# This lecture is being recorded

## 18-452/750
## Wireless Networks and Applications
## Lecture 23:
## Dynamic Spectrum Access

**Peter Steenkiste**

**CSD and ECE, Carnegie Mellon University**

**Spring Semester 2021**

**http://www.cs.cmu.edu/~prs/wirelessS21/**

# Overview

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

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

Peter A. Steenkiste, CMU

# 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**
  - **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**

Peter A. Steenkiste, CMU

# 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
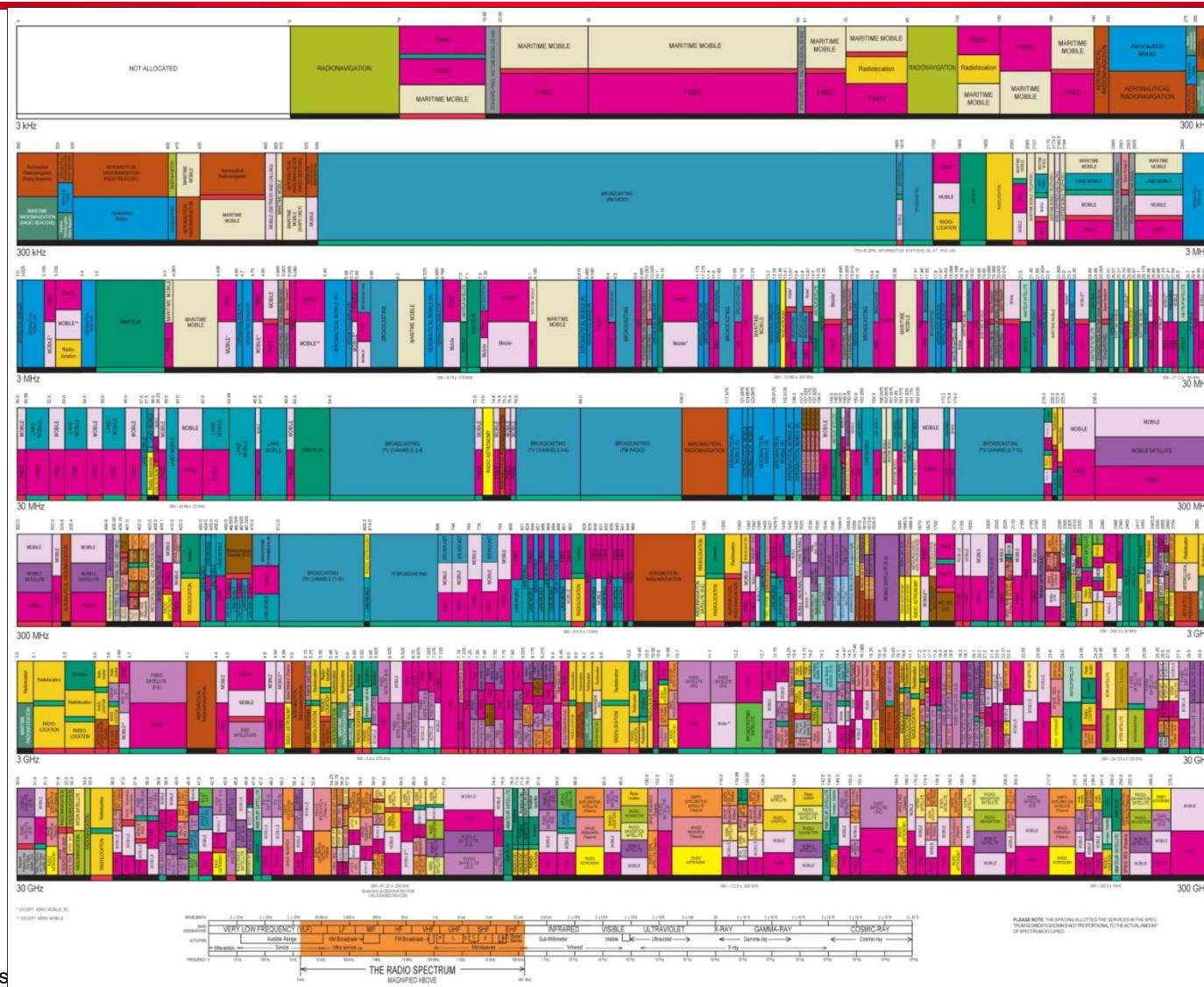
# Different Ways of Controlling Access to Bands

- **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 for new uses**
  - **Need to move current users somewhere**
  - **Significant investment in infrastructure**
- **Exception: higher frequency bands that become viable because of technology advances**

Peter A. Steenkiste, CMU

# 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**

Peter A. Steenkiste, CMU

# Examples of Low Utilization
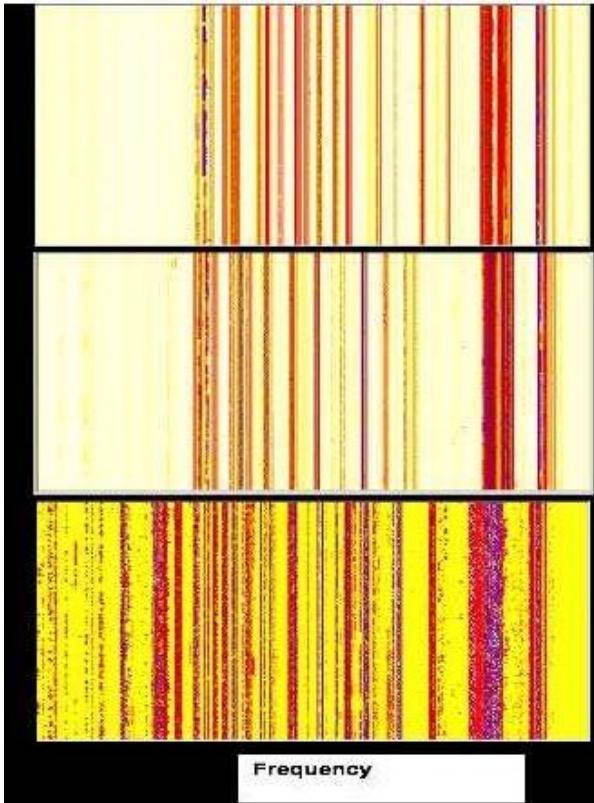


Snapshot of utilization of 700 MHz slice of spectrum below 1 GHz
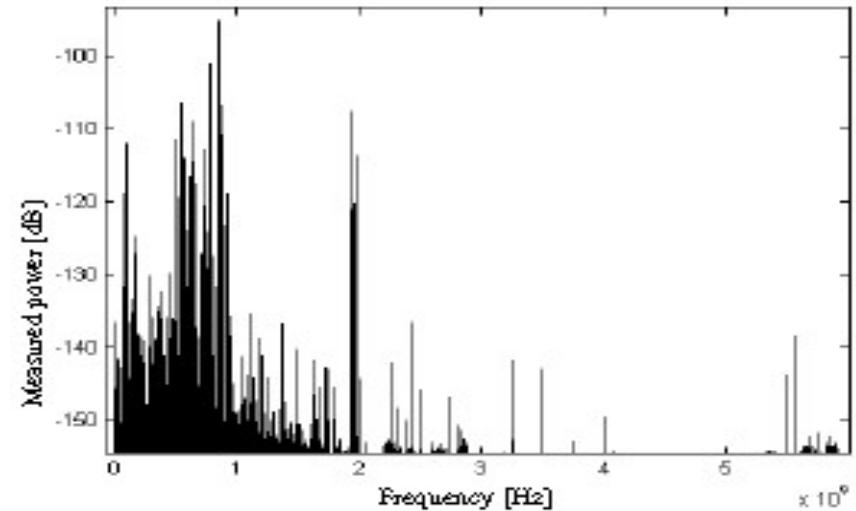


