18-759: Wireless Networks
Lecture 24:
Dynamic Spectrum Access

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

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 Agency (NTIA) for federal government communications

Spectrum Allocation
- 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

http://www.ntia.doc.gov/osmhome/allochrt.html
### Spectrum Allocation in US

#### 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

### 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

### 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

- 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

Spectrum Access Model

- Command and control
- Exclusive-use
- Shared-use of primary licensed spectrum
- Commons-use
  - Long-term exclusive-use
  - Dynamic exclusive-use
  - Spectrum overlay
  - Spectrum underlay
**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 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.

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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.

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
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.

Transmitter Detection Problem

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

Classification of Spectrum Sensing Techniques

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

\[ x(t) = \begin{cases} n(t) & H_0, \\ h s(t) + n(t) & H_1, \end{cases} \]

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.

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

- Architecture: Centralized, Distributed
- Spectrum Allocation Behavior: Cooperative, Non-Cooperative
- Spectrum Access Technique: Overlay, Underlay

overlay

underlay
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/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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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 White Spaces?

- Each channel is 6 MHz wide
- FCC Regulations
  - Sense TV stations and Mics
  - Portable devices on channels 21 - 51
  - White Spacess are Unoccupied TV Channels
The Promise of White Spaces

- More Spectrum
- Longer Range

Potential Applications
- Rural wireless broadband
- City-wide mesh

Up to 3x of 802.11g

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

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
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

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

IEEE 802.22 Regional Area Network

- 802.22 Base Station
- 802.22 CPE
- 802.11af LAN
- 802.11af AP
- 802.11af station