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Dynamic Spectrum Sharing Annual Report - 2014

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Introduction

Radio spectrum is a limited resource for wireless communications, and service providers in both the commercial and government domains are demanding increased spectrum to meet their customer's demands. The traditional approach to addressing these demands is through a static licensing model: granting exclusive spectrum access through a single commercial or government entity to one or more frequency bands both for a long duration and over a large geographic area. Under this model, for one entity to gain new spectrum, another must clear it. However, such clearing of spectrum is expensive, and not a sustainable mechanism for spectrum management. Multiple spectrum occupancy measurement campaigns have shown that many spectrum bands are heavily underutilized due to significant variations in spectrum occupancy over frequency, time and space. A significant increase in spectrum utilization efficiency is possible in specific underutilized bands if secondary users (SUs) are allowed access to spectrum licensed to primary spectrum owners. For these reasons, many people feel that this type of spectrum sharing is inevitable.

To support this emerging trend, the members of the Wireless Innovation Forum have created this report for Regulators, Policy Makers, Spectrum Managers, Network Planners, and Wireless Researchers who need to understand the state of technologies such as dynamic spectrum access and their ability to facilitate spectrum sharing. The report will act as a reference guide to clearly identify and synthesize a harmonized view of the results of spectrum sharing research and trials, identify what is in development, and articulate what issues are being addressed and what issues still need to be resolved.

In developing this report, the dependencies of business, regulation and technology in advancing dynamic spectrum sharing became obvious: regulation cannot proceed without a clear understanding of technological capabilities and business potential, business investment cannot proceed without a clear understanding of technology and the regulatory environment under which it will be deployed, and technology development cannot proceed without business investment and an understanding of the regulatory constraints. Research programs and activities are crucial for driving innovation into this cycle by extending the knowledge of what is technically possible and therefore addressing the need for evidence-based advice to support the development of appropriate policies, regulations and licensing. The development and evaluation of new concepts and strategies for sharing of, and dynamic access to, spectrum can be leverage or done in collaboration with industry who can in turn devise new business models.

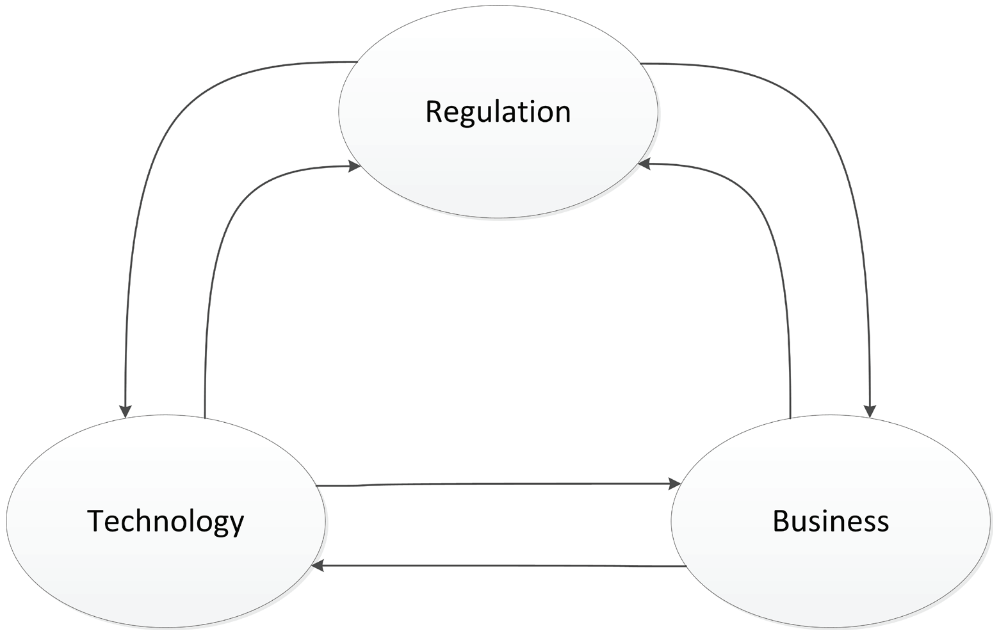

Figure 1: Dynamic Spectrum Sharing is Driven Equally by Technology, Regulation, and Business Models

To address these dependencies, this report has been divided into 9 sections as follows:

1. Definition of Spectrum Sharing
2. Spectrum Occupancy Measurements
3. Benefits of Spectrum Sharing
4. Spectrum Sharing Regulation
5. Economics of Spectrum and related Business Models
6. Test beds and Field Trials
7. Standards Developments
8. Programs
9. Technologies

The content for these sections were collected from a number of sources, including direct contributions from researchers and developers, interviews with decision and policy makers, and researching available publications, conference proceedings, etc. It should be noted that dynamic spectrum sharing in an evolving area. The contributors to this report recognize that the material provided herein is by no means complete, and that many of the elements of the report will change over time. It is the intention of the Wireless Innovation Forum to address these issues by publishing an addendum to this report on an annual basis, highlighting updates on relevant items covered in this inaugural edition, and providing information on new areas not addressed, such as security. Suggestions and contributions for subsequent releases are welcome and encouraged.