- Utilization of 0.5% in the 3-4 GHz

- 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

Peter A. Steenkiste, CMU

# Overview

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

Peter A. Steenkiste, CMU

# Dynamic Spectrum Access (DSA)

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

```
                    ┌─────────────────────────────┐
                    │   Spectrum Access Model      │
                    └─────────────────────────────┘
         ┌──────────────┬──────────────┬──────────────────┐
   ┌──────────┐  ┌──────────────┐  ┌──────────────┐  ┌──────────────┐
   │ Command  │  │ Exclusive-use│  │ Shared-use of│  │ Commons-use  │
   │and control│  │              │  │primary licensed│ │              │
   └──────────┘  └──────────────┘  │   spectrum   │  └──────────────┘
                                    └──────────────┘
              ┌──────────┬──────────┐        ┌──────────┬──────────┐
        ┌──────────┐ ┌──────────┐       ┌──────────┐ ┌──────────┐
        │Long-term │ │ Dynamic  │       │ Spectrum │ │ Spectrum │
        │exclusive-use│ exclusive-use│  │ overlay  │ │ underlay │
        └──────────┘ └──────────┘       └──────────┘ └──────────┘
```

Peter A. Steenkiste, CMU
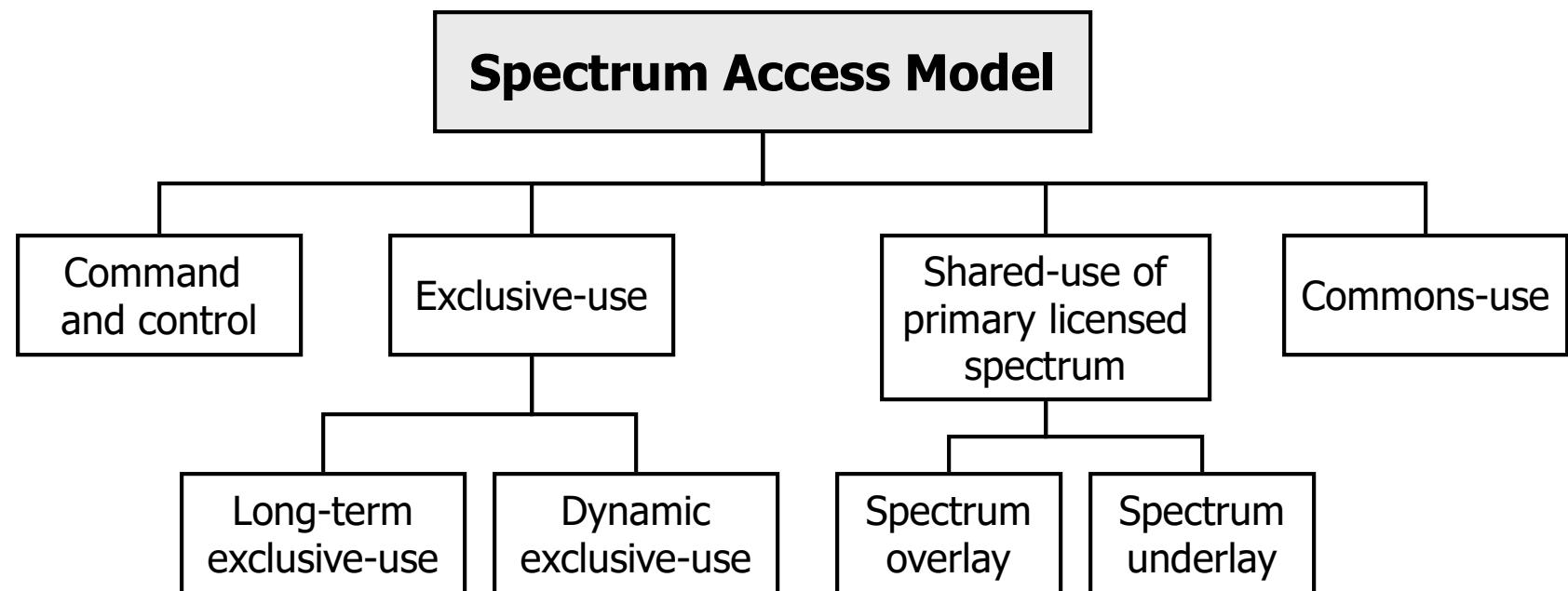
# Exclusive-Use Model

**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 Model
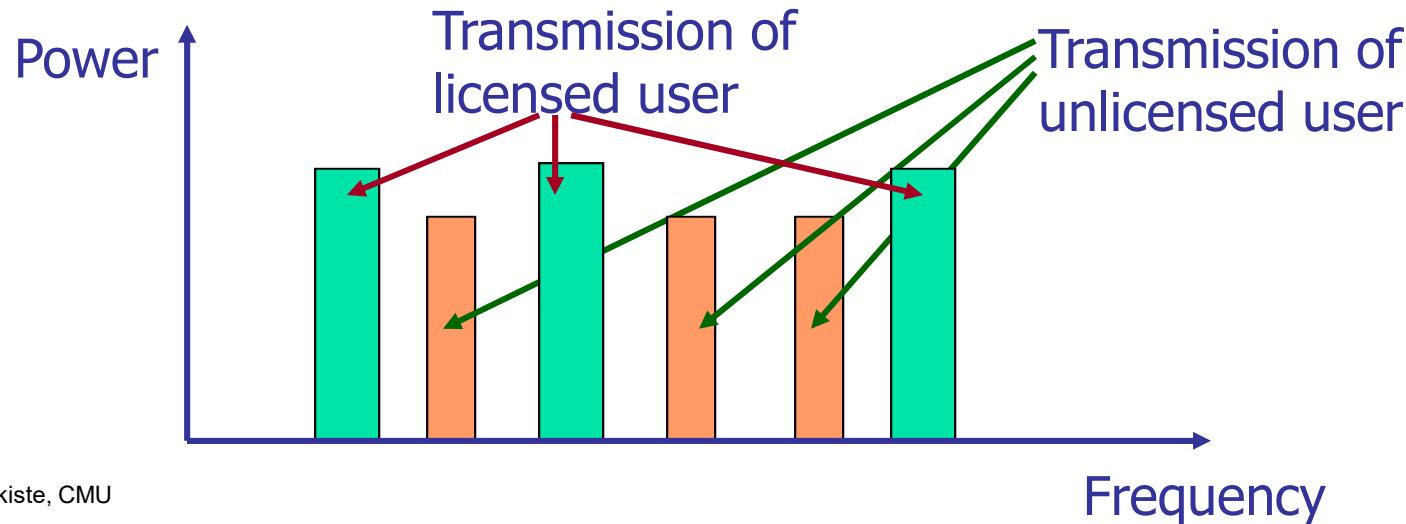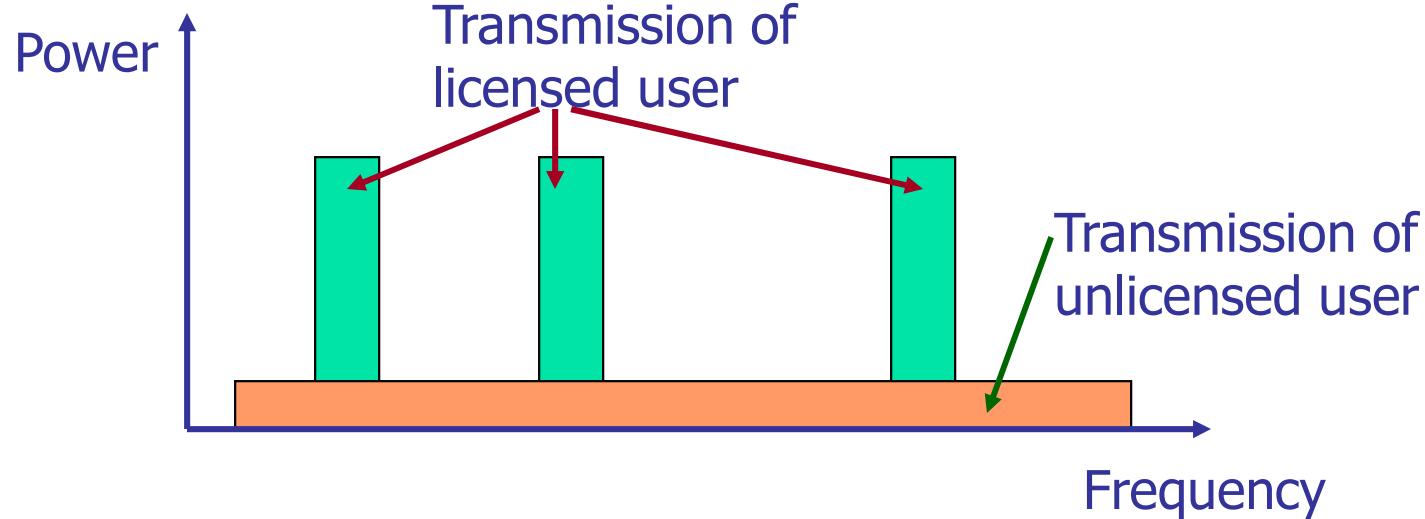
# Spectrum Underlay

