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

Peter Steenkiste
CSD and ECE, Carnegie Mellon University

Spring Semester 2020
http://www.cs.cmu.edu/~prs/wirelessS20/

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

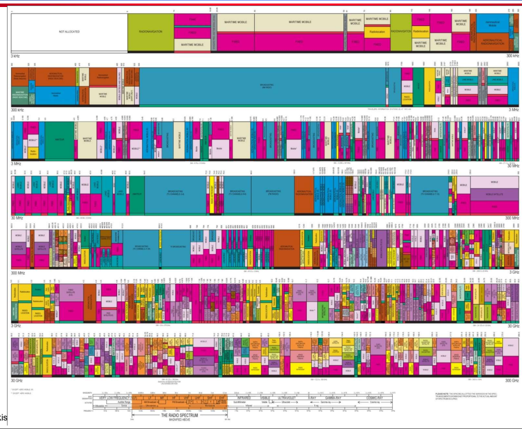
- **300 GHz is huge amount of spectrum!**
  - **Spectrum can also be reused in space**
- **Not quite that easy:**
  - **Most of it is hard or expensive to use!**
  - **Noise and interference limits efficiency**
  - **Most of the spectrum is allocated by FCC**
- **FCC controls who can use the spectrum 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**

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

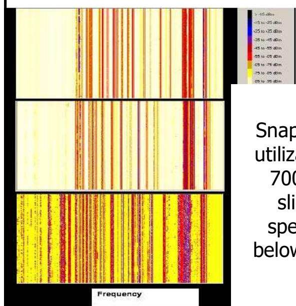
New Spectrum is Scarce

- 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

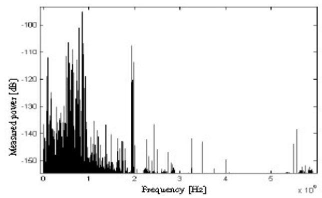
But Allocated Spectrum is not Used Effectively

- 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

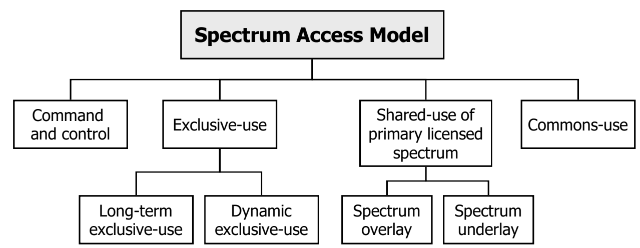
- **Make allocation "more dynamic"**
  - **Can better adjust to allocation to needs**
- **Main concern: avoid interference to "incumbents"**
  - **Often have major investment in infrastructure**
  - **Interference can be fatal, e.g. first responders, businesses, …**
- **Many models are possible:**
  - **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**

Overview

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

Dynamic Spectrum Access (DSA)

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

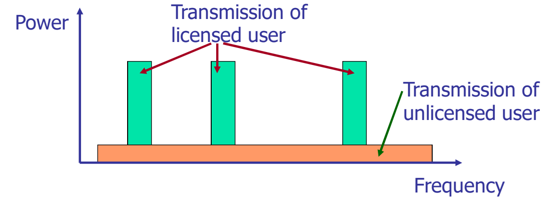


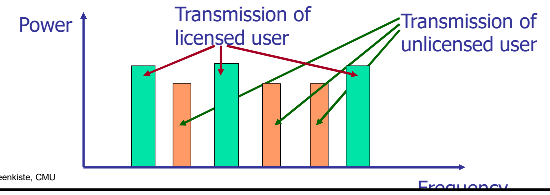
Exclusive-Use Model

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 Model





Spectrum Underlay

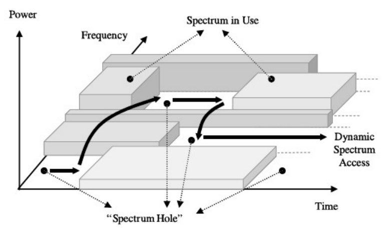
- Spectrum underlay approach constraints the transmission power of secondary users so that they operate below the interference temperature limit of primary users.
- One possible approach is to transmit the signals in a very wide frequency band (e.g., UWB communications) so that high data rate is achieved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

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.

