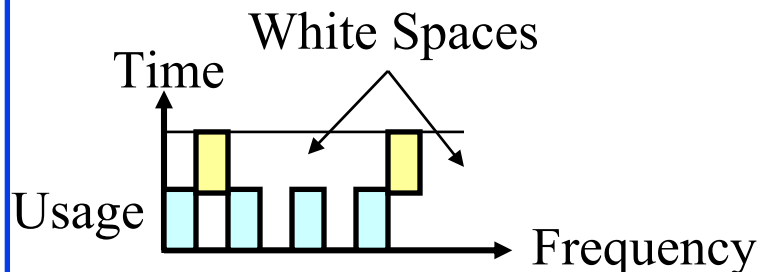
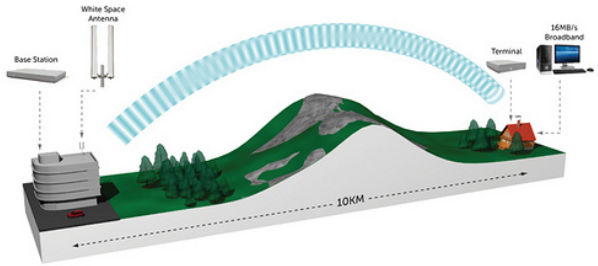
Wireless Networking in White Spaces





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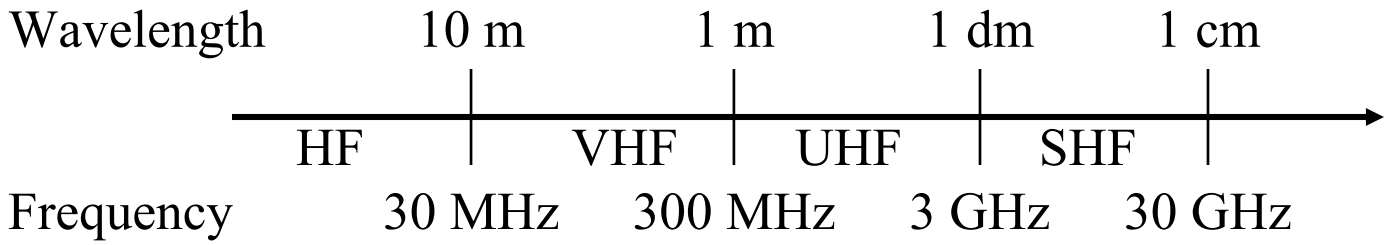
Audio/Video recordings of this class lecture are available at:
http://www.cse.wustl.edu/~jain/cse574-18/

Overview

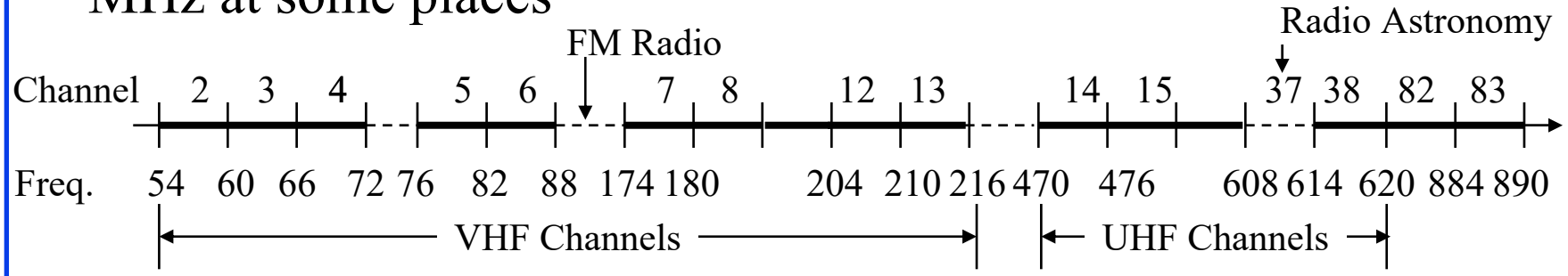
1. Television Channels
2. Software Defined and Cognitive Radios
3. Spectral White Spaces
4. FCC Rules for White Spaces
5. Wireless Standards for White Space: 802.11af, 802.19.1, PAWS

Note: IEEE 802.22 Regional Area Network and 802.15.4m Personal Area Network may be covered in other modules

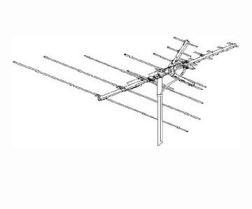
Over-the-Air Television Channels



- 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

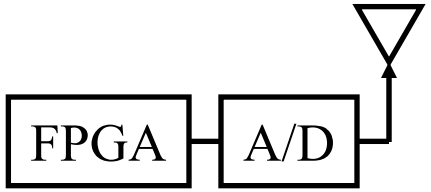


Digital Television

- 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

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.