- **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.**

Peter A. Steenkiste, CMU

# 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.**

Peter A. Steenkiste, CMU

16

# Example

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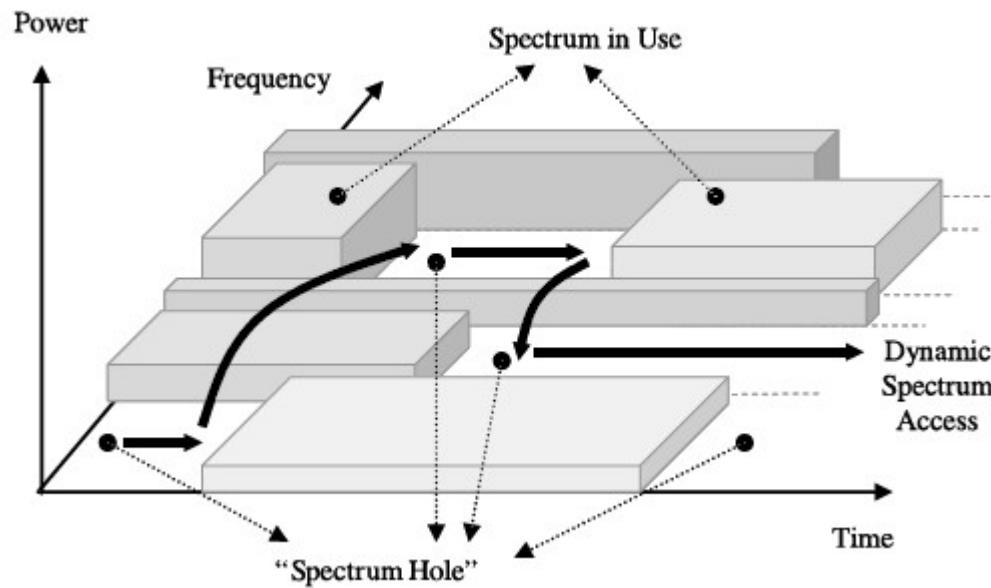
Peter A. Steenkiste, CMU

# Overview

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

Peter A. Steenkiste, CMU

# 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.**
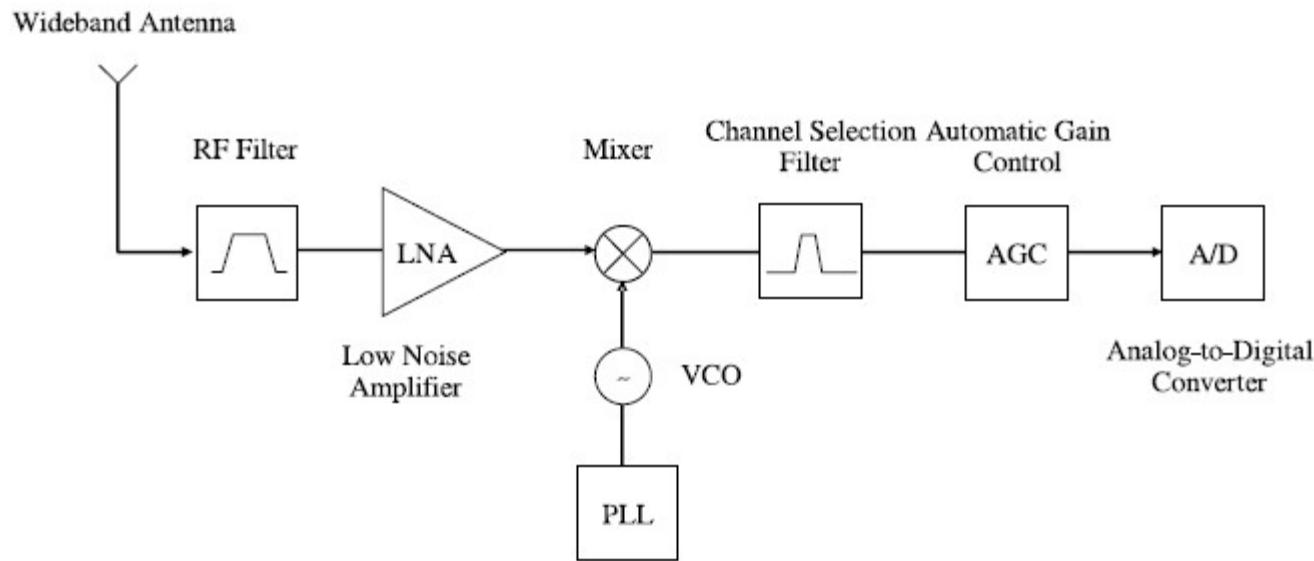
# Cognitive Radio - Reconfigurability

