - Reconfigurability

- The capability to adjust operating parameters for 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

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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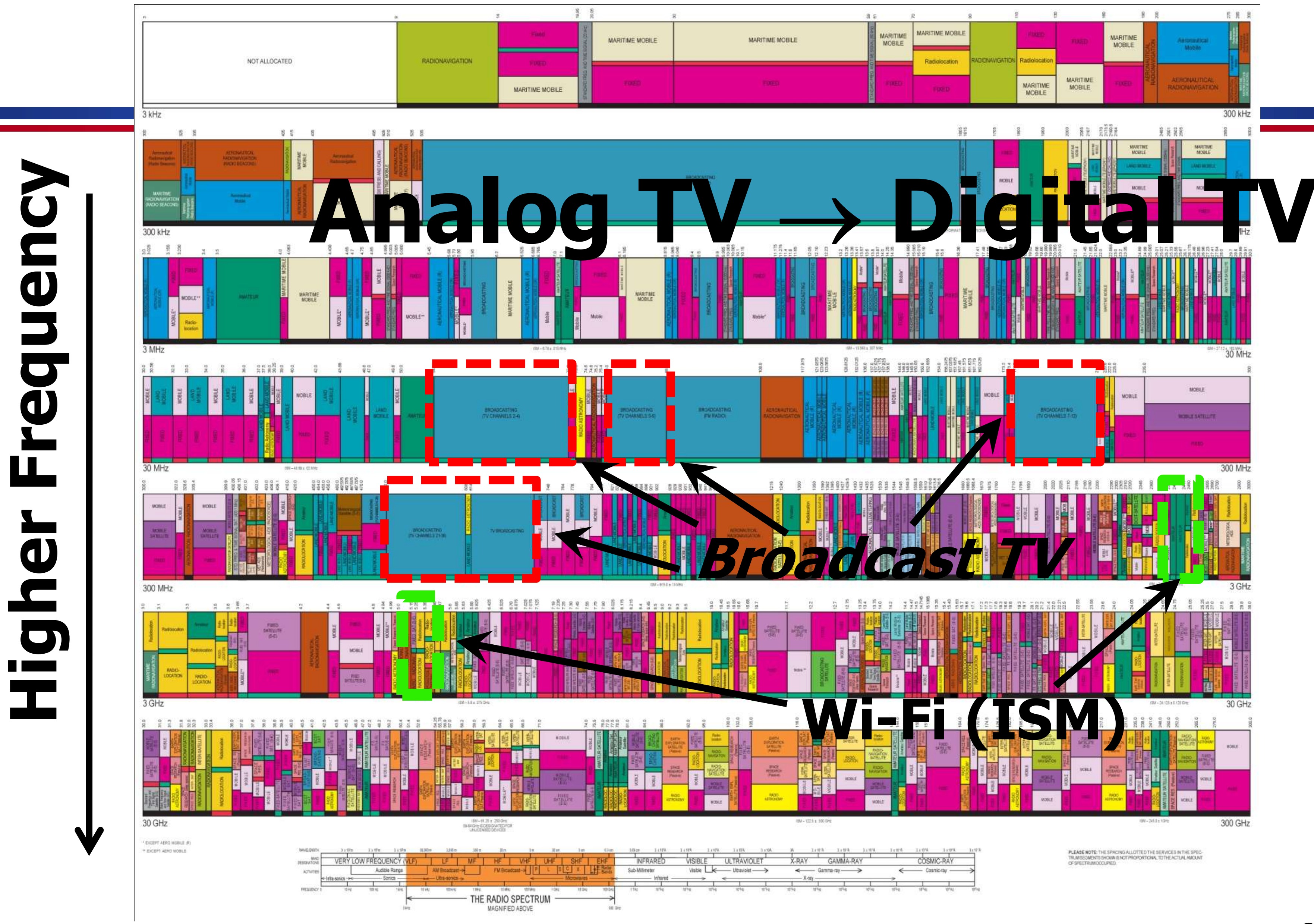
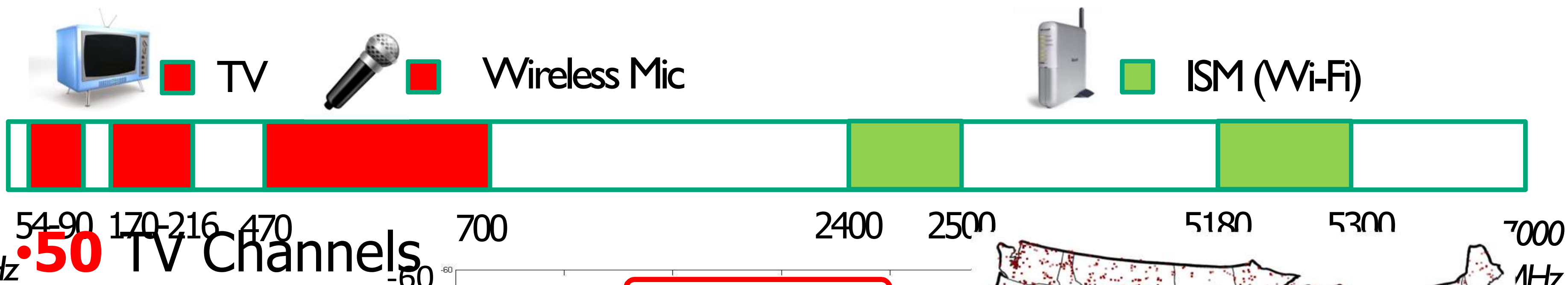