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What is Spectrum Sharing

For the purposes of this report, the Wireless Innovation Forum has broken spectrum sharing into five distinct levels as follows:

- **Level 0: Exclusive Use –** Spectrum is assigned on an exclusive basis to a primary holder of spectrum rights (primary user) across the regulatory region.

  This establishes an incumbent, and can include, for example, cellular operators and radar installations. The expectation is that there is no interference**.**
- **Level 1: Static Spectrum Sharing –** Exclusive use spectrum is shared by primary users on a geographic basis, not a temporal basis.
- **Level 2: Managed Shared Access**
  - ◊ **Level 2A: Industry Managed:** Unused exclusive use spectrum in a specific location may be leased by the primary user to a 3rd party on a temporary basis (secondary user). Secondary users at this level are protected, exclusive users for the assigned period.

    Policies/Rules under which such arrangements can occur are set through negotiations between the primary and secondary users following regulatory requirements established for such activities, and such rules may require the secondary user to clear the spectrum under specific conditions should the primary user require the spectrum.

    Examples: Licensed Shared Access (LSA), Leased Management Agreements (LMA)
  - ◊ **Level 2B: Government Managed –** Exclusive use spectrum in a specific location may be assigned by a regulatory agency on a temporary basis to a 3rd party (secondary user). Secondary users at this level are protected, exclusive users for the assigned period. Primary users who are using the spectrum may be required to vacate for the assigned period.

    Policies/Rules under which the secondary user operates are set by the regulatory agency.
- **Level 3: Dynamic Spectrum Sharing**
  - ◊ **Level 3a: No Priority Access –** Spectrum access is non-exclusive. Spectrum held by a primary user that is not being utilized in a specific location and at a specific time is available for use by secondary users on a first come, first served basis so long as they do not interfere with the primary user. Such secondary use is unprotected, and the secondary user must vacate the spectrum when required by the primary user. There is a management function, via a database or other means, that ensures non-interference with the primary user, and such management functions may be used to support coexistence between secondary users.

    Example: TV Band Devices, 5 GHz U-NII

◊ **Level 3b: Priority Access (3 Tier Model) –** Spectrum access is non-exclusive. Spectrum held by a primary user that is not being utilized in a specific location and at a specific time is available for use by a secondary user so long as they do not interfere with the primary user. Certain secondary users are assigned priority access privileges. Prioritization can be made based on multiple models (cost based/micro auctions, public good, social factors/uses, fifo, etc.). Access by priority users is protected, while access by all other secondary users is not protected: priority users have first rights to available spectrum, and other secondary users must vacate if a priority user wishes access. There is a management function, via a database or other means, that ensures non-interference with the primary user, manages access by priority users, and such management functions may be used to support coexistence between secondary users.

Example: 3.5 GHz Citizens Broadband Radio Service (CBRS)

- **Level 4: Pure Spectrum Sharing**

◊ **Level 4a: Lightly Licensed –** Spectrum is not assigned to a specific primary user. Use of spectrum is protected while occupied. Rules may exist for length of time spectrum may be occupied.

Example: US 3650 to 3700 MHz band

◊ **Level 4b: Unlicensed –** Spectrum is not assigned to a specific primary user. Use the spectrum is completely unprotected, and is available to any network or user within limitations/rules/policies established for each band.

Example: ISM bands

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Spectrum Occupancy Measurement

3.1 Spectrum / Channel Occupancy Criteria

Spectrum occupancy and availability determination methods must take into account the spectral characteristics of the expected incumbent. Often, they need also consider the characteristics of the signaling of information present, on a temporal basis, by the incumbent. Generally, two fundamental use-cases exist for incumbent systems: Continuous spectrum occupancy and active when needed. The former case is well represented by services such as broadcast television and entertainment radio, many public carrier systems including LTE, and other continuous emission systems. The latter is best represented by narrowband voice and data systems, many data transmission standards such as variants of 802.11 and 802.15, and systems that strive to minimize power consumption. In general, continuous transmission systems are easier to detect and will always indicate a high spectral occupancy value. Active-when-needed systems are often more difficult to detect and require additional cognition to avoid interference. The additional constraints of the latter are offset by the potential of providing vast amounts of discontiguous spectrum that may be used dynamically and opportunistically.