- **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**

# 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

Peter A. Steenkiste, CMU
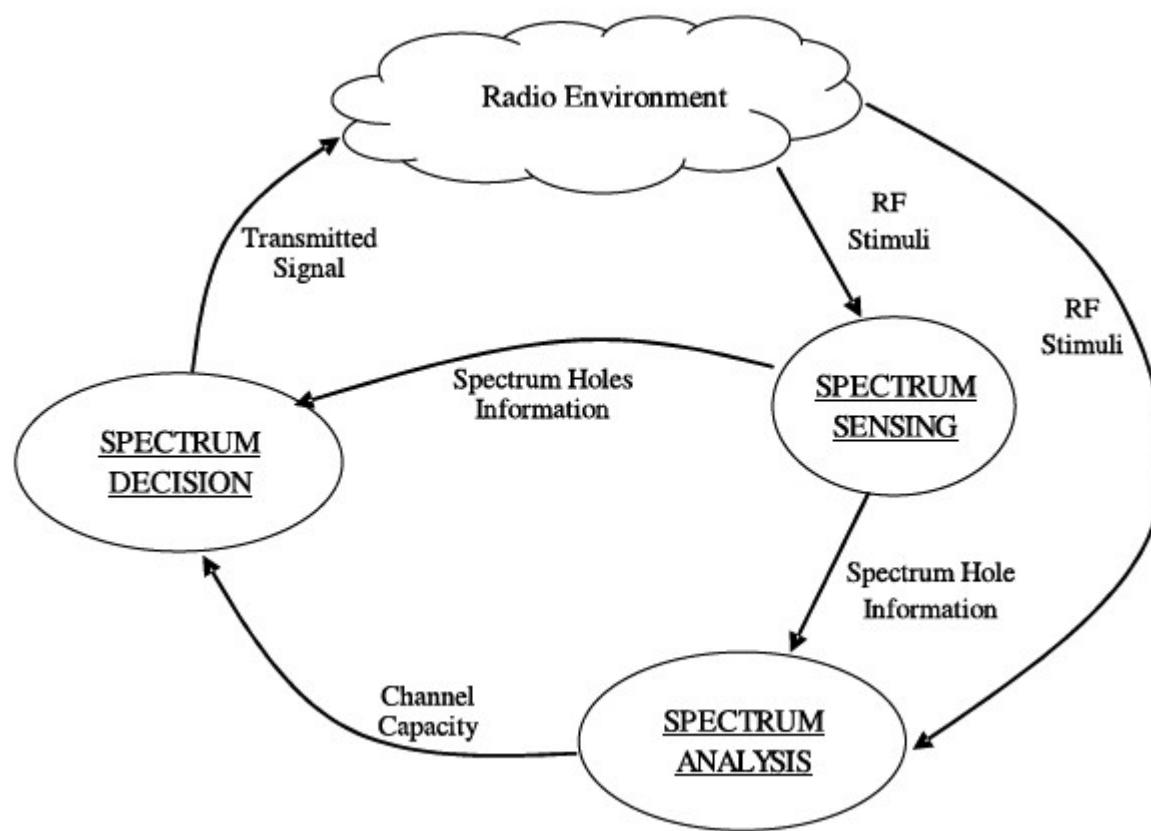
# Example of DSA

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

Primary Network is typically a legacy network

Secondary network must be DSA capable

Primary Base-Station

Primary Network

Secondary Base-Station

Dynamic Spectrum Access

Primary User

xG User

xG User
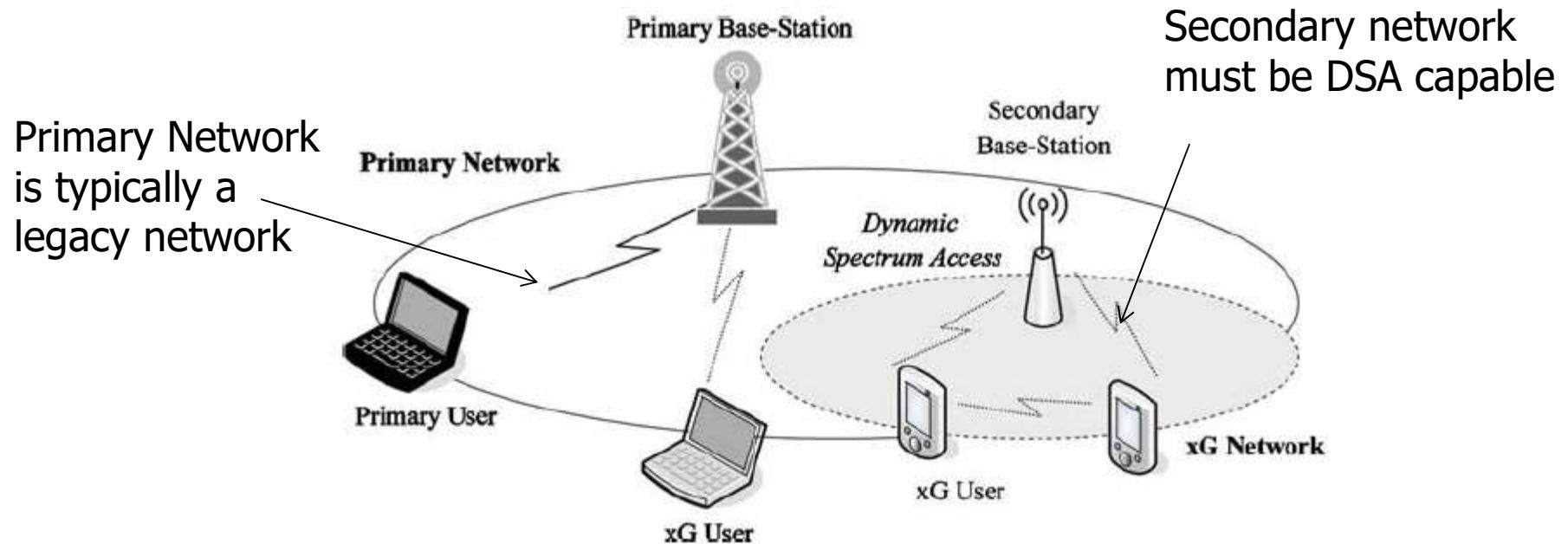
xG Network

# 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.**
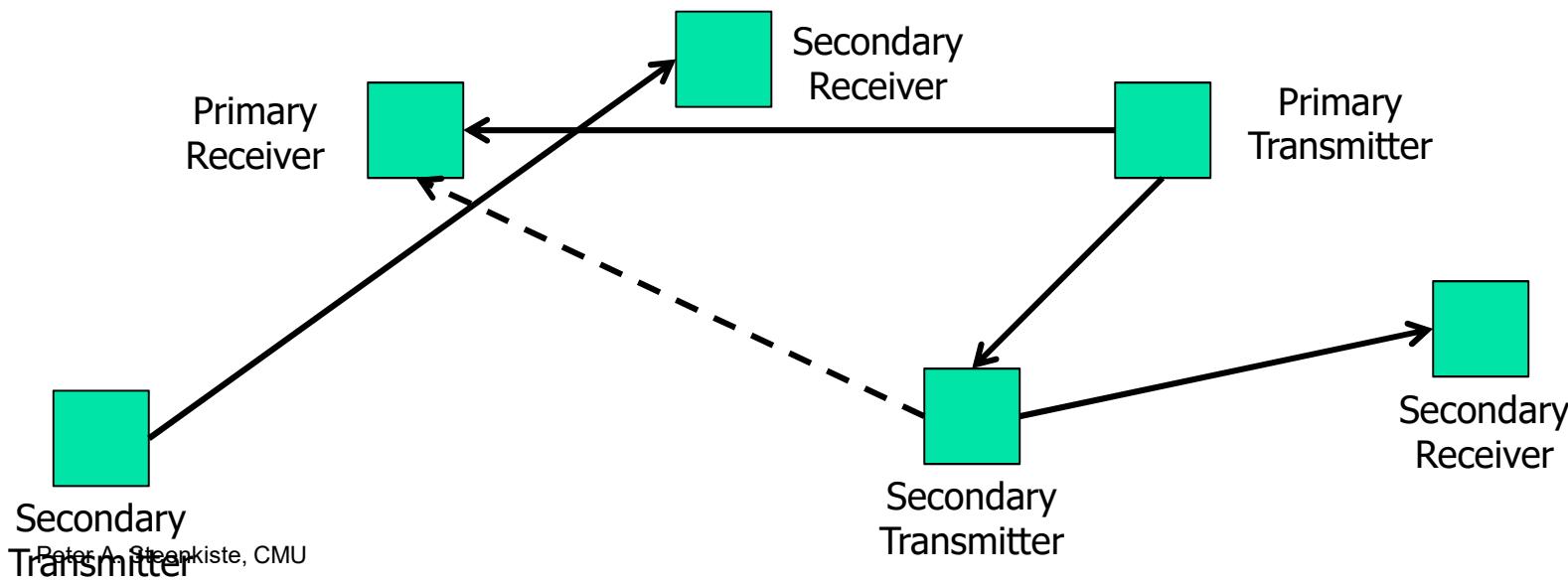
# Classification of Spectrum Sensing Techniques