Higher Frequency
Analog TV → Digital TV
Broadcast TV
Wi-Fi (ISM)
3 kHz
300 kHz
300 kHz
3 MHz
30 MHz
30 MHz
300 MHz
300 MHz
3 GHz
3 GHz
30 GHz
30 GHz
300 GHz
THE RADIO SPECTRUM

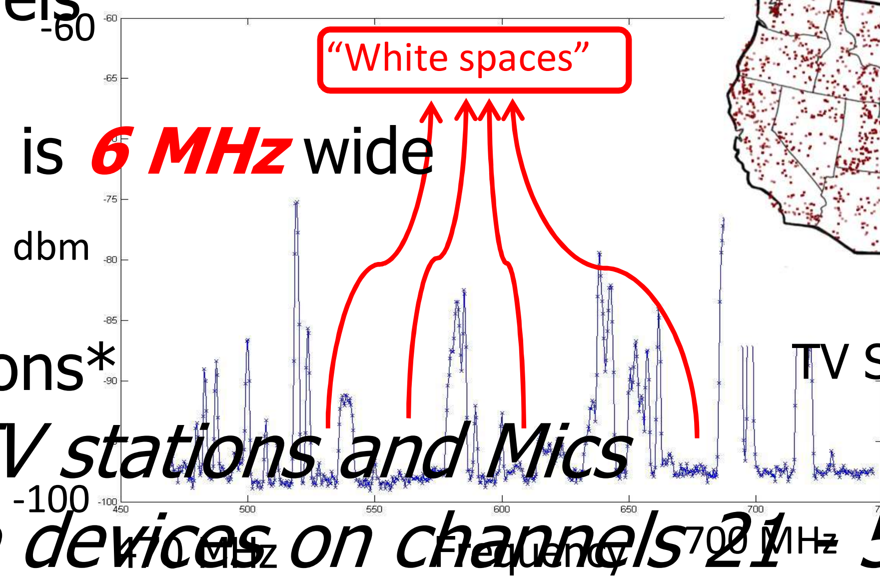
TV White Spaces

- 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

What are TV White Spaces?



