Wireless Networking in White Spaces

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Audio/Video recordings of this class lecture are available at:
http://www.cse.wustl.edu/~jain/cse574-18/
1. Television Channels
2. Software Defined and Cognitive Radios
3. Spectral White Spaces
4. FCC Rules for White Spaces
5. Wireless Standards for White Space: 802.11af, 802.19.1, PAWS

Note: IEEE 802.22 Regional Area Network and 802.15.4m Personal Area Network may be covered in other modules
Over-the-Air Television Channels

- Television channels use Very High Frequency (VHF) and Ultra High Frequency (UHF) bands
- Each channel uses 6 MHz in USA, 8 MHz in Europe, and 7 MHz at some places
- At least one channel is skipped between two analog stations in neighboring areas to avoid interference

Wavelength

<table>
<thead>
<tr>
<th></th>
<th>10 m</th>
<th>1 m</th>
<th>1 dm</th>
<th>1 cm</th>
</tr>
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<tbody>
<tr>
<td>HF</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>VHF</td>
<td></td>
<td></td>
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<td></td>
</tr>
<tr>
<td>UHF</td>
<td></td>
<td></td>
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</tr>
<tr>
<td>SHF</td>
<td></td>
<td></td>
<td></td>
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</tr>
</tbody>
</table>

Frequency

<table>
<thead>
<tr>
<th></th>
<th>30 MHz</th>
<th>300 MHz</th>
<th>3 GHz</th>
<th>30 GHz</th>
</tr>
</thead>
<tbody>
<tr>
<td>HF</td>
<td></td>
<td></td>
<td></td>
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</tr>
<tr>
<td>VHF</td>
<td></td>
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<tr>
<td>UHF</td>
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<tr>
<td>SHF</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

- FM Radio
- Radio Astronomy

VHF Channels

<table>
<thead>
<tr>
<th>Channel</th>
<th>Freq.</th>
</tr>
</thead>
<tbody>
<tr>
<td>2 3 4</td>
<td>54 60 66 72 76 82 88 174 180</td>
</tr>
</tbody>
</table>

UHF Channels

<table>
<thead>
<tr>
<th>Channel</th>
<th>Freq.</th>
</tr>
</thead>
<tbody>
<tr>
<td>12 13</td>
<td>204 210 216 470 476</td>
</tr>
<tr>
<td>14 15</td>
<td>608 614 620 884 890</td>
</tr>
<tr>
<td>37 38 82</td>
<td>83</td>
</tr>
</tbody>
</table>
Digital Television

- Converting pixels to bits
  ⇒ Can easily encrypt, multiplex, mix with data
- Change Standard Definition (SD), High Definition (HD)
- Do not need empty channels between neighbors
- Need about 19 Mbps ⇒ Can transmit 6-8 channels in 6-8 MHz.
- US FCC stopped analog transmissions on June 12, 2009
- A lot of TV spectrum became available ⇒ **Digital Dividend**
- Big demand for this “new” spectrum in **700 MHz band**:
  - Cellular, Emergency Services, ISM, every one wants it
  - Government raised $19.5 billion from auction to cellular companies and saved some for unlicensed use

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Software Defined Radio

- Analog radio circuits are specific to frequency, channel width, data rate, modulation (AM, FM), multiplexing (FDMA, TDMA, CDMA, OFDMA)
- Need multi-mode radios: Multiband, multi-channel, multi-carrier, multi-mode (AM, FM, CDMA), Multi-rate (samples per second) ⇒ Possible using digital computation
- Generally using Digital Signal Processing (DSP) or field programmable gate arrays (FPGAs)
- Signal is digitized as close to the antenna as possible. Logic reconfigured on demand.
- Software reconfigurable radio
- Flexibility, Upgradability, Lower cost (digital), Lower power consumption.
- **Software Defined Antenna**: Small pixel elements reconfigured by software for desired band.
GNU Radio

- Open-source software defined radio toolkit
- Uses Python and C++ on Linux
- Performance critical signal processing in C++
- Universal Software Radio Peripheral (USRP): General purpose computer for SDRs.
  - Host CPU for waveform specific processing, like modulation, demodulation
  - High-Speed operations in Field Programmable Gate Arrays (FPGAs)