Spectrum Sensing

- Transmitter Detection
  - Matched Filter Detection
  - Energy Detection
  - Cyclostationary Feature Detection
- Cooperative Detection
- Interference-Based Detection
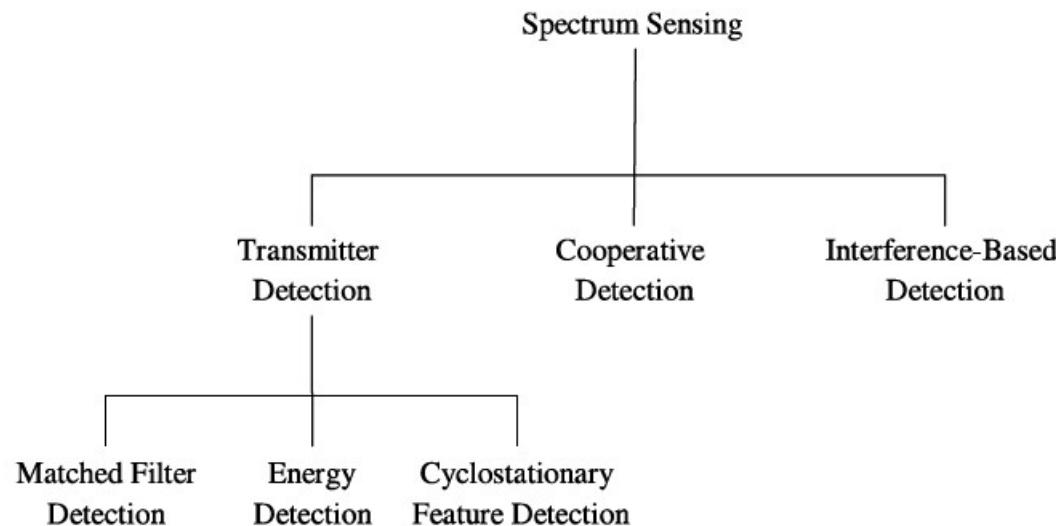
- **Transmitter detection approach: the detection of the weak signal from a primary transmitter through the local observations**

- **Basic hypothesis**

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

the AWGN

transmitted signal of the primary users

the amplitude gain of the channel

# Transmitter Detection Problem

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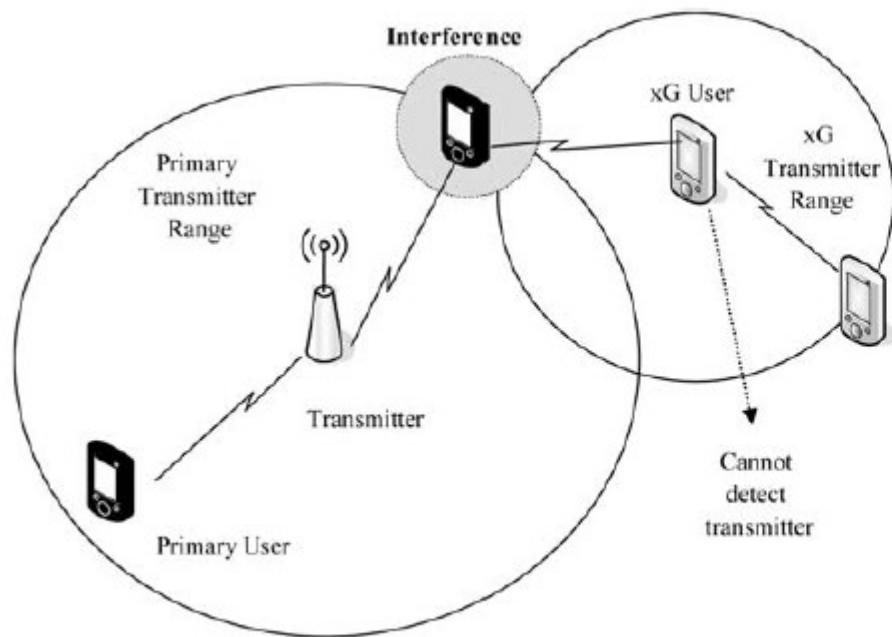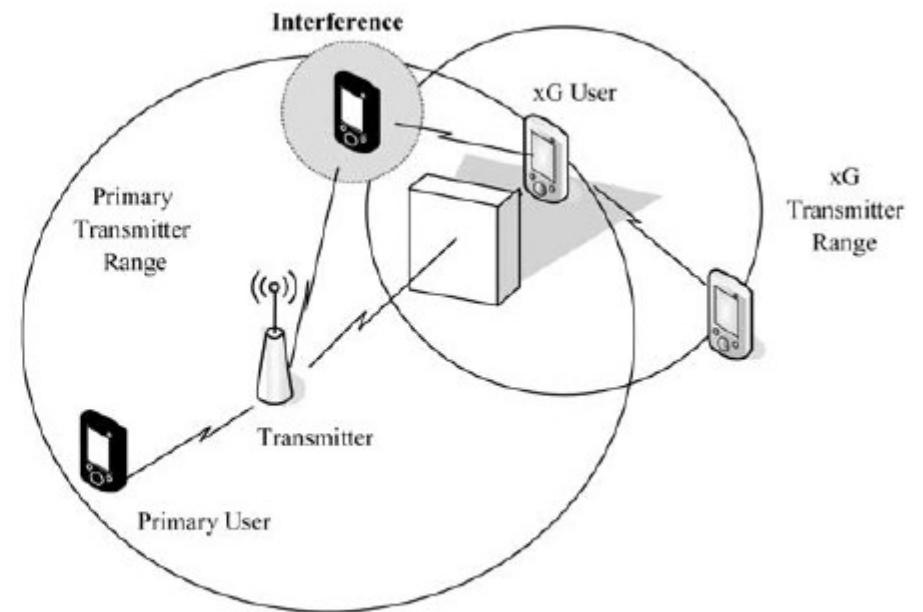


(a)                    (b)