To take advantage of active-when-needed spectrum on a secondary, dynamic basis, a fundamental understanding of the incumbent use-cases and sensing requirements must be considered. To further explain these fundamental sensing differences and requirements, the common use of narrowband land-mobile communications is citied as a commonplace example:

The active use of a given channel in a rasterized spectrum plan, such as that often utilized in narrowband, land mobile applications, differs of that for broadband systems. By definition, narrowband systems may be "conventional," i.e., each channel represents a fixed, logical channel that is permanently assigned to at least one selectable channel by a user of a subscriber device, or the system may be "trunked"; i.e., it utilizes one or more control channels which may be either fixed or utilized in a known, predictable pattern. Trunked systems assign a frequency resource on a per-call or per group basis. Common to these cited examples, and with the exception of the actual control channel in use at any instance in time, the channel is idle, without emission, when devoid of a call representing transmitted information – whether it be voice, data, or a combination of both. Such channels are often "paired"; they operate on a Frequency Division Duplex (FDD) basis and, generally, in half-duplex mode at the subscriber and full-duplex at the base radio site. Criteria regarding availability of these allocations for DSA use-cases are varied and should consider the sub-assignment of the spectrum under scrutiny for use as a DSA candidate. Sub-assignments vary world-wide; in the US, for example, Part 90 spectrum is subdivided into Public Safety and Private Land-mobile elements with varying regulatory practices and levels of required protection. In addition, the larger allocations generically referred to in terms such as "VHF," "UHF," and 800 MHz " are also interleaved with other Rule Parts (US examples) such as Part 22, Part 74, etc. Each, also, has varying criteria to contend with; all of which must be considered when dynamic spectrum access and spectrum sharing is contemplated.

Contrasting this, broadcast services (TV and entertainment radio) certain Public Carrier systems, and in particular, broadband systems such as LTE, operate differently. In FDD-based systems of this type, the uplink channels indicate a good measure of the temporal occupancy levels; however, the downlink allocations often follow an "always on" protocol in which energy is broadcast whether it is communicating intelligence to a subscriber or not. (Intelligence, in this case, describes data outside of signaling required to establish and maintain connection between the subscriber and the base radio). Furthermore, the downlink channels in general, provide significantly higher received channel power at the sensing device easing the issue of occupancy determination based on energy detection. Such systems will always indicate extremely high levels of spectral occupancy yet this does not necessarily convey high levels of spectral effectiveness with regard to the transfer of data.

Fortunately, a-priori knowledge of deployed narrowband systems can assist in determining the true occupancy of spectrum. Narrowband systems tend to be wider service area systems, radiating on the downlink side from high site locations, and operating in narrow RF bandwidths. While predicted coverage of these systems is usually determined as a service radius at which received signal strength (RSSI) levels 10 – 18dB above kTb noise, the uplink side must often contend with RSSI levels reaching lows of 8dB carrier to nose (C/N) or worse. Several known aspects of deployed narrowband systems can be taken advantage of when sensing whether a channel is actually in use: 1) The known pairing of the channel offset adds significantly to the sensing of activity on a given channel; it is a form of frequency diversity with the caveat that, in general, the downlink signal will be far more easily detected than the uplink channel, 2) Further knowledge of the waveform in use can allow the use of feature detection (i.e., baud rate correlation detection, etc.) rather than simple energy detection to determine occupancy of a given channel pair, and, 3) past knowledge of a given channel occupancy and detected, stored parameters such as sub-audible tones, digital squelch access codes, specific header blocks, etc. can simplify and speed detection of subsequent use of a given channel by the primary / incumbent user.

3.2 Methods and Techniques Available for the Determination of Spectral Occupancy

Various autonomous sensing / detection means are available to determine if a given allocation is in use. These include, and may be summarized as but are not limited to:

1) Energy Detection
2) Matched Filter Detection
3) Cyclostationary Feature Detection Techniques[1]

Furthermore, the efficiency of detection can be increased though the use of cooperative sensing. Cooperative sensing assists in alleviating problems associated with "hidden nodes" wherein at least one device within an active communications network is shielded or otherwise not visible to the sensing device[2].