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Cognitive Radio

- Cognition = Perception = Sense
- Cognitive Radio: A radio that can sense the radio environment, select the proper frequency, bandwidth, power, modulation to avoid interference.
- Continue to sense and reconfigure when necessary
- Allows using even licensed spectrum when no one is using it
  Reduces waste of unused spectrum
  ⇒ FCC allowed such operation in certain bands

Diagram:

```
  Configure ----> Software Defined Radio ----> Spectrum Sensing
```

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Effect of Frequency

- Higher Frequencies have higher attenuation, e.g., 18 GHz has 20 dB/m more than 1.8 GHz
- Higher frequencies need smaller antenna
  Antenna ≥ Wavelength/2, 800 MHz ⇒ 6”
- Higher frequencies are affected more by weather
  Higher than 10 GHz affected by rainfall
  60 GHz affected by absorption of oxygen molecules
- Higher frequencies have more bandwidth and higher data rate
- Higher frequencies allow more frequency reuse
  They attenuate close to cell boundaries. Low frequencies propagate far.
Effect of Frequency (Cont)

- Lower frequencies have longer reach
- Lower frequencies require larger antenna and antenna spacing
  ⇒ MIMO difficult particularly on mobile devices
- Lower frequencies ⇒ Smaller channel width
  ⇒ Need aggressive MCS, e.g., 256-QAM
- Doppler shift = \( \frac{vf}{c} = \text{Velocity} \times \text{Frequency}/(\text{speed of light}) \)
  ⇒ Lower Doppler spread at lower frequencies
- Mobility ⇒ Below 10 GHz
700 MHz Band

- Lower attenuation (1/7\textsuperscript{th} to 1/9\textsuperscript{th} of 1800/1900/2100 MHz)  
  \(\Rightarrow\) Lower transmission power  
  \(\Rightarrow\) Longer mobile battery life
- Larger Cell radius  \(\Rightarrow\) Smaller number of towers
- Long distance propagation  \(\Rightarrow\) Good for rural areas.

(Rural Areas)
Spectral White Spaces

- Any spectrum at a given area at a given time available for use on a non-interfering basis:
  - Unallocated spectrum
  - Allocated but under-utilized
  - Channels not used to avoid interferences in adjacent cells
  - Digital Dividend

Spectrum Usage Example


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FCC Rules for White Spaces

- Two types of devices: Fixed, Portable
- **Fixed Devices:**
  - Must include geo-location (i.e., GPS) with 50m accuracy.
  - Must verify location periodically. Spectrum sensing **not** required.
  - Get Channel availability daily using national databases (operated by third parties)
  - Must register with the database. Get grant for 48 hours
  - White spaces in channels 2, 5-36, 38-51 available
  - White spaces in channels 3, 4, 37 for backhaul
  - Two channels in every area reserved for wireless microphones
  - Outdoor antenna max 30m **height above ground level** (HAGL) and 250 m **height above average terrain** (HAAT)


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FCC Rules (Cont)

- Portable/Mobile Devices: w GPS (Mode II), w/o GPS (Mode I)
  - Mode II devices register with the database
  - Mode I devices: Not required to register with FCC
    - Must obtain channel availability from Mode II or fixed
      at HAAT less than 106 m.
    - Must receive a Channel Verification Signal from Mode II or fixed device

- Distance from protected contour:
  - 4-31 km in co-channel, and
    0.4-2.4 km in adjacent channel depending upon the HAAT.
  - Higher antenna ⇒ Longer separation to avoid interference
  - Contours: Protected, Co-channel, Adjacent Channel
FCC Emission Limits

- FCC changed the transmit power limit to be specified in “power spectral density (PSD)” per 100 kHz. This way many devices can not collude and transmit in the same channel resulting in total power over that previously specified in 6 MHz.

- The spectral mask was also changed from a fixed -55 dBr to PSD limit of -55.4 dBm/100 kHz. Too costly to achieve.