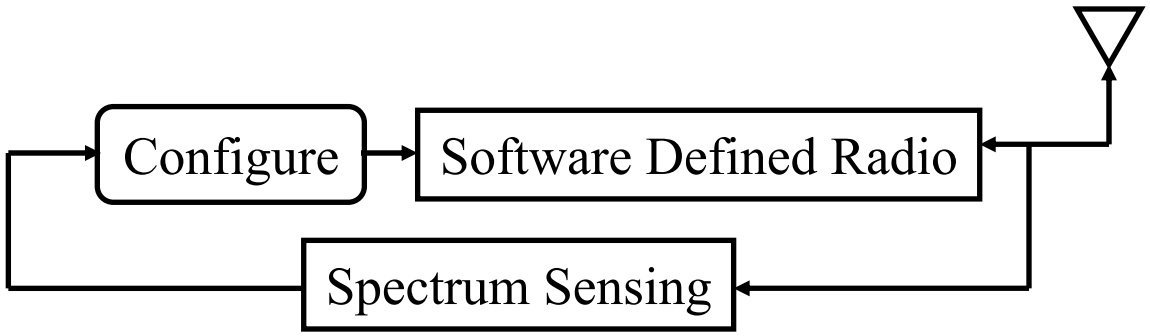
GNU Radio

- 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)

Ref: GNU Radio, http://gnuradio.org/redmine/,
http://en.wikipedia.org/wiki/GNU_Radio
http://en.wikipedia.org/wiki/Universal_Software_Radio_Peripheral
Ettus Research, "USRP Bus Series Products," https://www.ettus.com/product/category/

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
  $\Rightarrow$ FCC allowed such operation in certain bands



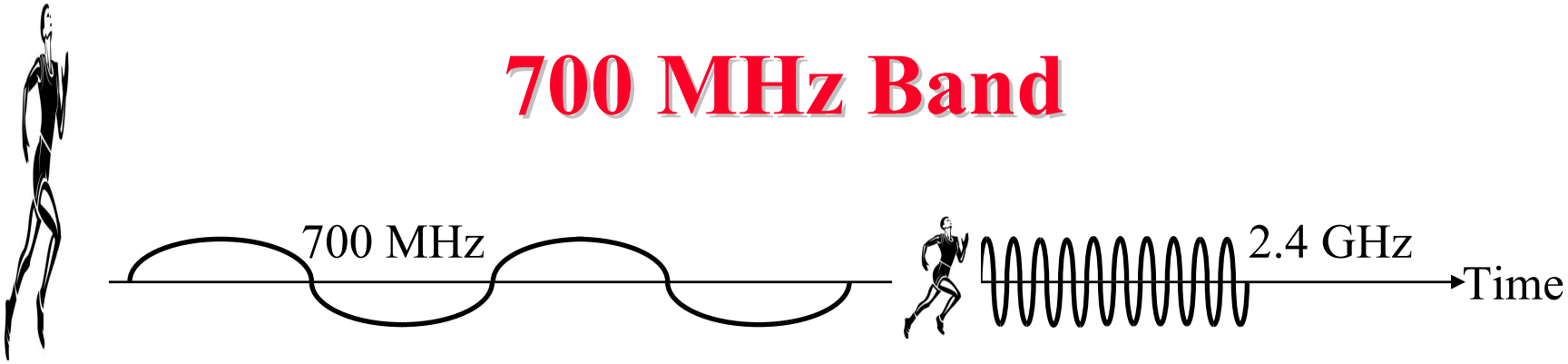
Effect of Frequency

- Higher Frequencies have higher attenuation,
  e.g., 18 GHz has 20 dB/m more than 1.8 GHz
- Higher frequencies need smaller antenna
  Antenna $\geq$ Wavelength/2, 800 MHz $\Rightarrow$ 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.

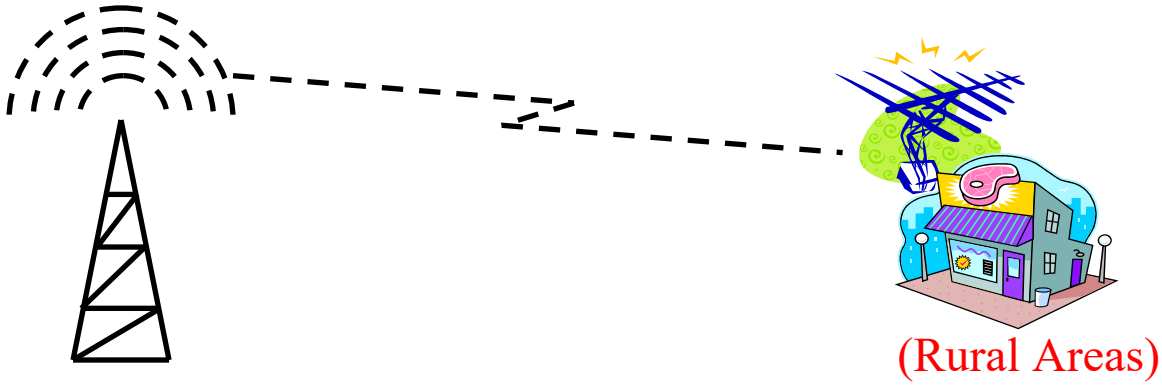
Effect of Frequency (Cont)

- 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 = vf/c = Velocity ×Frequency/(speed of light)
  ⇒ Lower Doppler spread at lower frequencies
- Mobility ⇒ Below 10 GHz