It is beyond the scope of this document to discuss each technique in detail; please refer to the cited works published on these topics. Only simple energy detection will be discussed further as it represents the method by which the bulk of the currently published data is based.

1 An excellent overview can be found: Partha Pratim Bhattacharya et al, International Journal of Computer Science & Communication Networks, Vol 1(2), 196-206; A Survey on Spectrum Sensing Techniques in Cognitive Radio; http://www.ijcscn.com/Documents/Volumes/vol1issue2/ijcscn2011010213.pdf

2 http://groups.winnforum.org/d/do/1563

3.3 Criteria and Limitations of Energy Detection Methods

Energy detection, as a means of sensing use of a given spectral channel or allocation, is a simple concept: A threshold is pre-determined above which point, with a certain integration time in use, a flag is set and the channel is marked as "in use / occupied." Concept and theory diverge from practice in that each service to be detected often has unique threshold criteria. Early detection thresholds, utilized in initial spectrum occupancy studies, was set at levels as high as -90dBm for narrowband signals. This was due to the use of equipment that was broadband in nature, did not optimize noise figure and dynamic range within the various bands of interest, and did not optimize detection level thresholds. Experience soon indicated that sensing levels needed to be significantly lower. Improvements in dynamic range, resulting in a reduction of self-generated inter-modulation (IM) terms that artificially raised noise floors within the test environment, and improved (reduced) effective Noise Figure (NF) improved results but threshold criteria still often place the energy detection threshold at 6 – 10dB above the system noise floor. This is reflected in more recent and excellent studies, such as those performed by the Illinois Institute of technology (IIT) and others. Citing a 2011 IIT publication:

"This issue of varying sensitivity is problematic in occupancy estimation as the noise floor is not flat across bands. The thresholds used to determine occupancy are intended to be set at a fixed offset above the noise floor of the measurement system, but variations in the system's response over frequency and over time necessitated different thresholds for each measurement band and each year. Typically the value chosen was set between 5 and 10 dB above the noise floor, allowing for compensation due to equipment changes (such as an upgraded preselector and the use of a backup spectrum analyzer), and parameter changes (different attenuator values). Care was exercised in choosing the occupancy threshold to avoid system induced inaccuracies in the occupancy calculations"[3].

In further example, narrowband systems are often designed with operate with confidence levels approaching 97% at RSSI levels of -110dBm and lower. Taking into account selective channel fading, shadow factors, and other criteria, such systems operate, with acceptable impairments, to levels -119dBm. This requires system designs consistent with industry-practiced design criteria of contracted coverage physical area and specified audio quality, often described in terms of Detected Audio Quality (DAQ) measured, thermal noise (kTB or -128dBm in a typical narrowband communications operating bandwidth at room temperature) plus 18dB; a resultant figure of -110dBm. Shadow factor and flat channel fading due to clutter and other factors drop this value to -118dBm. To allow no more than 1dB degradation of the incumbent signal, threshold levels must be at least 10dB below kTB noise; in this case, ~ -138dBm. It is often the case that such levels of protection are not attainable; the channel is interference limited rather than thermal noise limited. In these cases, detection thresholds do not need to reach the -138dBm level. Again, there is much work to be done in determining protection criteria; factors noted above will ultimately set regulatory requirements for dynamic and opportunistic use of spectrum.

This is not to say that detection, protection and shard use is impossible; rather, proper use of the techniques can overcome these obstacles. One must simply be cognizant of the limitations of each approach, choose the method, or combined methods that offer the necessary level of protection of incumbents for the service and associated spectrum to be shared on a dynamic basis, and insure that reasonable protection criteria are met. A combination of energy detection, coupled with at least one additional detection means, situational memory of recent environment observations and, possible combination with cooperative sensing show promise toward the goal of dynamic, opportunistic use of spectrum in even the most difficult of protection environments. This is an area that is ripe for continued and further research.

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3 Tanim M. Taher, Roger B. Bacchus, Kenneth J. Zdunek, "Long-term Spectral Occupancy Findings in Chicago," Department of Electrical and Computer Engineering, Illinois Institute of Technology, Chicago, IL; IEEE DySpan 2011.