<table>
<thead>
<tr>
<th>Type</th>
<th>Power Limit (6 MHz)</th>
<th>PSD Limit (100 kHz)</th>
<th>Adjacent Channel PSD Limit (100 kHz)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fixed</td>
<td>30 dBm (1W)</td>
<td>12.6 dBm</td>
<td>-42.8 dBm</td>
</tr>
<tr>
<td>Portable (in Adjacent Channel)</td>
<td>16 dBm (40mW)</td>
<td>-1.4 dBm</td>
<td>-56.8 dBm</td>
</tr>
<tr>
<td>Sensing only</td>
<td>17 dBm (50 mW)</td>
<td>-0.4 dBm</td>
<td>-55.8 dBm</td>
</tr>
<tr>
<td>All other</td>
<td>20 dBm (100 mW)</td>
<td>2.6 dBm</td>
<td>-52.8 dBm</td>
</tr>
</tbody>
</table>
TVWS Device Examples

- Can offload bulk cellular data traffic to white spaces (similar to WiFi currently)
- Combined VHF+UHF band is too wide to cover with a single radio frontend and antenna
TVWS Databases

- FCC has authorized 10 companies to administer TVWS databases.
  - Get info from FCC database
  - Register fixed TVWS devices and wireless microphones
  - Synchronize databases with other companies
  - Provide channel availability lists to TVWS devices

- FCC does not require spectral sensing.
  No need to stop transmission and sense
  ⇒ Continuous multimedia

- Europe requires devices to check every two hours and allows higher power transmission but requires spectral sensing (closed loop system)
White Spaces Near WUSTL

- 17 channels. Zipcode 63130.

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Standards for White Space Wireless

- **IEEE 802.11af-2014**: Wireless Local Area Network
- **IEEE 802.22-2011**: Cognitive Wireless Regional Area Network
- **IEEE 802.15.4m-2011**: Wireless Personal Area Network
- **IEEE 802.19.1**: Coexistence
- **IEEE 1900.4a**: Resource Optimization
- **IETF PAWS**: Database access
- **ETSI BRAN**: European Telecommunications Standards Institute Broadband Radio Access Networks
- **Weightless SIG**: Special Interest Group
- **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
802.11af-2014: White-Fi

- A.k.a. Super-Fi (initially incorrectly called super Wi-Fi)
  Both MAC and PHY different from 802.11 ⇒ Not WiFi
- Draft approved by the Working Group and 802 Executive Committee. Final approved standard expected March 2014.
- White-space wireless using cognitive radios up to 5 km
- 256-QAM, 5/6, 3 us Guard Interval
  ⇒ 26.7 Mbps per 6 MHz channel
- Up to 4 channels may be bonded in one or two contiguous blocks
- MIMO operation with up to 4 streams using space-time block code (STBC) or multi-user MIMO
- 4 spatial streams × 4 channels ⇒ 426.7 Mbps
IEEE 802.11af PHY

- Basic Channel Unit (BCU): One TV Channel
  \[ W = 6 \text{ MHz in USA} \]
- Single channel mandatory
- Channel Bonding: Optional
  - Contiguous: 2W, 4W
  - Non-contiguous: W+W, 2W+2W
- MIMO with 4x Space Time Block Coding (STBC)
  or MU-MIMO with 4x
- OFDM similar to 40 MHz in 802.11n down-clocked by 7.5x to give a 5.33 MHz waveform
  - 108 Data, 3 DC, 6 pilots, 36 Guard =144 carriers in 6 MHz
Coexistence Problem

- Exposed Terminal: 802.11af cannot transmit because 802.22 keeps the channel busy
- Hidden Terminal: 802.11af interferes with 802.22 transmissions
IEEE 802.19.1-2014

- IEEE 802.19: Radio access technology (RAT) independent methods of coexistence ⇒ 802.11, 802.15, 802.22 can all use one common method for coexistence.
- IEEE 802.19.1: Coexistence in TV white spaces.
IEEE 802.19.1 (Cont)