700 MHz Band

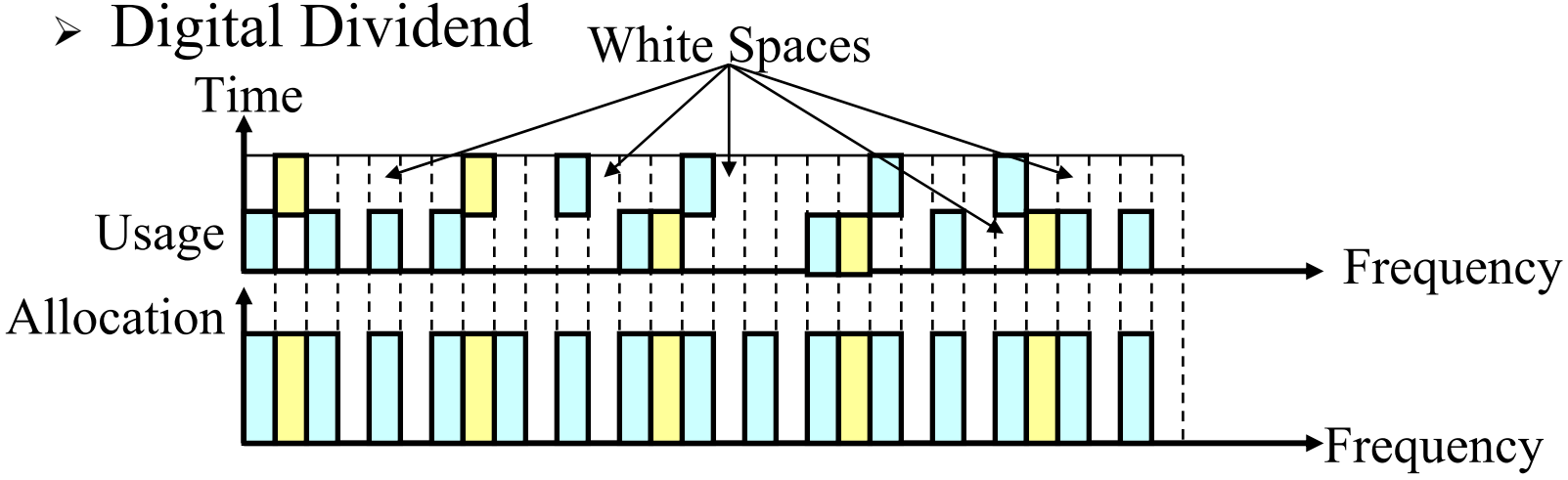


- Lower attenuation ($1/7^{th}$ to $1/9^{th}$ of 1800/1900/2100 MHz)
  ⇒ Lower transmission power
  ⇒ Longer mobile battery life
- Larger Cell radius ⇒ Smaller number of towers
- Long distance propagation ⇒ Good for rural areas.



Spectral White Spaces

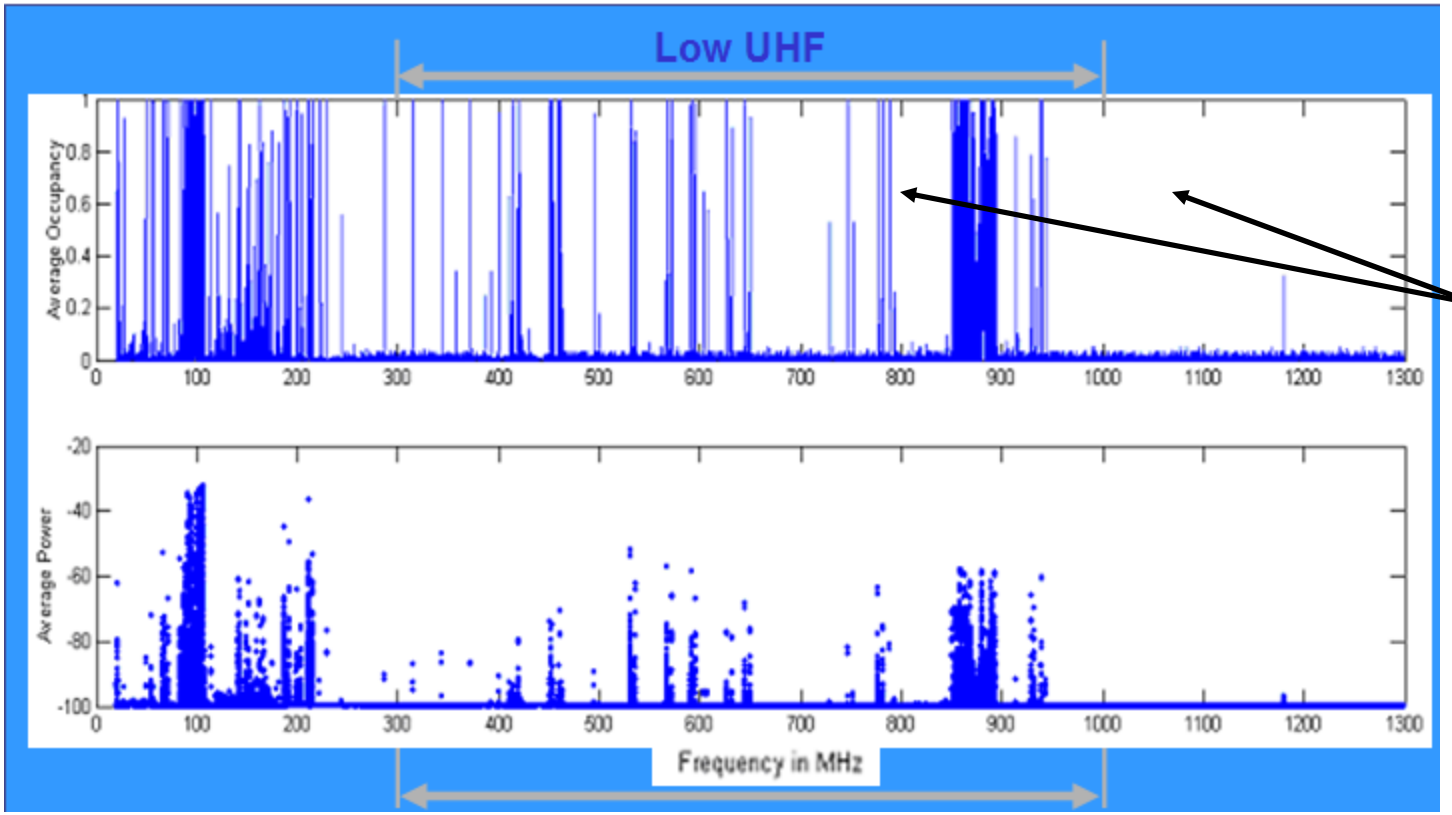
- Any spectrum at a given area at a given time available for use on a non-interfering basis:
  - Unallocated spectrum
  - Allocated but under-utilized
  - Channels not used to avoid interferences in adjacent cells
  - Digital Dividend