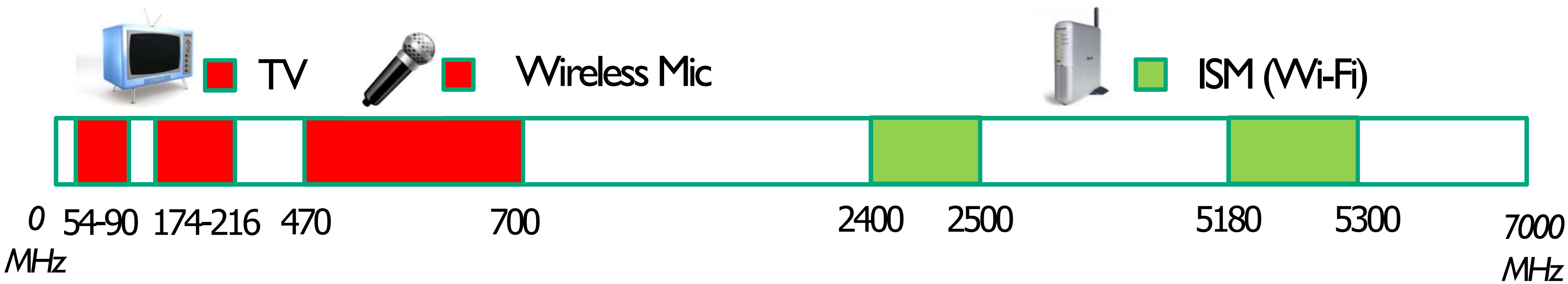
- **50** TV Channels
- Each channel is ***6 MHz*** wide
- FCC Regulations*
  - *Sense TV stations and Mics*
  - *Portable devices on channels 21 - 51*



