Overview

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

Some slides based on slides by Ian Akyildiz
SIGCOMM paper summary based on slides by Rohan Murty and Matt Welsh

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 agencies

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
  - Uses outdated technology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
- Snapshot of utilization of 700 MHz slice of spectrum below 1 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, affect business, ...
- 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

<table>
<thead>
<tr>
<th>Frequency</th>
<th>Power</th>
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Spectrum Underlay

- Spectrum underlay approach constrains 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 – Key Challenge
- Limitations
  - The wideband RF antenna receives signals from various transmitters operating at different power levels, bandwidths, and locations.
  - The RF front-end should have the capability to detect a weak signal in a large dynamic range.
  - The capability requires a multi-GHz speed A/D converter with high resolution, which might be infeasible.
- Solutions
  - Reduction of dynamic range of the signal, e.g., tunable notch filters
  - Multiple antennas such that signal filtering is performed in the spatial domain rather than frequency domain, e.g., beamforming.
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

Example of DSA

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

DSA - Cognitive Cycle

[Diagram showing the cognitive cycle of DSA]

Primary Network is typically a legacy network

Secondary network must be DSA capable
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 observation
- Basic hypothesis
  \[ x(t) = \begin{cases} n(t) & H_0, \\ h_0 s(t) + n(t) & H_1, \end{cases} \]
  - \( n(t) \): AWGN
  - \( h_0 \): amplitude gain of the channel
  - \( s(t) \): transmitted signal of the primary user

Transmitter Detection Problem

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

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 Analysis – Parameters

- **Interference**
  - From the amount of the interference at the primary receiver, the permissible power of a secondary user can be determined
- **Path loss**
  - The path loss increases with operating frequency
  - Therefore, for a fixed transmit power, the transmission range decreases at higher frequencies.
- **Wireless link errors**
  - Depending on the modulation scheme and the interference level of the spectrum band
- **Link layer delay**
  - Different datalink layer protocols may be used
- **Holding time**
  - Spectrum that can used for a longer time is better
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

<table>
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<tr>
<th>Architecture</th>
<th>Spectrum Allocation Behavior</th>
<th>Spectrum Access Technique</th>
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</thead>
<tbody>
<tr>
<td>Centralized</td>
<td>Cooperative</td>
<td>Overlay</td>
</tr>
<tr>
<td>Distributed</td>
<td>Non-Cooperative</td>
<td>Underlay</td>
</tr>
</tbody>
</table>

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.
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.

Upper Layer Issues - Routing

- Common control channel
- Intermittent connectivity
  - In DSA networks, the reachable neighbors of a node may change rapidly.
    - The available spectrum may change or vanish as licensed users exploit the networks.
    - Once a node selects a channel for communication, it is no longer reachable through other channels.
    - The connectivity concept used for wireless networks depends on the spectrum.
- Re-routing
- Queue Management

Upper Layer Issues – Transport Layer

- TCP performance depends on packet loss probability and round trip time.
- Wireless errors and the packet loss probability depends on
  - the access technology
  - the frequency in use
  - interference level
  - the available bandwidth
- RTT of a TCP connection depends on
  - the frequency of operation
  - packet retransmissions due to higher frame error rate at particular frequency bands
  - spectrum handoff latency
  - the interference level
  - the medium access control protocol
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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 Spaces are Unoccupied TV Channels
The Promise of White Spaces

TV
Wireless Mic
ISM (Wi-Fi)

Up to 3x of 802.11g
Potential Applications
- Rural wireless broadband
- City-wide mesh

More Spectrum

Longer Range at least 3 - 4x of Wi-Fi

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, ...
  - Difficulty with reliably detecting wireless microphones
  - No ability to determine presence of passive receive sites
- Disagreement in record regarding 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. sooner implementation using existing technology and techniques
- Require geolocation capability in conjunction with a database to provide each device a list of available channels specific to its location

TV White Space Rules

- Final rules adopted 9/010; modified 4/2012
  - First new spectrum for unlicensed devices below 5 GHz in many years
  - Access based on geolocation & database
  - Also allows for sensing after authorization
- Incumbent services protect by database
  - TV broadcast stations, translator and booster stations, cable TV headends, ...
  - Land mobile (in some cities); wireless mics

Mode 1: device obtains location/channels from fixed device
Mode 2: device uses its own geolocation/database access capability

TV White Space Spectrum Availability Map - Fixed
Number of Available Channels by Census Block Groups

- Not Available
- 0 - 2
- 3 - 5
- 6+
MSR WhiteFi Goal:
Deploy Infrastructure Wireless

Why not reuse Wi-Fi based solutions, as is?

White Spaces Spectrum Availability

Differences from ISM (Wi-Fi)
- Fragmentation
- Variable channel widths

Each TV Channel is 6 MHz wide. Spectrally combine multiple channels for more bandwidth.
White Spaces Spectrum Availability

Differences from ISM (Wi-Fi)
- Fragmentation
- Variable channel widths
- Spatial Variation
- Cannot assume same channel free everywhere

Location impacts spectrum availability ➞ Spectrum exhibits spatial variation

Temporal Variation
- Incumbents appear/disappear over time
- Must reconfigure after disconnection

Spatial Variation
- Cannot assume same channel free everywhere

Channel Assignment in Wi-Fi

Fixed Width Channels ➞ Optimize which channel to use

Spectrum Assignment in WhiteFi

Spectrum Assignment Problem

- Goal: Maximize Throughput
- Include: Spectrum at clients
- Assign: Center Channel & Width

Fragmentation ➞ Optimize for pair of center channel and width
Spatial Variation ➞ BS must use channel if free at client
Accounting for Spatial Variation

Intuition

Discovering a Base Station

SIFT, by example

### Accounting for Spatial Variation

- Use widest possible channel
- Limited by most busy channel
- Carrier Sense Across All Channels
- All channels must be free
  \[ \rho_{BS}(2 \text{ and } 3 \text{ are free}) = \rho_{BS}(2 \text{ is free}) \times \rho_{BS}(3 \text{ is free}) \]

### Intuition

- Use widest possible channel
- Limited by most busy channel
- Carrier Sense Across All Channels
- All channels must be free
  \[ \rho_{BS}(2 \text{ and } 3 \text{ are free}) = \rho_{BS}(2 \text{ is free}) \times \rho_{BS}(3 \text{ is free}) \]

### Discovering a Base Station

- Discovery Time = \( O(B \times W) \)
- Fragmentation \( \Rightarrow \) Try different center channel and widths

### SIFT, by example

- **SIFT**: Signal Interpretation before Fourier Transform
- **SIFT** does not decode packets
- Pattern match in time domain

- **ADC**
- **SIFT**
- **Data**
- **ACK**
- **SIFS**
**WhiteFi Prototype Performance**

- WhiteFi
- OPT

**Announcements**

- This was the last lecture!
- Three more surveys on Wednesday
- Posted homework 4 – due on last day of classes
- Project presentations on last Friday of the semester
- Please use office hours to discuss project issues