# 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.

# 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.**
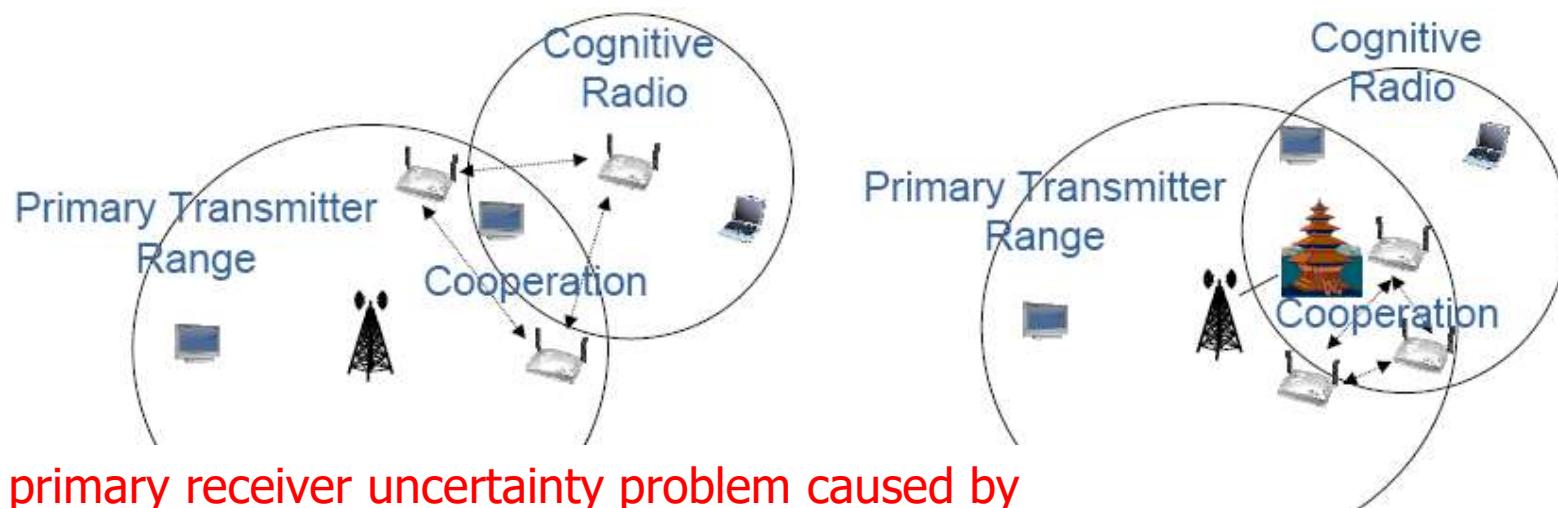


The primary receiver uncertainty problem caused by
the lack of the primary receiver location knowledge is unsolved.

# 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.**

Peter A. Steenkiste, CMU

# 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**

Peter A. Steenkiste, CMU

# Overview

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

Peter A. Steenkiste, CMU

**Higher Frequency**

Analog TV → Digital TV

*Broadcast TV*

Wi-Fi (ISM)

Peter A. Steenkiste, CMU

33
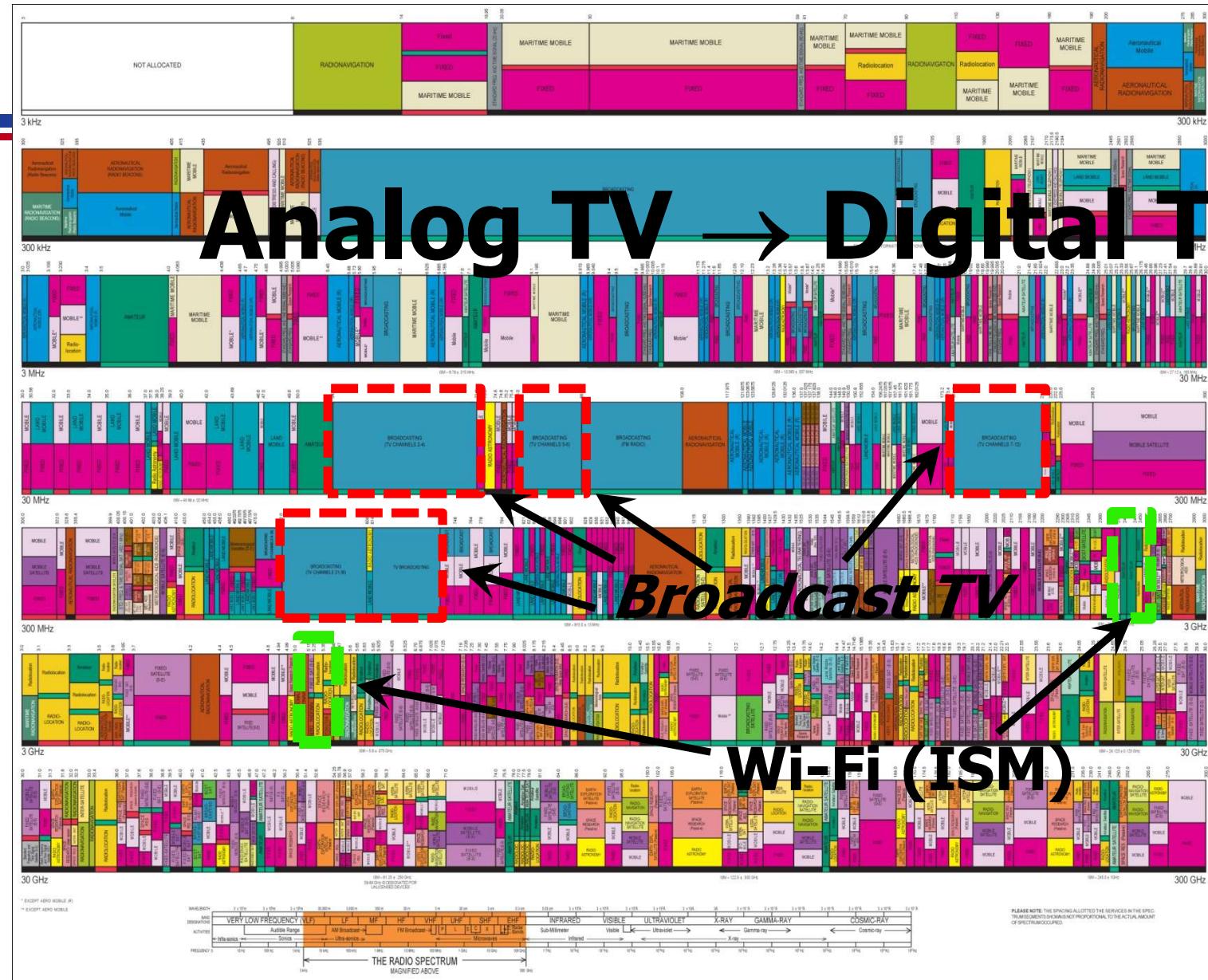
# TV White Spaces

- **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**

# What are TV White Spaces?



TV  Wireless Mic  ISM (Wi-Fi)

0 54-90 170-216 470        700              2400  2500           5180  5300        7000
MHz                                                                                 MHz

- **50** TV Channels

"White spaces"

- Each channel is **6 MHz** wide

- FCC Regulations*
  - *Sense TV stations and Mics*
  - *Portable devices on channels 21 – 51*