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

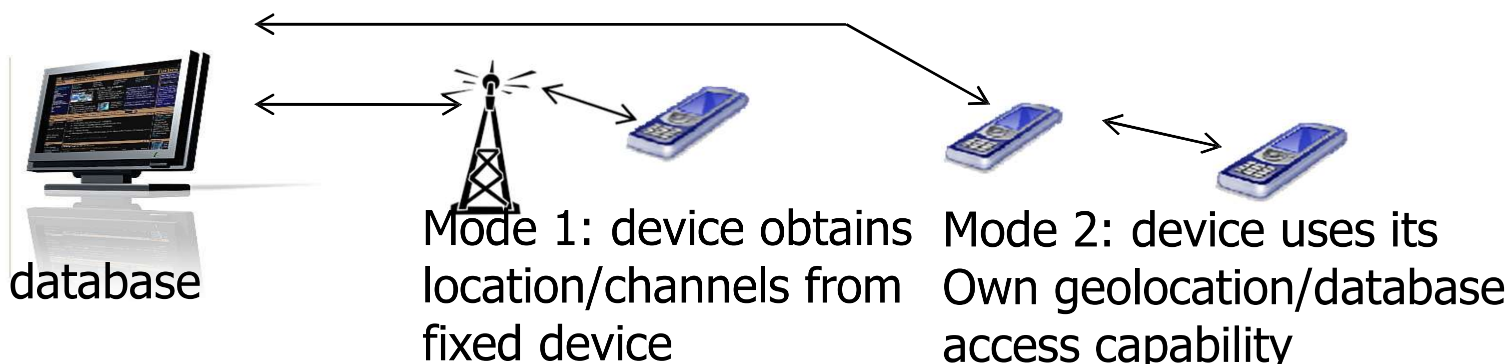
Why Using Geolocation & Database

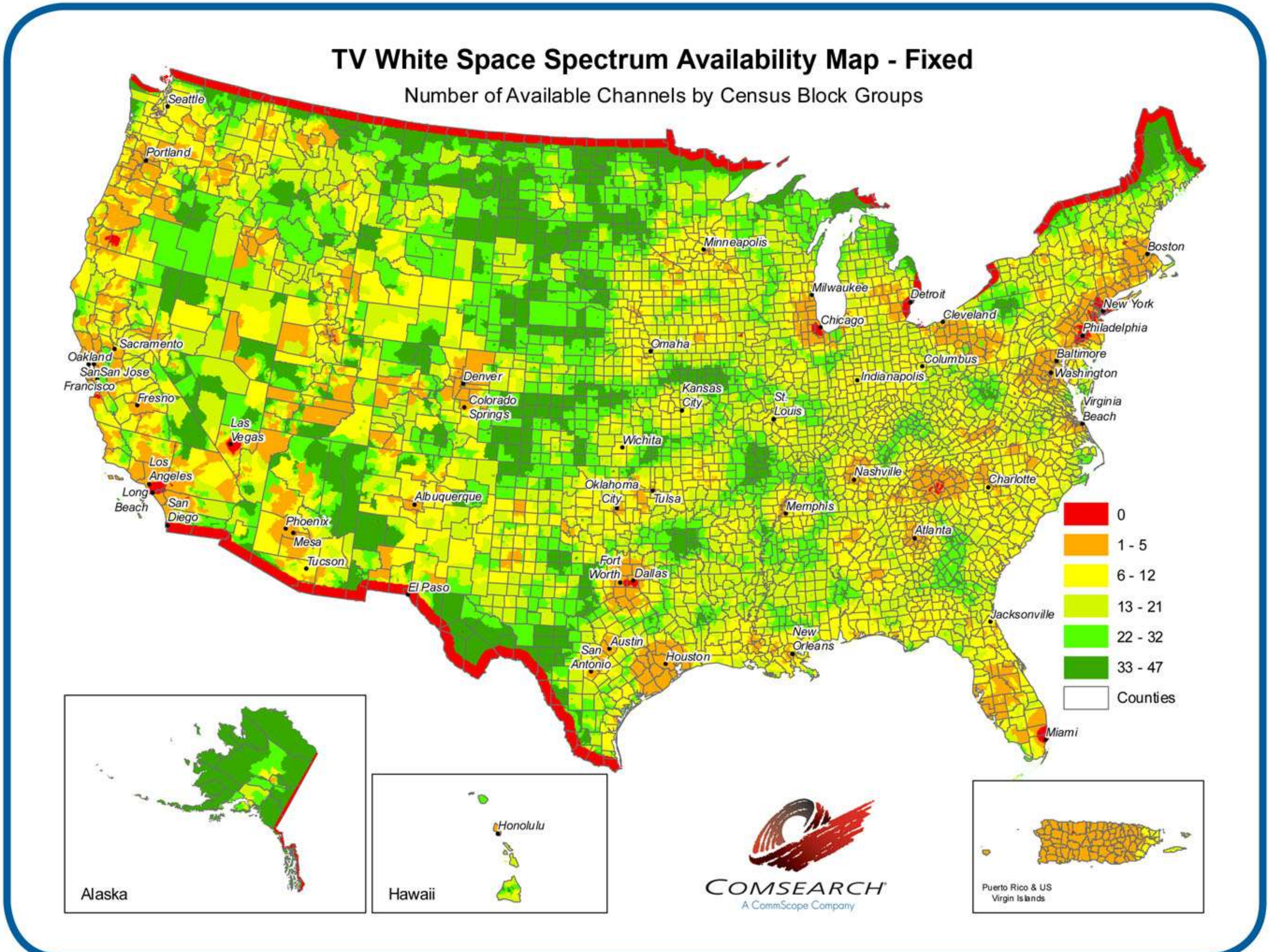
- Based on prototype test program sensing-only solutions not sufficiently developed
  - Very long scan times, poor performance in presence of strong adjacent channel signal, ..
  - Difficult to reliably detecting wireless microphones
  - Inability to determine presence of passive receive sites
- Disagreement 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