Ref: C. Gomez, "White Spaces for Rural Broadband," April 2013, http://www.itu.int/ITU-D/asp/CMS/Events/2013/PacificForum/ITU-APT-S3_Cristian_Gomez.pdf

Spectrum Usage Example

(Test conducted with antenna at a height of 22.1 metres above the ground in the rural sector west of Ottawa, Canada)

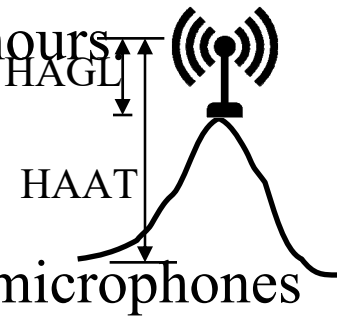


White Spaces

Ref: C. Stevenson, et al., "Tutorial on the P802.22.2 PAR for: *Recommended Practice for the Installation and Deployment of IEEE 802.22 Systems"* http://www.ieee802.org/802_tutorials/06-July/Rec-Practice_802.22_Tutorial.ppt

FCC Rules for White Spaces

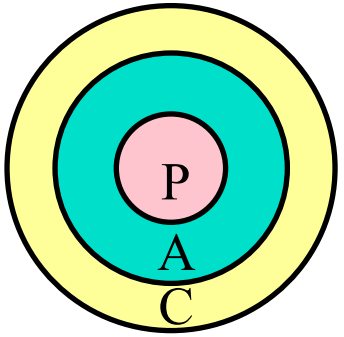
- Two types of devices: Fixed, Portable
- **Fixed Devices**:
  - Must include geo-location (i.e., GPS) with 50m accuracy.
  - Must verify location periodically. Spectrum sensing not required.
  - Get Channel availability daily using national databases (operated by third parties)
  - Must register with 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)



Ref: *FCC, "Unlicensed Operation in the TV Broadcast Bands*," ET Docket No. 04-186, and 02-380 Third Memorandum Opinion and Order, April 4, 2012, available at http://transition.fcc.gov/Daily_Releases/Daily_Business/2012/db0405/FCC-12-36A1.pdf

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.

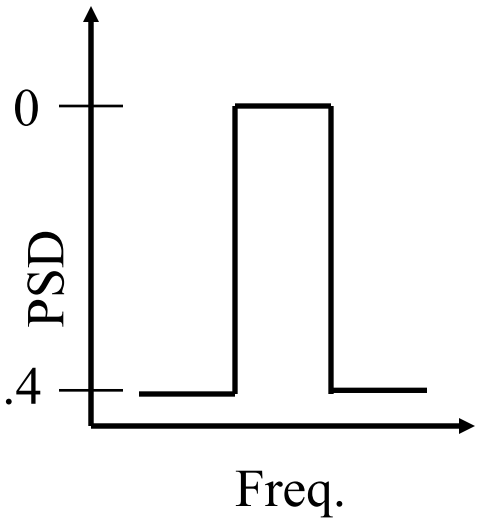


  - Higher antenna ⇒ Longer separation to avoid interference
  - Contours: Protected, Co-channel, Adjacent Channel