3.4 Cumulative and Specialized Sources and Victims of Interference

A final criterion that must be considered with regard to protection of incumbent services is the cumulative effect of out of band emissions (OOBE). While proper engineering and regulatory limits on allowable emissions from opportunistic radiators such as dynamic spectrum access devices will, in general, address such issues, not all adjacent allocations require uniform protection ratios. While generalized limits on OOBE and spurious emissions can address the vast majority of the incumbent systems, some service will require additional protection. Services that utilize extremely weak signal systems, such as GNSS services, satellite-based communications systems, and some radiolocation services may also require stricter limitations be placed upon the opportunistic spectrum access device. While the simple approach would require all devices to meet the most stringent use-case, this is impractical from a cost, power budget, and, in general, practicality standpoint. Rather, some device offerings might have limited allocations to choose from that do not require the most stringent OOBE limits while advanced devices might alter operating parameters to offer stricter OOBE limits when operating adjacent to allocations requiring further protection. Rules-based parameters that are allocation and location-specific cannot be ruled out in advanced opportunistic spectrum / DSA devices. Several tiers of device classes may exist: Low cost with somewhat limited spectrum availability and advanced devices that offer greater, and often favorable, spectrum availability.

3.5 Predictive and Cyclic Use of Spectrum

A-priori knowledge of the incumbent signal allows the use of matched filter and cyclostationary feature detection methods to be utilized to determine occupancy of the spectrum. Further study of the spectrum, coupled with decision engines that take into account external factors such as time of day, day of week, location, flagging of localized factors (on-going incident, etc.) may also be utilized to open additional spectrum. A recent IIT publication cited data collected from their Spectrum Observatory in Chicago – see Figure 2 and Figure 3 [4]:

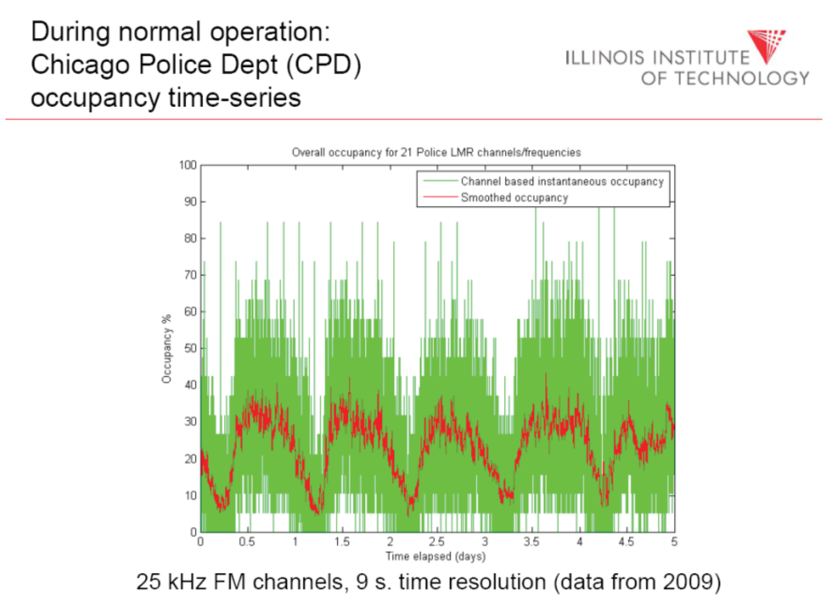

Figure 2: CPD Occupancy Time Series

4 http://www.cs.iit.edu/~mbilgic/seminar/pdfs/roberson_whoweare2013.pdf

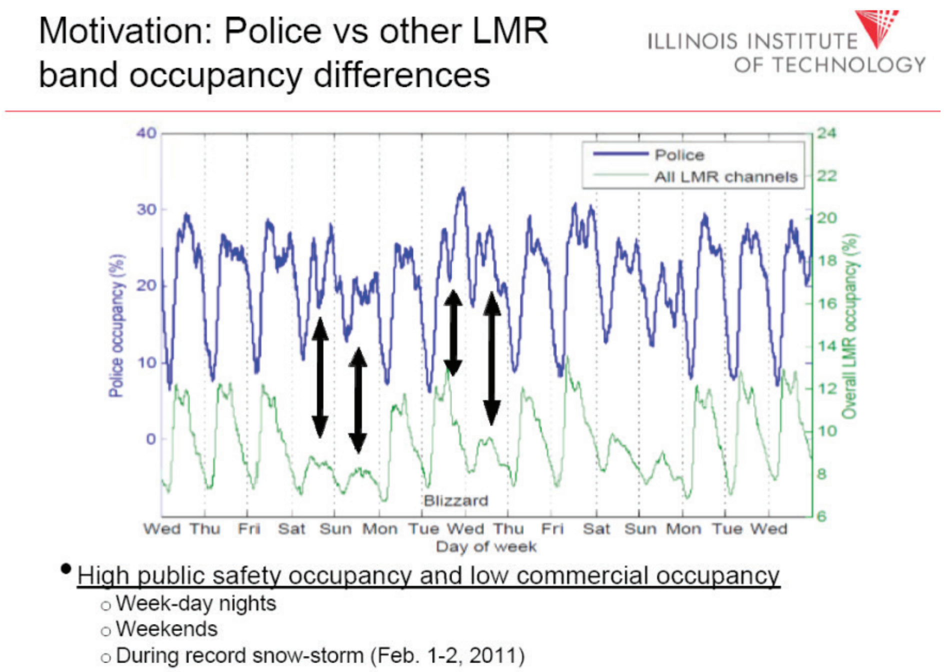

Figure 3: Band Occupancy Differences

Clearly, the availability of spectrum is not constant in many allocations. Many factors must be taken into account in determining if, and when, spectrum may be available. However, analytics of collected data and application of rules-based decision engines, combined with additional external inputs, will produce significant gains in the amount of available spectrum available for sharing at any given time.

3.6 Spectrum Occupancy Measurement Campaigns[5]

Worldwide, spectrum occupancy measurement campaigns have and are being launched driven by the need to identify additional wireless spectrum to support ever-increasing data capacity and throughput requirements.

3.6.1 Europe

Multiple spectrum occupancy measurement campaigns are ongoing in Europe under the auspices of the ITU[6] and CEPT[7] regulatory organizations. The ITU, in particular, has taken the lead in the area of spectrum occupancy measurements and evaluation [10]. In addition, there is strong participation from educational institutions focusing on both data collection and the derivation of spectrum occupancy models based on the observed data.

5 The number of spectrum occupancy measurement campaigns listed is by no means complete in any of the major geographical locations. As measurement campaigns are discovered, the lists will be updated.

6 International Telecommunications Union, Recommondations: Spectrum Management Series, http://www.itu.int/rec/R-REC-SM/en.

7 Electronic Communications Committee, Monitoring and Enforcement, http://www.cept.org/ecc/groups/ecc/wg-fm/fm-22.

Figure 4: Spectrum Occupancy Measurement Campaigns

A representative listing of measurement campaigns in Europe is shown below:

1. A week in London: Spectrum usage in Metropolitan London; Alexandros Palaios*, Janne Riihijarvi*, Oliver Holland†, Petri Mähönen*; *Institute for Networked Systems, RWTH Aachen University, Aachen, Germany; †Centre for Telecommunications Research, King's College London, UK
2. Two days of European Spectrum: Preliminary analysis of concurrent spectrum use in seven European sites in GSM and ISM bands; Alexandros Palaios*, Janne Riihijarvi*, Petri Mähönen*, Vladimir Atanasovski*, Liljana Gavrilovska*, Peter Van Wesemael**, Antoine Dejonghe**, Peter Scheele†; *Institute for Networked Systems, RWTH Aachen University, Aachen, Germany; *Faculty of Electrical Engineering, Ss. Cyril and Methodius, Skopje, Macedonia; **Interuniversity Micro Electronics Center (imec), Leuven, Belgium; †Federal Network Agency, Mainz, Germany
3. Comparing Historical and Current Spectrum Occupancy Measurements in the Context of Cognitive Radio; M.Mehdawi, N.Riley, M.Ammar, M.zolfaghari; University of Hull, Department of Engineering, Hull, UK
4. Broadband Spectrum Survey Measurements for Cognitive Radio Applications; Robert URBAN, Tomas KORINEK, Pavel PECHAC; Department of Electromagnetic Field, Faculty of Electrical Engineering, Czech Technical University in Prague, Technicka 2, 166 27 Prague, Czech Republic
5. Evaluation of Spectrum Occupancy in an Urban Environment in a Cognitive Radio Context; Alexandru Marţian, Călin Vlădeanu, Ioana Marcu, Ion Marghescu; Department of Telecommunications Faculty of Electronics, Telecommunications and Information Technology Politehnica University of Bucharest 1-3 Iuliu Maniu, Bucharest 6, 061071, Romania
6. Spectrum Occupancy in Realistic Scenarios and Duty Cycle Model for Cognitive Radio; Miguel López-Benítez and Fernando Casadevall
7. Survey on Spectrum Utilization in Europe: Measurements, Analyses and Observations; Václav Valenta[1, 2], Roman Maršálek[2]; [1]Université Paris-Est and [2]Brno University of Technology 1ESYCOM, ESIEE Paris; [2]DREL; 1Noisy-le-Grand,