Example

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



Peter A. Steenkiste, CMU

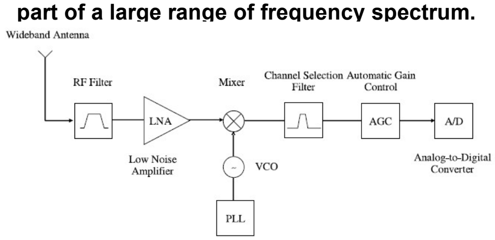
Overview

- 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.



Peter A. Steenkiste, CMU

Cognitive Radio - Reconfigurability

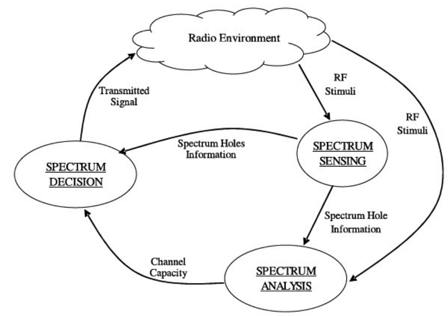
- The capability to adjust operating parameters for transmission on the fly without any modifications on the hardware components
  - **Operating frequency**
  - **Modulation**
    - Reconfigure the modulation scheme adaptive to the users requirements and channel conditions.
  - **Transmission power**
    - 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**

Peter A. Steenkiste, CMU

Main Function in DSA

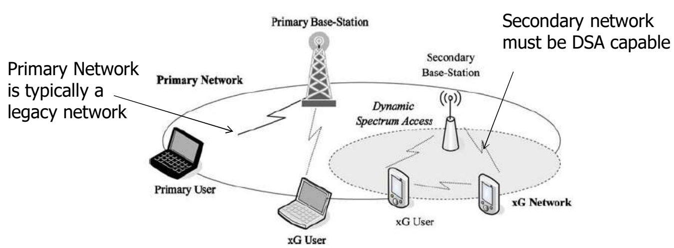
- **Spectrum sensing**
  - Detecting unused spectrum and sharing the spectrum without harmful interference with other users
- **Spectrum management**
  - Capturing the best available spectrum to meet user communication requirements
- **Spectrum mobility**
  - Maintaining seamless communication requirements 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

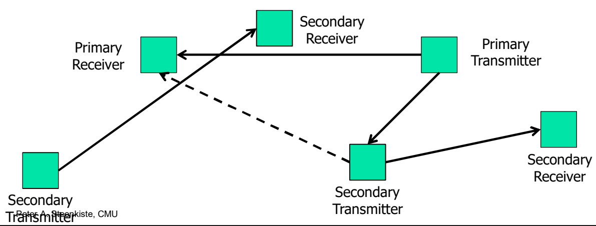


Network Applications

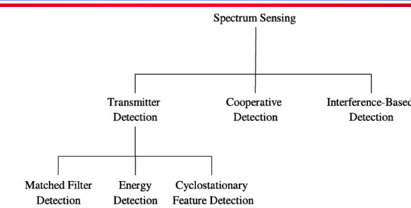
- **Leased network**
  - The primary network can provide a leased network by
    - allowing opportunistic access to its licensed spectrum with the agreement with a third party without sacrificing the service quality of the primary users.
  - e.g., Mobile Virtual Network Operator (MVNO)
- **Cognitive 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.



Classification of Spectrum Sensing Techniques



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

the AWGN

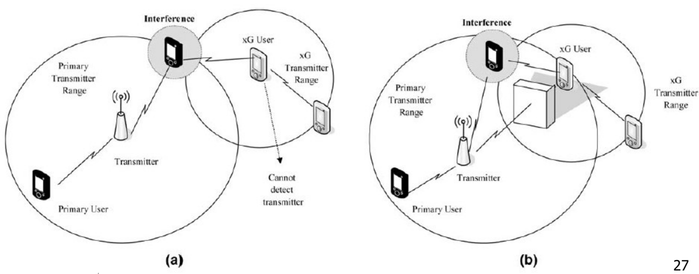
$$x(t) = \begin{cases} n(t) & H_0, \\ hs(t) + n(t) & H_1, \end{cases}$$