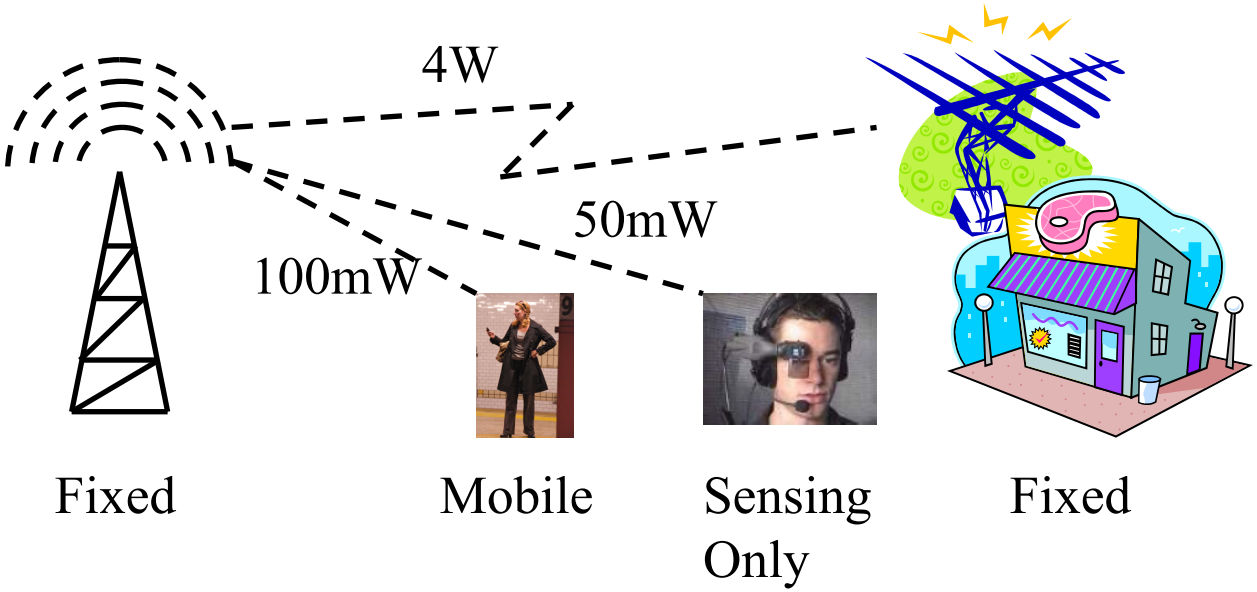
FCC Emission Limits

Type	Power Limit (6 MHz)	PSD Limit (100 kHz)	Adjacent Channel PSD Limit (100 kHz)
Fixed	30 dBm (1W)	12.6dBm	-42.8 dBm
Portable (in Adjacent Channel)	16 dBm (40mW)	-1.4dBm	-56.8 dBm
Sensing only	17 dBm (50 mW)	-0.4dBm	-55.8 dBm
All other	20 dBm (100 mW)	2.6 dBm	-52.8 dBm

- 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.



TVWS Device Examples

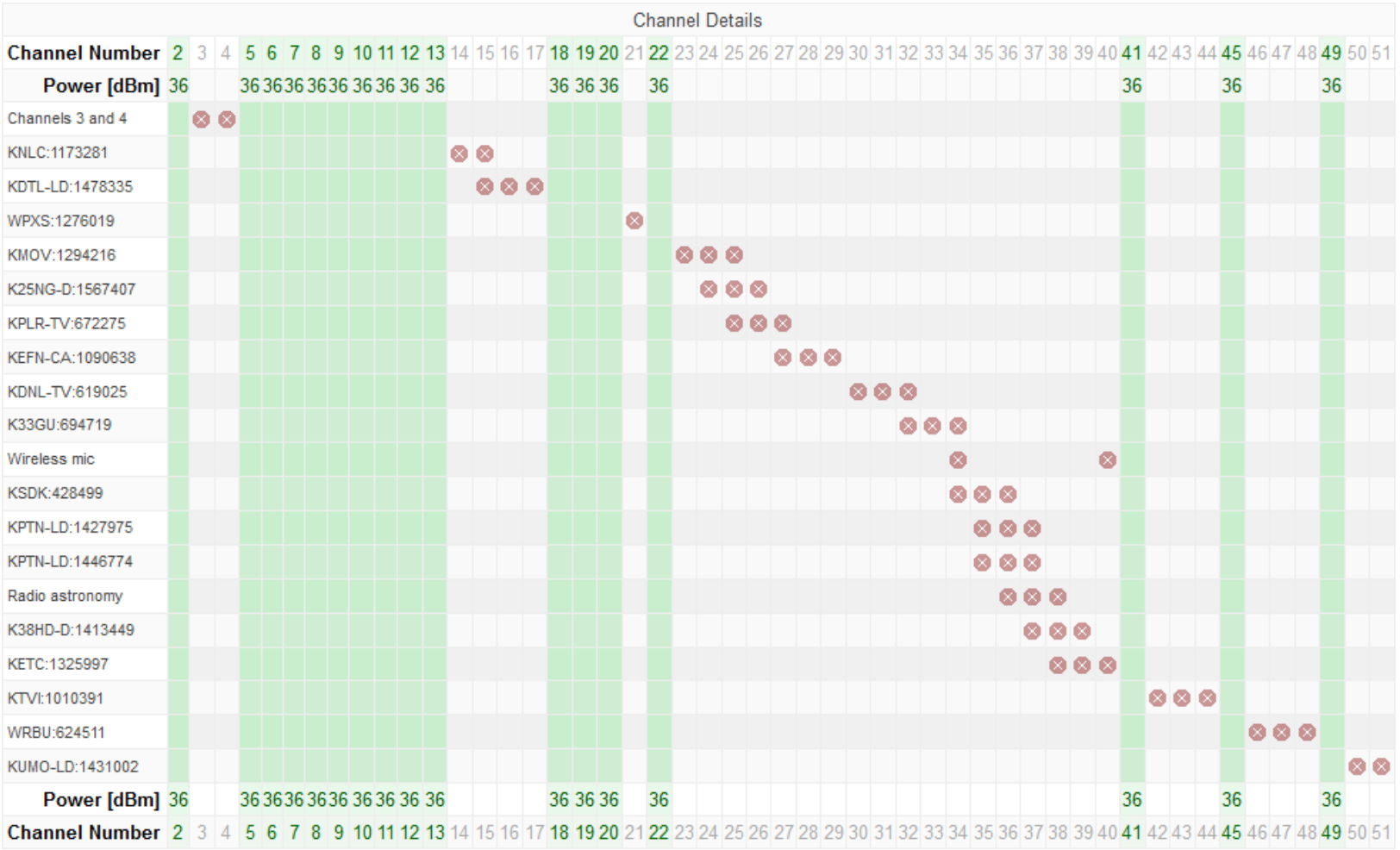


- Can offload bulk cellular data traffic to white spaces (similar to WiFi currently)
- Combined VHF+UHF band is too wide to cover with a single radio frontend and antenna

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
  $\Rightarrow$ 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.