France; [2]Brno, Czech Republic; Geneviève Baudoin, Martine Villegas, Martha Suarez, Fabien Robert; Université Paris-Est ESYCOM, ESIEE Paris, Noisy-le-Grand, France

8. Lessons Learned from an Extensive Spectrum Occupancy Measurement Campaign and a Stochastic Duty Cycle Model; Matthias Wellens and Petri Mähönen, Department of Wireless Networks, RWTH Aachen University Kackertstrasse 9, D-52072 Aachen, Germany
9. SSC: Dublin, Ireland; Spectrum Occupancy Measurements Collected On April 16-18, 2007; Tugba Erpek Karl Steadman David Jones

3.6.2 Africa

A representative listing of measurement campaigns in Africa is shown below:

1. Spectrum Occupancy Investigation: Measurements in South Africa; S.D. Barnes, P.A. Jansen van Vuuren, B.T. Maharaj
2. Radio Spectrum Occupancy in South Africa; Gerhard Petrick
3. An Insight into Spectrum Occupancy in Nigeria; Bara'u Gafai Najashi, Feng Wenjiang, Choiabu Kadri

3.6.3 North America

From the early 1970's, various agencies, private companies and educational institutions have been collecting data on radio frequency spectrum utilization. Included among these groups are the NTIA[8], Shared Spectrum Company[9] (SSC) and the Illinois Institute of Technology (IIT) in Chicago, Illinois via its Spectrum Observatory Project [6] and spectrum occupancy modeling.

The NTIA has also developed the Radio Spectrum Measurement Sciences (RSMS) system[10] to perform thorough, accurate and repeatable spectrum occupancy measurements in virtually any location in a broad range of spectrum bands.

A representative listing of measurement campaigns is shown below:

1. NTIA Technical Report TR-14-502; Broadband Spectrum Survey in the Chicago, Illinois, Area April 2014, Chriss Hammerschmidt
2. NTIA Technical Report TR-14-500; Spectrum Occupancy Measurements of the 3550–3650 Megahertz Maritime Radar Band Near San Diego, California; January 2014; Michael Cotton and Roger Dalke
3. NTIA Technical Report TR-14-498; Broadband Spectrum Survey in the San Diego, California, Area; November 2013; Chriss A. Hammerschmidt
4. NTIA Technical Report TR-13-496; Broadband Spectrum Survey in the Denver Area; August 2013; Chriss Hammerschmidt, Heather E. Ottke, J. Randy Hoffman
5. NTIA: Spectrum Occupancy Results from Several Surveys; 2013; Chriss Hammerschmidt, Heather Ottke
6. NTIA Technical Report TR-08-455; Measurements to Characterize Land Mobile Channel Occupancy for Federal Bands 162–174 MHz and 406–420 MHz in the Denver, CO Area; September 2008; John E. Carroll J. Randy Hoffman Robert J. Matheson

8 National Telecommunications & Information Administration, "Exploring Spectrum Sharing Through Technical Studies," January 10, 2014, http://www.ntia.doc.gov/blog/2014/exploring-spectrum-sharing-through-technical-studies.

9 http://www.sharedspectrum.com/

10 http://www.its.bldrdoc.gov/programs/rsms/rsms-home.aspx

7. NTIA Report TR-00-373; Measured Occupancy of 5850-5925 MHz and Adjacent 5-GHz Spectrum in the United States; December 1999; Frank H. Sanders

8. NTIA Technical Report TR-97-334; Broadband Spectrum Survey at San Diego, California; December 1996 F.S. Sanders, B. Ramsey, and V. Lawrence

9. NTIA Technical Report TR-95-321; Broadband Spectrum Survey at Denver, Colorado; September 1995; Frank H. Sanders and Vince S. Lawrence

10. SSC: General Survey of Radio Frequency Bands – 30 MHz to 3 GHz;Version 2.0; September 23, 2010

11. SSC: Spectrum Occupancy Measurements: Loring Commerce Centre, Limestone, Maine, September 18-20, 2007; Tugba Erpek, Mark Lofquist, Ken Patton

12. SSC: Spectrum Occupancy Measurements: Chicago, Illinois, November 16-18, 2005; Mark A. McHenry, Dan McCloskey

13. SSC: Spectrum Occupancy Measurements: Riverbend Park, Great Falls, Virginia, April 7, 2004; Mark A. McHenry, Karl Steadman

14. SSC: Spectrum Occupancy Measurements: Tyson's Square Center, Vienna, Virginia, April 9, 2004; Mark A. McHenry, Karl Steadman