- White Space Object (WSO): A WS device or a network
- Coexistence Enabler (CE): Represents a WSO in the coexistence system
- Coexistence Manager (CM): Makes decisions about configuration of a set of WSOs so that they can coexist
- Coexistence Discovery and Information Server (CDIS): Notifies CMs about potential neighbors of its WSOs.
- Interfaces B, B1, B2, and B3 are specified in IEEE 802.19.1
  Interface C is PAWS.
- Each WSO registers with a CM
- CM collects data about its members and gets data about other CMs from CDIS.
Protocol to Access White-Space (PAWS)

- IETF working group
- Mechanism to discover white space database
- Protocol to communicate with the database
- Interface Agnostic: 802.11af, 802.15.4m, 802.22, ...
- Spectrum agnostic: 6 MHz, 7 MHz, 8 MHz, ...
- Master Device: White-Space Device (WSD) connects to database
- Slave Device: WSD that get info from master devices

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PAWS (Cont)

- Stations should be able to discover WS Database, its regulatory domain. May be preconfigured similar to DNS or Certification Authorities.
- Listing Server: Web page listing all national database servers. Highly static ⇒ Can be cached by master
- Master may register with the database (model, serial, owner, …) of itself and its slaves
- Mutual authentication and authorization using certificates or passwords
- Master can then query the database
- The database should be able to push updates on channel availability changes
- Ensure security of discovery mechanism, access method, and query/response

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PAWS (Cont)

- Allows WSD to specify geolocation, height, serial number, Certificates, device class, radio access technology (RAT), antenna gain, maximum EIRP, radiation pattern, spectrum mask, owner contact information

- Allows database to specify available spectrum, available area, allowed power levels

- Allows WSD to register its selected spectrum for use

- Allows privacy to WSD (encryption)


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PAWS Messages

- Database
- Initialization Request
- Initialization Response
- Registration Request
- Registration Response
- Available Spectrum Query
- Available Spectrum Response
- Available Spectrum Batch Query
- Available Spectrum Batch Response
- Spectrum Use Notify
- Spectrum Use Response
- Device Validation Request
- Device Validation Response

- Master Device
PAWS Messages (Cont)

- Listing Request/Response: To/from listing server (not shown)
- Initialization: Exchange capability, location, get rules
- Registration: Model, serial, antenna characteristics, owner, etc
- Available Spectrum: individual or batch request
- Spectrum Use: register used spectrum, location, antenna etc. Get time limits in response.
- Device Validation: Database may ask masters to authenticated slaves
Summary

1. Analog to Digital conversion of TV channels has freed up spectrum in 700 MHz band ⇒ White Space.
2. FCC has allowed license-exempt use of some of the white space in TV bands. Requires a cognitive radio.
3. IEEE 802.11af White-Fi spec uses 5, 10, 20 MHz channels to give up to 426.7 Mbps using OFDM, MU-MIMO, and 256-QAM.
4. IEEE 802.19.1 solves the coexistence problem by coordinating spectrum usage by several networks in the same area.
5. PAWS proves the protocol for access to National white space databases.
Reading List

Wikipedia Links

References

- http://www.whitespacealliance.org
References (Cont)

- United Kingdom Office of Communications (OfCom) - www.ofcom.org.uk
References (Cont)

- IEEE 1900.4a-2011,
Acronyms

- AM  Amplitude Modulation
- AP  Access Point
- BCU Basic Channel Unit
- BRAN Broadband Radio Access Network
- BS Base Station
- BSS Basic Service Set
- CBS Cognitive Base Station
- CBSMC CBS Measurement Collector
- CBSRC CBS Resource Controller
- CBSRM CBS Resource Manager
- CDIS Coexistence Discovery and Information Server
- CDMA Code Division Multiple Access
- CE Coexistence Enabler
- CEPT European Conference of Postal and Telecommunications Administrations
- CM Coexistence Manager
Acronyms (Cont)