Ref: Google Spectrum Database, https://www.google.com/get/spectrumdatabase/channel/

Standards for White Space Wireless

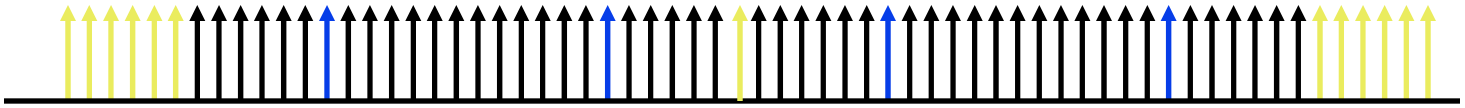
- **IEEE 802.11af-2014**: Wireless Local Area Network
- **IEEE 802.22-2011**: Cognitive Wireless Regional Area Network
- **IEEE 802.15.4m-2011**: Wireless Personal Area Network
- **IEEE 802.19.1**: Coexistence
- **IEEE 1900.4a**: Resource Optimization
- **IETF PAWS**: Database access
- ETSI BRAN: European 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

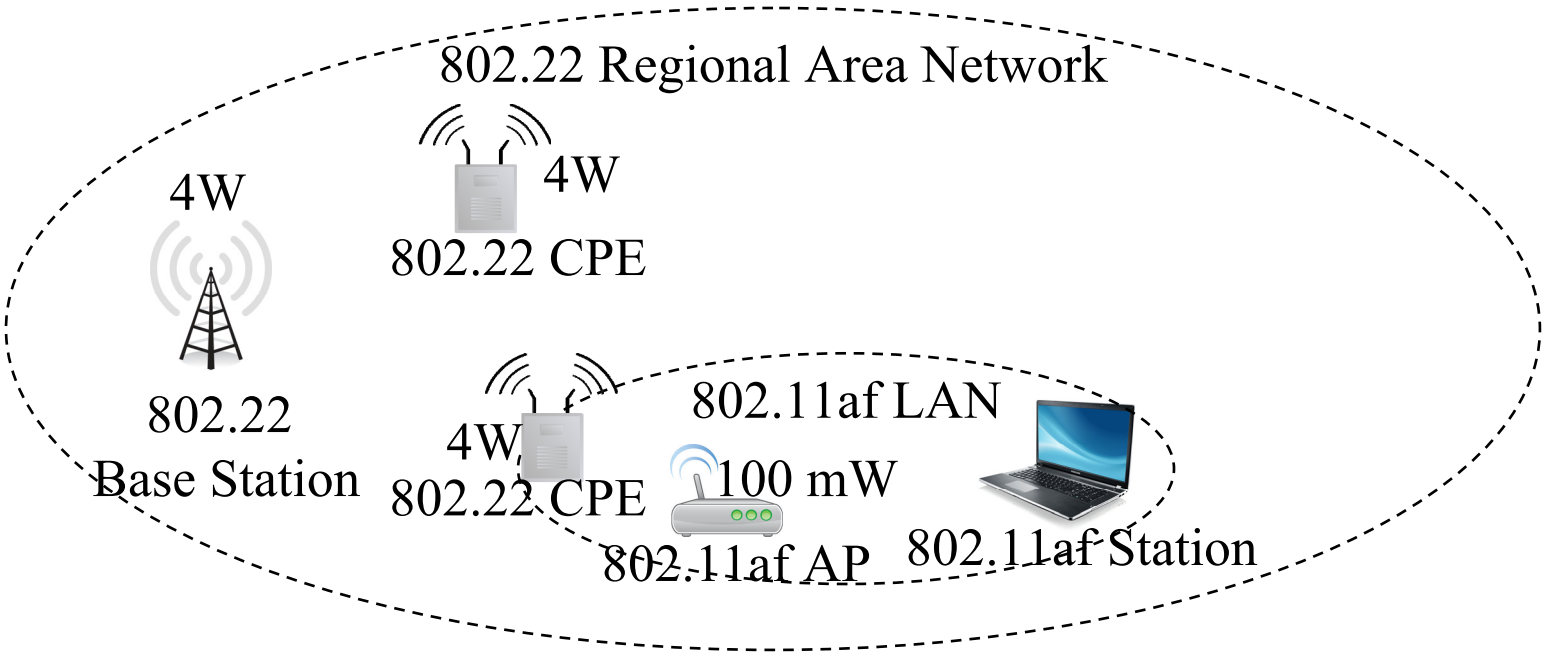
IEEE 802.11af PHY

- Basic Channel Unit (BCU): One TV Channel
  W = 6 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