dbm

TV Stations in America
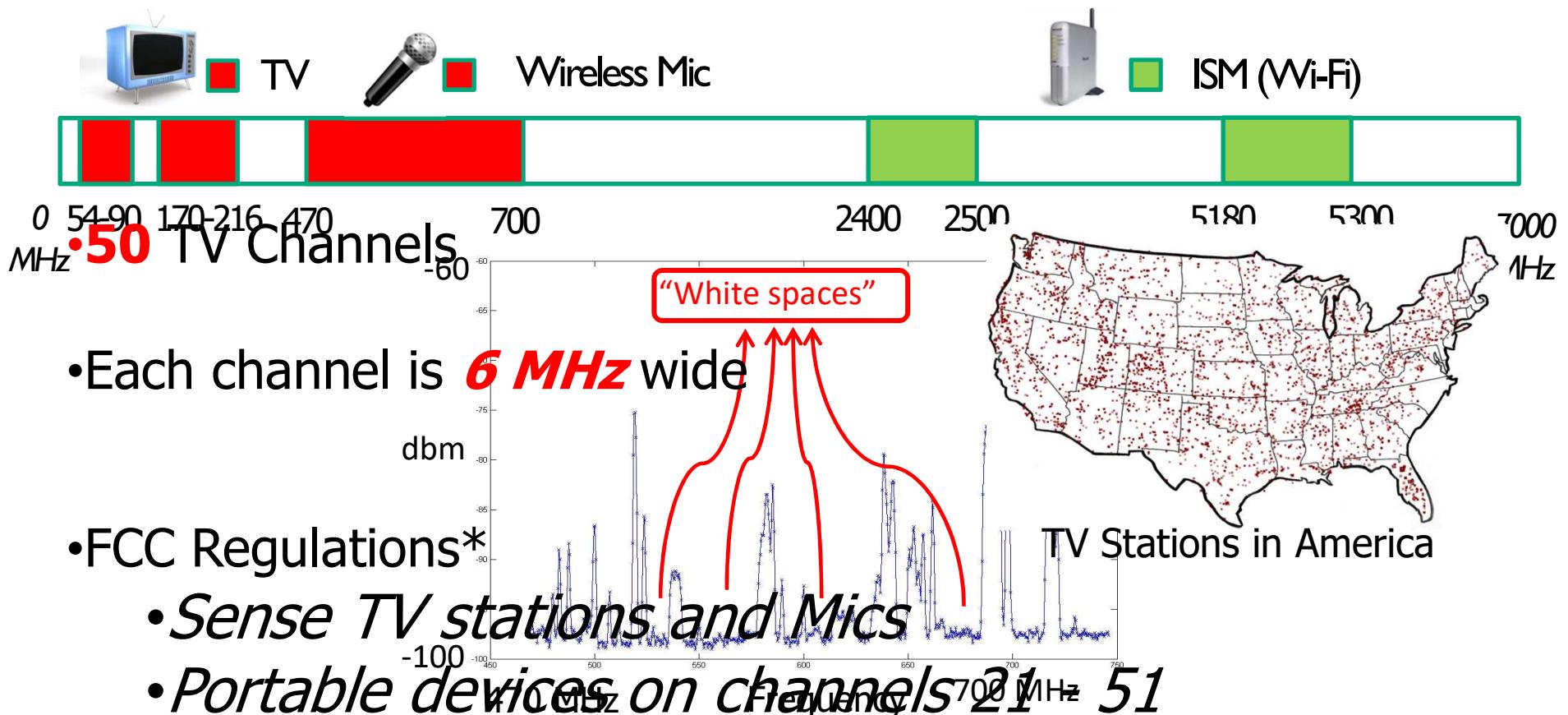
White Spaces  are *Unoccupied* TV Channels

Peter A. Steenkiste, CMU

# The Promise of White Spaces

| | TV | | Wireless Mic | | ISM (Wi-Fi) |
|---|---|---|---|---|---|

0
MHz — 54-90 — 174-216 — 470 — 700 — 2400 — 2500 — 5180 — 5300 — 7000 MHz
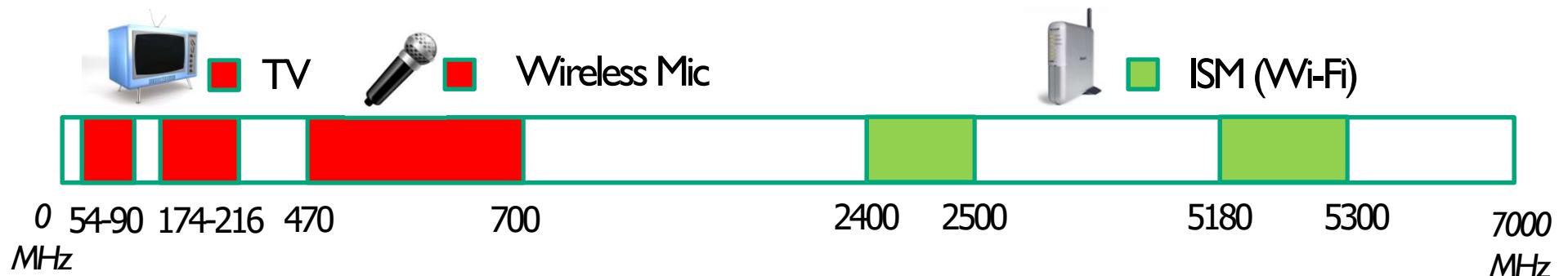
**Up to 3x of 802.11g**

**More Spectrum**

**Longer Range**

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

**Potential Applications**

Rural wireless broadband

City-wide mesh

........

........

Peter A. Steenkiste, CMU

# 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**

https://www.whitespaceforus.com/wsdb/wsdb_ui/Channel_Availability.html



database

Mode 1: device obtains location/channels from fixed device

Mode 2: device uses its Own geolocation/database access capability

Seattle
Portland
Minneapolis
Boston
Milwaukee
Detroit
New York
Chicago
Cleveland
Philadelphia
Sacramento
Omaha
Columbus
Baltimore
Oakland
Indianapolis
Washington
San San Jose
Denver
Francisco
Fresno
Colorado
Kansas
St.
Virginia
Springs
City
Louis
Beach
Las
Vegas
Wichita
Los
Angeles
Nashville
Charlotte
Long
San
Oklahoma
Beach
Diego
Albuquerque
City
Tulsa
Phoenix
Memphis
Mesa
Atlanta
Tucson
Fort
El Paso
Worth
Dallas
Jacksonville
New
San
Austin
Orleans
Antonio
Houston
Miami

| | Channels |
|---|---|
| 🟥 | 0 |
| 🟧 | 1 - 5 |
| 🟨 | 6 - 12 |
| | 13 - 21 |
| 🟩 | 22 - 32 |
| 🟩 | 33 - 47 |
| ⬜ | Counties |