- CPE  Customer Premise Equipment
- CPU  Central Processing Unit
- dB   deci-Bel
- dBm  deci-Bel milli-watt
- dBr  deci-Bel relative
- DC   Direct Current
- DNS  Domain Name System
- DSP  Digital Signal Processing
- DYSPAN Dynamic Spectrum Access Networks
- ECC  Electronics Communications Committee
- EIRP Equivalent Isotropically Radiated Power
- ETSI European Telecommunications Standards Institute
- FCC  Federal Communications Commission
- FDMA Frequency Division Multiple Access
- FM   Frequency Modulation
## Acronyms (Cont)

- **FPGAs**: Field Programmable Gate Arrays
- **GDB**: Geolocation Database
- **GHz**: Giga Hertz
- **GNU**: GNU is Not Unix
- **GPS**: Global Positioning System
- **HAAT**: Height above average terrain
- **HAGL**: Height above ground level
- **HD**: High Definition
- **HF**: High Frequency
- **IEEE**: Institution of Electrical and Electronic Engineers
- **IETF**: Internet Engineering Task Force
- **ISM**: Instrumentation, Scientific, and Medical
- **ISP**: Internet Service Provider
- **ITU**: International Telecommunications Union
- **LAN**: Local Area Network
- **MAC**: Media Access Control
<table>
<thead>
<tr>
<th>Acronym</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>MCS</td>
<td>Modulation and Coding Scheme</td>
</tr>
<tr>
<td>MHz</td>
<td>Mega Hertz</td>
</tr>
<tr>
<td>MIMO</td>
<td>Multi-Input Multi-Output</td>
</tr>
<tr>
<td>MU</td>
<td>Multi-User</td>
</tr>
<tr>
<td>mW</td>
<td>milli Watt</td>
</tr>
<tr>
<td>NCC</td>
<td>Network Channel Control</td>
</tr>
<tr>
<td>NRM</td>
<td>Network Reconfiguration Manager</td>
</tr>
<tr>
<td>OFDM</td>
<td>Orthogonal Frequency Division Multiplexing</td>
</tr>
<tr>
<td>OFDMA</td>
<td>Orthogonal Frequency Division Multiple Access</td>
</tr>
<tr>
<td>OSM</td>
<td>Operator Spectrum Manager</td>
</tr>
<tr>
<td>PAR</td>
<td>Project Authorization Request</td>
</tr>
<tr>
<td>PAWS</td>
<td>Protocol to access White-Space</td>
</tr>
<tr>
<td>PHY</td>
<td>Physical Layer</td>
</tr>
<tr>
<td>QAM</td>
<td>Quadrature Amplitude-Phase Modulation</td>
</tr>
<tr>
<td>R&amp;TTE</td>
<td>Radio and Terminal Test Equipment</td>
</tr>
</tbody>
</table>
Acronyms (Cont)

- RAT  Radio Access Technology
- RFC  Request for Comment
- RLSS Registered Location Secure Server
- SCC  Standards Coordinating Committee
- SD   Standard Definition
- SDR  Software Defined Radio
- SE   Spectrum Engineering
- SHF  Super High Frequency
- SIG  Special Interest Group
Acronyms (Cont)

- STBC  Space Time Block Coding
- TDMA  Time Division Multiple Access
- TV    Television
- TVWS  Television White Spaces
- UHF   Ultra High Frequency
- UK    United Kingdom
- US    United States
- USRP  Universal Software Radio Peripheral
- VHF   Very High Frequency
- WiFi  Wireless Fidelity
- WP    Working Party
- WS    White Space
- WSD   White-Space Device
Acronyms (Cont)

- WSM  White Space Manager
- WSO  White Space Object
- WUSTL  Washington University in Saint Louis
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https://www.youtube.com/playlist?list=PLjGG94etKypJEKjNAa1n_1X0bWWNyZcof

CSE473S: Introduction to Computer Networks (Fall 2011),
https://www.youtube.com/playlist?list=PLjGG94etKypJWOSPMh8Azegy5e_10TiDw

Recent Advances in Networking (Spring 2013),
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CSE571S: Network Security (Fall 2011),
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https://www.youtube.com/channel/UCN4-5wzNP9-ruOzQMs-8NUW