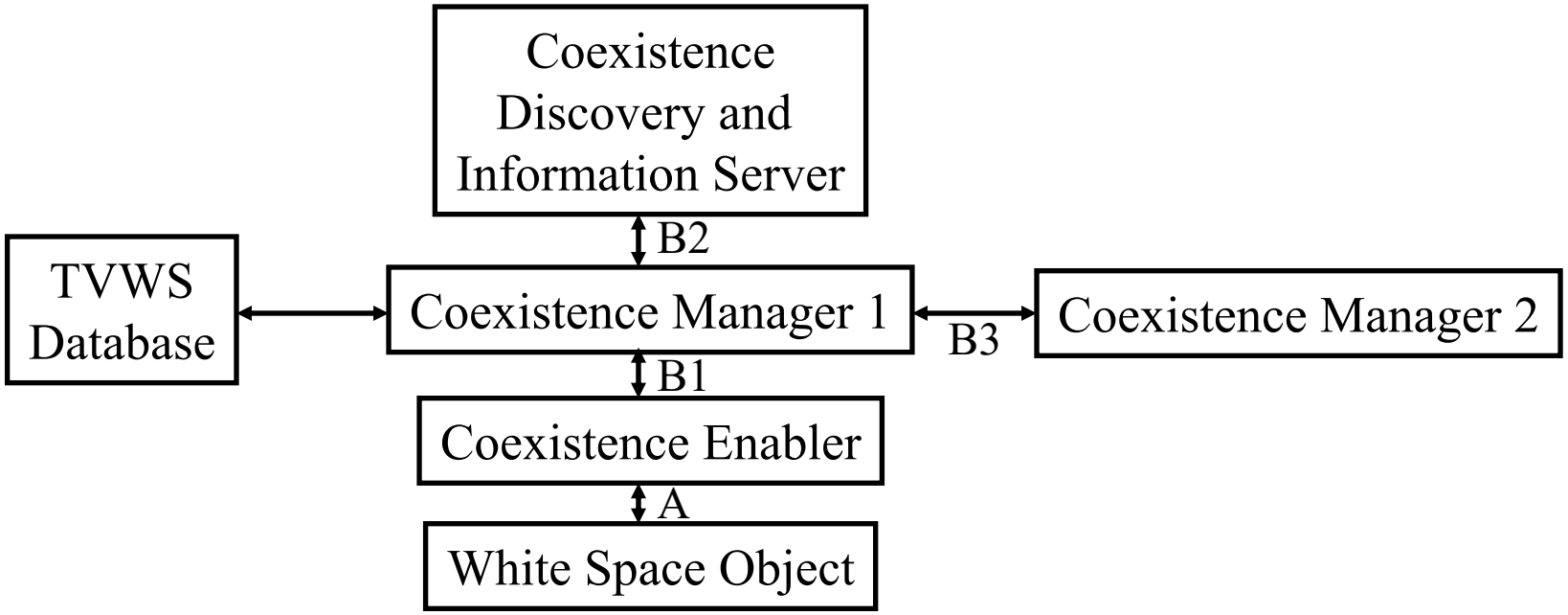
Coexistence Problem

- Exposed Terminal: 802.11af can not 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.

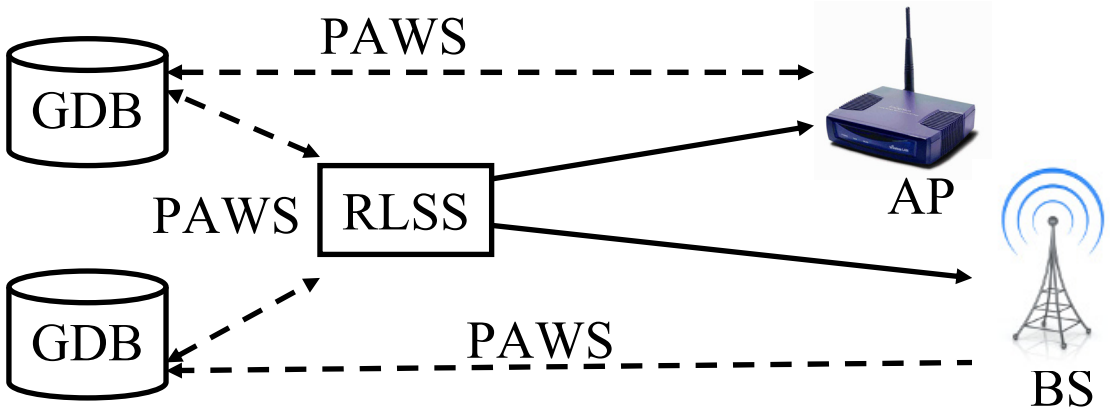


IEEE 802.19.1 (Cont)

- 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



Ref: V. Chen, et al, ed. "Protocol to access White-Space (PAWS) Databases," Feb 2014, http://datatracker.ietf.org/doc/draft-ietf-paws-protocol/