Alaska

Hawaii

Honolulu

COMSEARCH
A CommScope Company

Puerto Rico & US
Virgin Islands

Peter A. Steenkiste, CMU

Map from Jan 2010

# TV White Space Spectrum Availability Map - Mode II

## Number of Available Channels by Census Block Groups



Legend:
- 0
- 1 - 5
- 6 - 10
- 11 - 16
- 17 - 23
- 24 - 30
- Counties
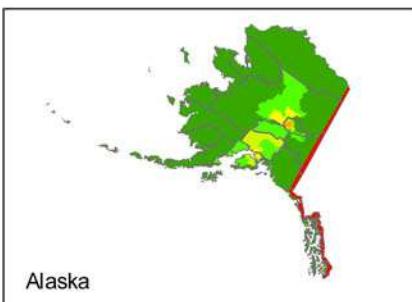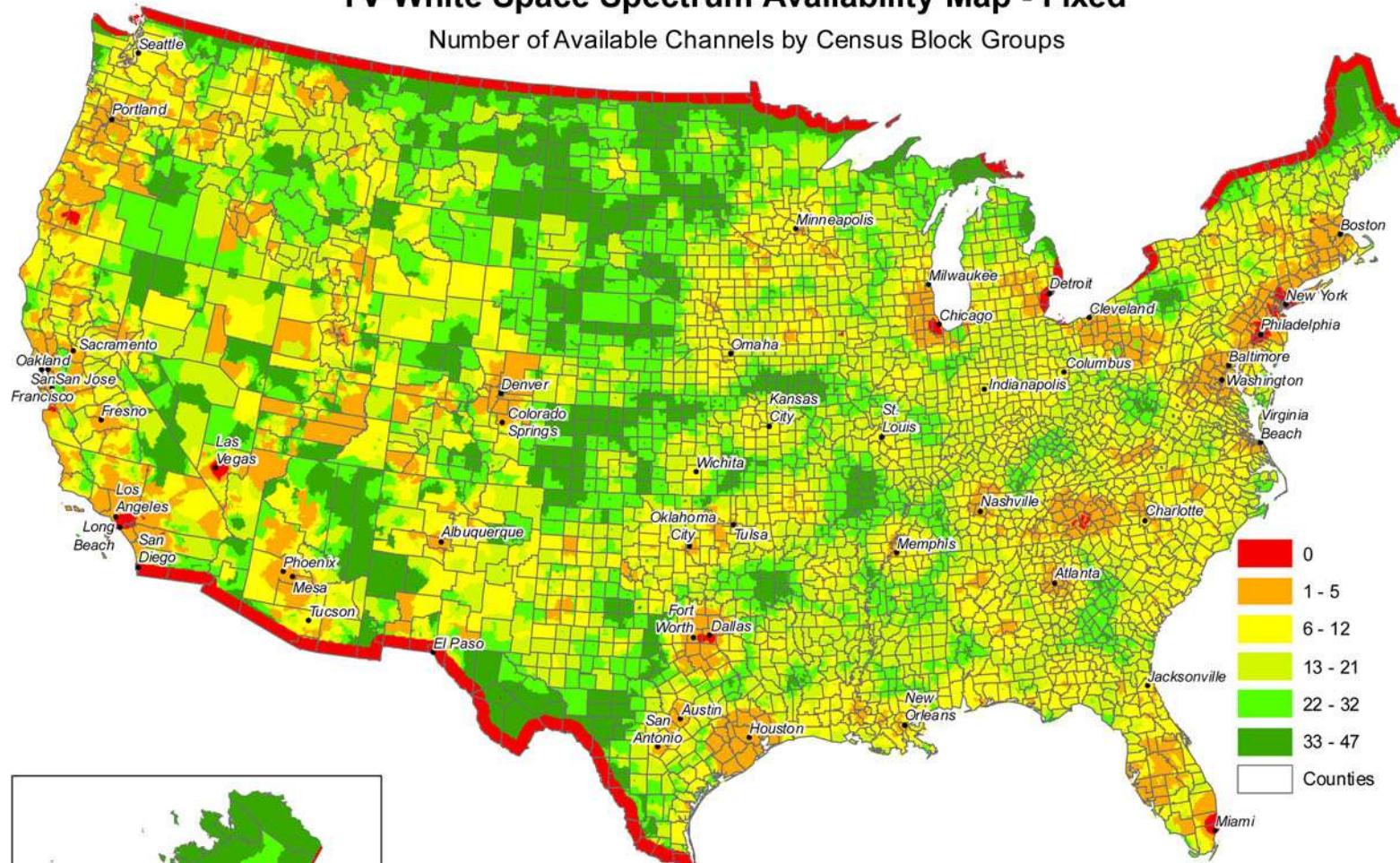
Alaska
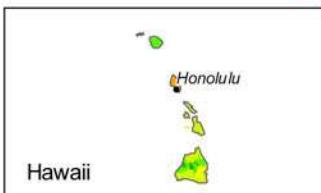
Hawaii

COMSEARCH
A CommScope Company

Puerto Rico & US Virgin Islands

Peter A. Steenkiste, CMU

Map from Jan 2010
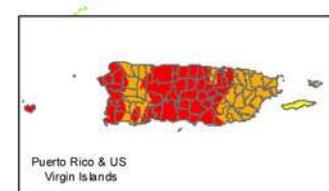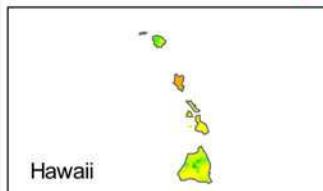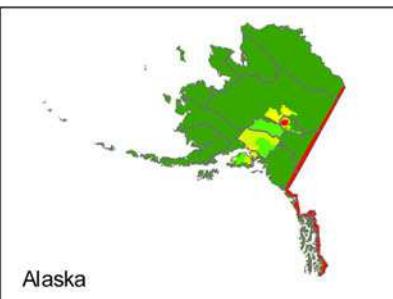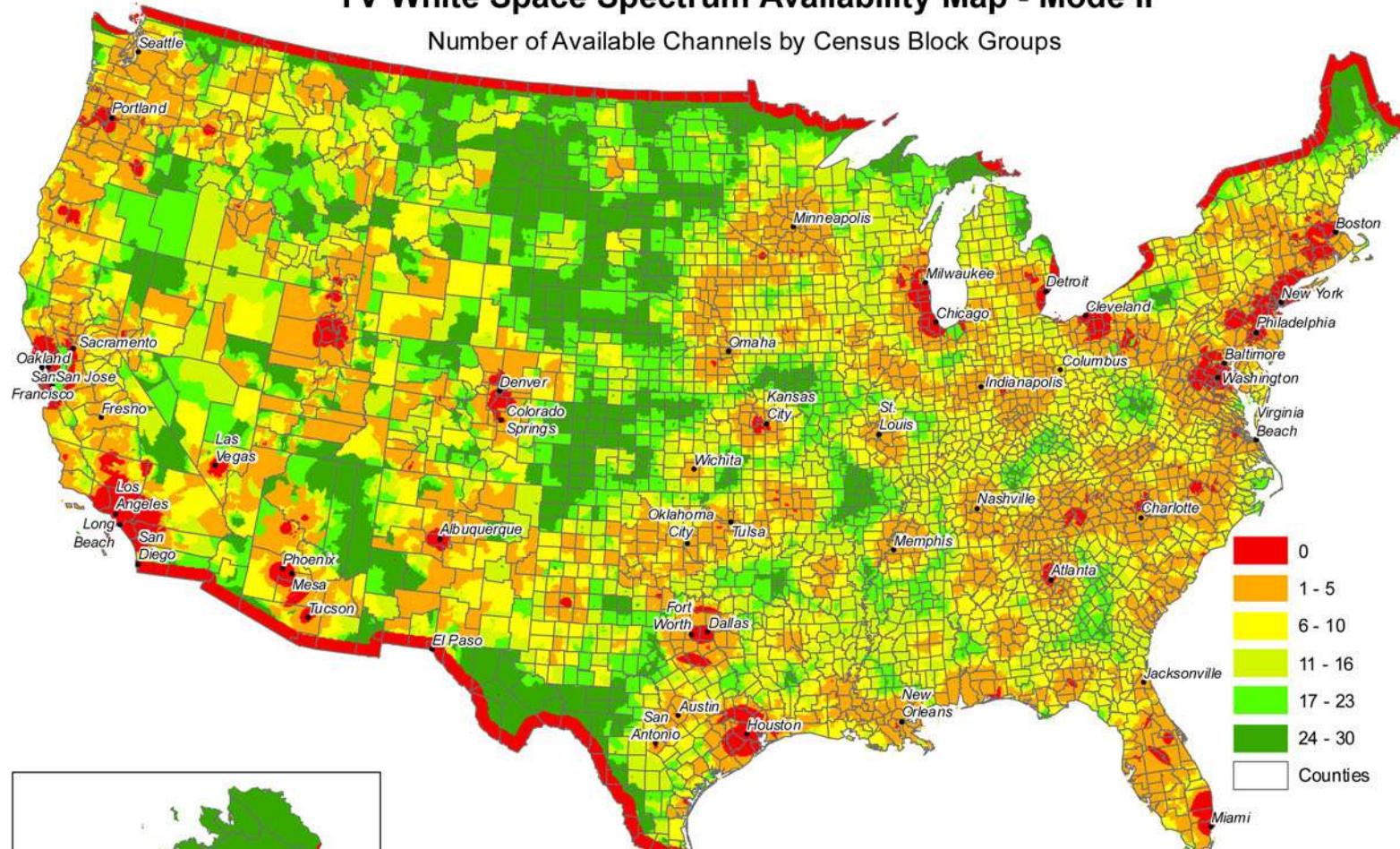
# Standards for White Spaces

- **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**

Peter A. Steenkiste, CMU

# 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**

802.22 CPE

**802.11af LAN**

802.22
Base Station

802.22 CPE

802.11af AP

802.11af station