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

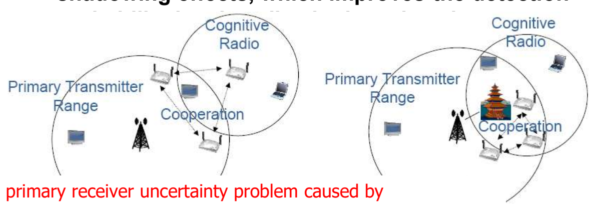


Sensing Techniques

- 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



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

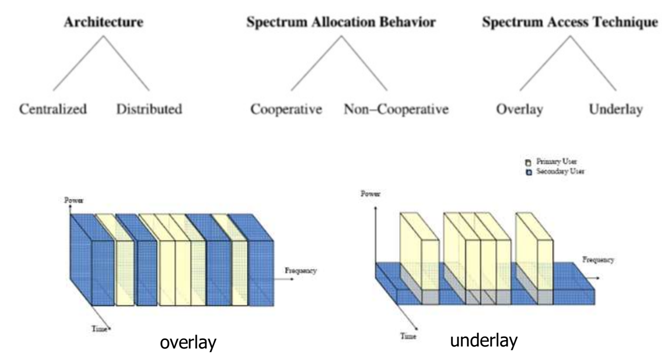
Spectrum Analysis

- 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.

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

Classification of Spectrum Sharing

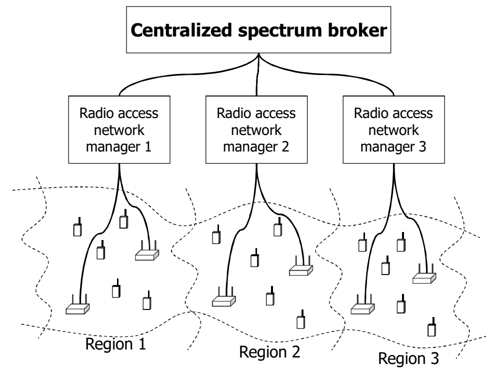


Cooperative/Centralized DSA

- 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.

Peter A. Steenkiste, CMU

Cooperative/Centralized DSA



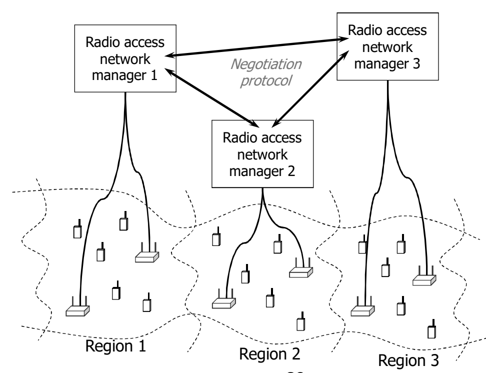
Peter A. Steenkiste, CMU

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.