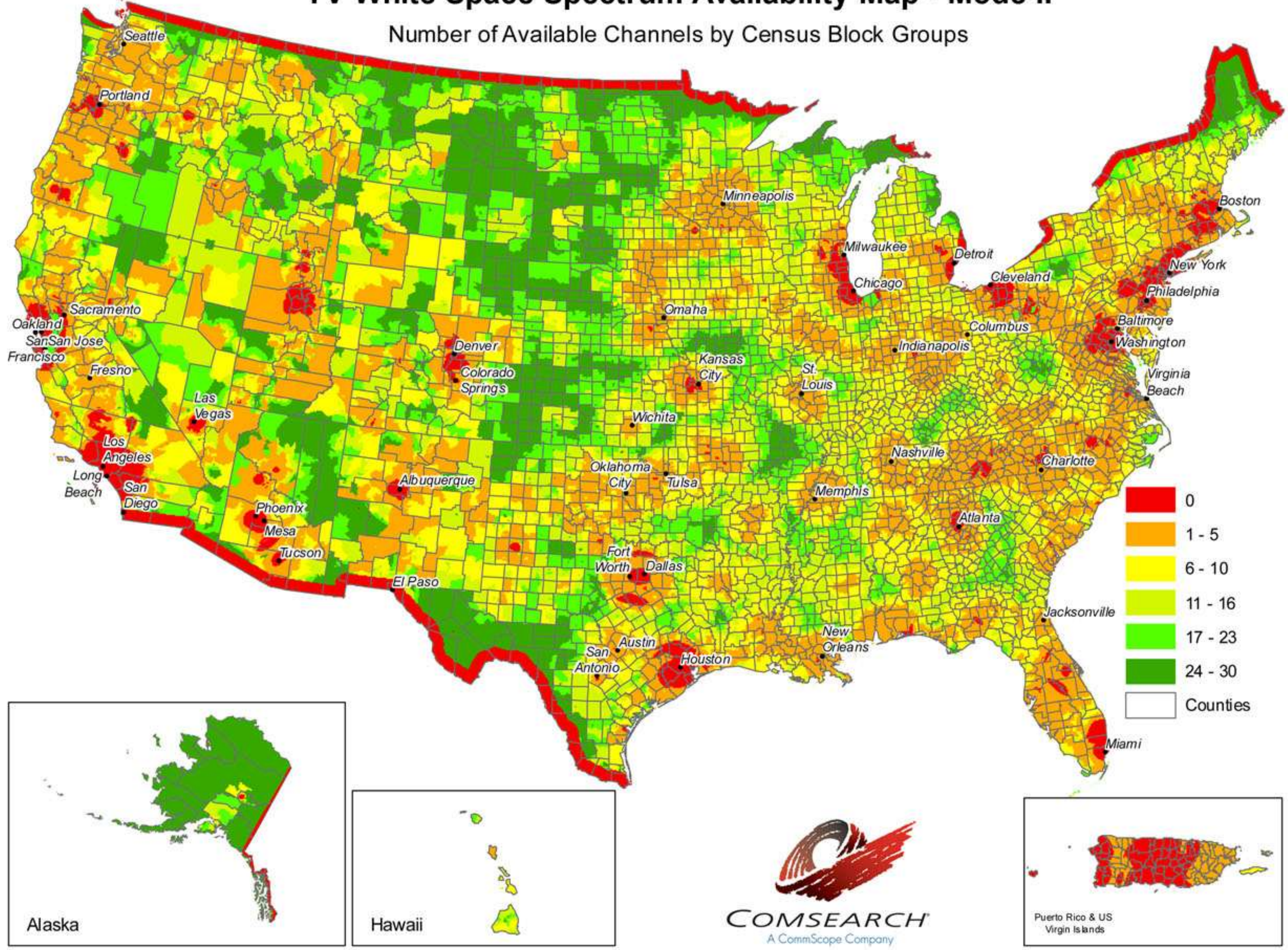




Map from Jan 2010

TV White Space Spectrum Availability Map - Mode II

Number of Available Channels by Census Block Groups



Map from Jan 2010

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

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**