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

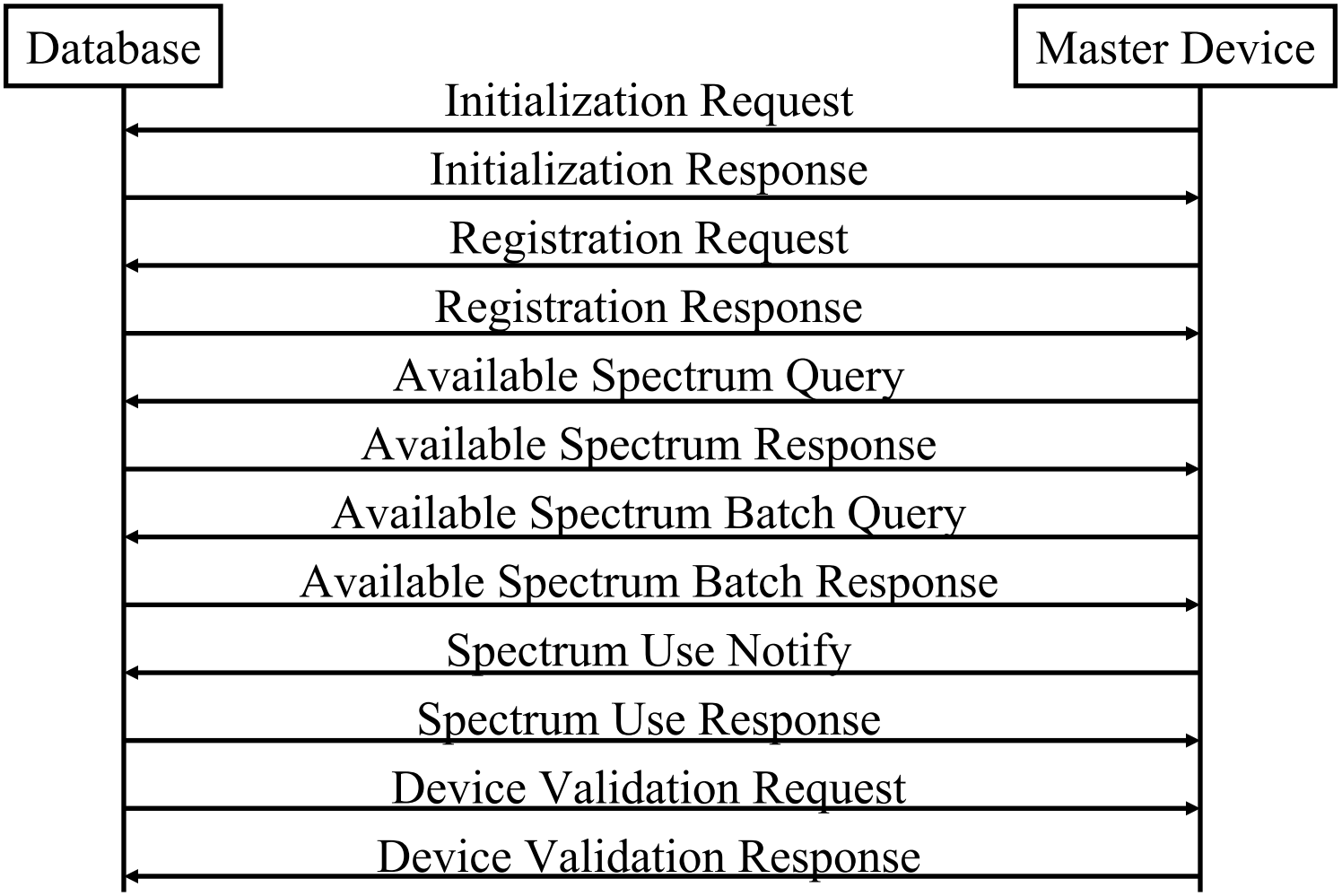
Ref: A. Mancuso, Ed., at al, "Protocol to Access White-Space (PQWS) Databases: Use Cases and Requirements," IETF RFC 6953, May 2013, http://tools.ietf.org/pdf/rfc6953

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)

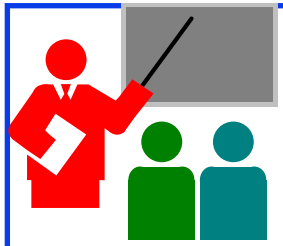
Ref: V. Chen, et al, ed. "Protocol to access White-Space (PAWS) Databases," IETF RFC 7445, May 2015, 90 pp.
https://www.rfc-editor.org/rfc/pdfrfc/rfc7545.txt.pdf

PAWS Messages



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

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- V. Chen, et al, ed. "Protocol to access White-Space (PAWS) Databases," Feb 2014, http://datatracker.ietf.org/doc/draft-ietf-paws-protocol/
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- Telesystem Innovations Inc., "TV White Spaces: Unlicensed Access Spectrum in Sub-700 MHz Band," http://frankrayal.files.wordpress.com/2012/04/tv-white-space-whitepaper.pdf

Wikipedia Links

- http://en.wikipedia.org/wiki/Software-defined_radio
- http://en.wikipedia.org/wiki/Cognitive_radio
- http://en.wikipedia.org/wiki/White_spaces_(radio)
- http://en.wikipedia.org/wiki/Super_Wi-Fi
- http://en.wikipedia.org/wiki/IEEE_802.11af
- http://en.wikipedia.org/wiki/IEEE_802.19
- http://en.wikipedia.org/wiki/DySPAN
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- IEEE 1900.4a-2011, http://ieeexplore.ieee.org/iel5/6022705/6022706/06022707.pdf?arnumber=6022707

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

Acronyms (Cont)

- MCS Modulation and Coding Scheme
- MHz Mega Hertz
- MIMO Multi-Input Multi-Output
- MU Multi-User
- mW milli Watt
- NCC Network Channel Control
- NRM Network Reconfiguration Manager
- OFDM Orthogonal Frequency Division Multiplexing
- OFDMA Orthogonal Frequency Division Multiple Access
- OSM Operator Spectrum Manager
- PAR Project Authorization Request
- PAWS Protocol to access White-Space
- PHY Physical Layer
- QAM Quadrature Amplitude-Phase Modulation
- R&TTE Radio and Terminal Test Equipment

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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