Peter A. Steenkiste, CMU 35

Cooperative/Distributed DSA Example



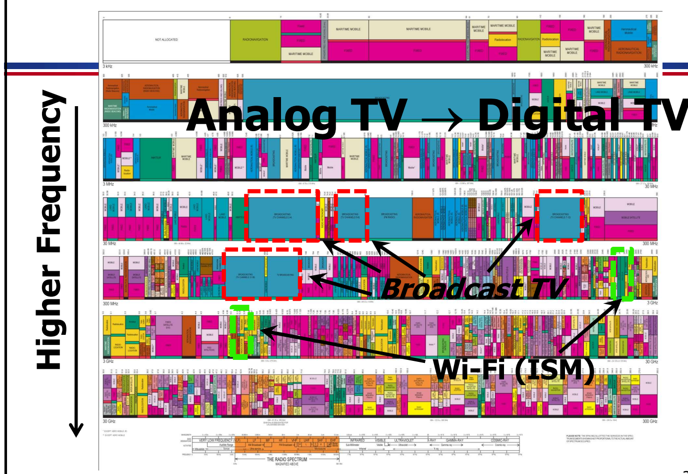
Peter A. Steenkiste, CMU 36

Overview

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

Peter A. Steenkiste, CMU

37



Peter A. Steenkiste, CMU

38

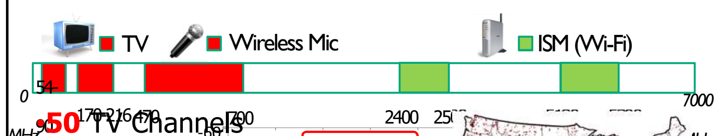
TV White Spaces

- 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

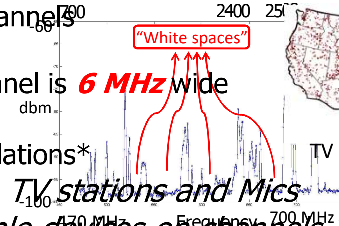
Peter A. Steenkiste, CMU

39

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*

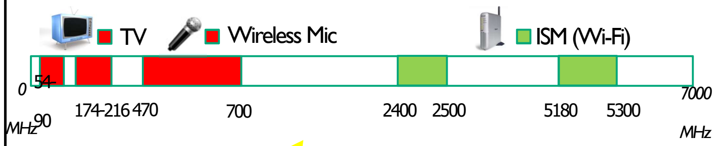


White Spaces are *Unoccupied* TV Channels

Peter A. Steenkiste, CMU

40

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

……..

……..

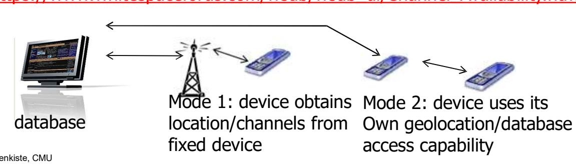
Why Using Geolocation & Database

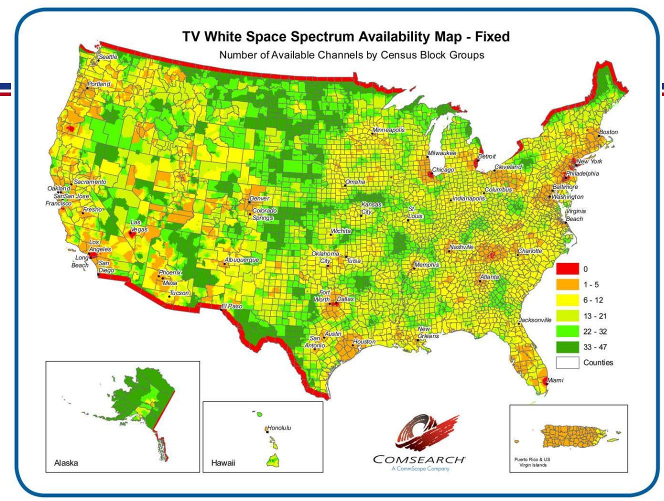
- **Based on prototype test program sensing-only solutions not sufficiently developed**
  - Very long scan times, poor performance in presence of strong adjacent channel signal, ..
  - Difficult to reliably detecting wireless microphones
  - Inability to determine presence of passive receive sites
-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

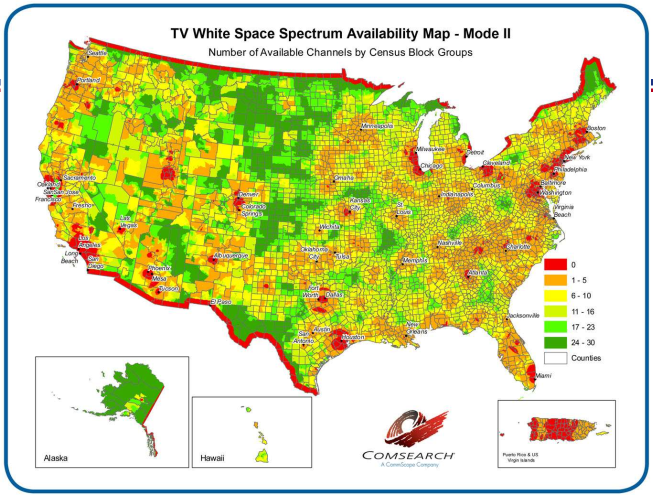
- **Final rules adopted 9/2010; modified 4/2012**
  - First new spectrum for unlicensed devices below 5 GHz in many years
  - Access based on geolocation & database
- **Incumbent services protect by database**
  - TV broadcast stations, translator and booster stations, cable TV headends, ..
  - Land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

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





Map from Jan 2010



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