15. SSC: Spectrum Occupancy Measurements: National Science Foundation Building Roof, April 16, 2004; Revision 2; Mark A. McHenry, Shyam Chunduri

16. SSC: Spectrum Occupancy Measurements: Republican National Convention, New York City, New York, August 30 – September 3, 2004; Revision 2; Mark A. McHenry, Dan McCloskey, George Lane-Roberts

17. SSC: National Radio Astronomy Observatory (NRAO); Green Bank, West Virginia; October 10 - 11, 2004; Revision 3; Mark A. McHenry, Karl Steadman

18. IIT: Long-term, wide-band spectral monitoring in support of Dynamic Spectrum Access Networks at the IIT Spectrum Observatory; Roger B. Bacchus, Antoni J. Fertner, Cynthia S. Hood and Dennis A. Roberson Wireless Network and Communication Research Center (WiNCom) Illinois Institute of Technology

19. IIT: Spectrum Utilization Study in Support of Dynamic Spectrum Access for Public Safety; Roger Bacchus, Tanim Taher, Kenneth Zdunek Department of Electrical and Computer Engineering; Dennis Roberson, Department of Computer Science Illinois Institute of Technology, Chicago, IL.

20. IIT: Long-term Spectral Occupancy Findings in Chicago; Tanim M. Taher, Roger B. Bacchus, Kenneth J. Zdunek Department of Electrical and Computer Engineering; Dennis A. Roberson, Department of Computer Science Illinois Institute of Technology, Chicago, IL.

3.6.4 South America

A representative listing of measurement campaigns in Latin America is shown below:

1. Cognitive Radio Simulation Based on Spectrum Occupancy Measurements at One Site in Brazil; Mauro Vieira de Lima, Telecommunications Metrology Division, INMETRO, Duque de Caxias, Brazil; Luiz da Silva Mello Center for Telecommunication Studies CETUC/PUC-Rio Rio de Janeiro, Brazil

2. Power Spectrum Measurements from 30 MHz to 910 MHz in the City of San Luis Potosi, Mexico; Rafael Aguilar-Gonzalez, Marco Cardenas-Juarez, Ulises Pineda Rico, Enrique Stevens-Navarro

3. Spectrum Occupancy Measurements below 1 GHz in the City of San Luis Potosi, Mexico; Rafael Aguilar-Gonzalez, Marco Cardenas-Juarez, Ulises Pineda-Rico and Enrique Stevens-Navarro

4. Spectrum Occupancy Statistics in Bogota-Colombia; Luis Fernando Pedraza, Andrés Molina; Ingrid Paez

3.6.5 Asia

A representative listing of measurement campaigns in Asia is shown below:

1. Spectrum Occupancy Measurements and Analysis in Beijing; Jiantao Xue*, Zhiyong Feng, Ping Zhang; Wireless Technology Innovation Institute (WTI), Beijing University of Posts & Telecommunications (BUPT), No.10 Xitucheng Road, Haidian District, Beijing, 100876, P.R.China
2. Quantitative spectrum occupancy evaluation in China: based on a large-scale concurrent spectrum measurement; YIN Liang, YIN Si-xing, WANG Shuai, ZHANG Er-qing, HONG Wei-jun, LI Shu-fang; School of Information and Communication Engineering, Beijing University of Posts and Telecommunications, Beijing 100876, China
3. Quantitative Assessment of TV White Space in India; Gaurang Naik, Sudesh Singhal, Animesh Kumar, and Abhay Karandikar Department of Electrical Engineering Indian Institute of Technology Bombay Mumbai – 400076
4. Spectrum Occupancy Statistics in the Context of Cognitive Radio; Kishor Patil1, Knud Skouby2, Ashok Chandra3, Ramjee Prasad4; Center for TeleInFrastruktur (CTIF), Aalborg University, Aalborg, Denmark1, 4 ; Center for Communication, Media and Information Technologies, Aalborg University, Copenhagen, Denmark2; Ministry of Communications and IT, Government of India, New Delhi, India3
5. Measurements and Analysis of Spectrum Occupancy in the Cellular and TV Bands; Malaysia; Shanjeevan Jayavalan, Hafizal Mohamad, Norazizah Mohd Aripin, Aiman Ismail, Nordin Ramli, Azmi Yaacob, and Ming Ann Ng
6. Spectrum Survey of VHF and UHF Bands in the Philippines; Annie Liza C. Pintor, Mark Ryan S. To, Jane S. Salenga, Gabriel M. Geslani, Daisy P. Agpawa, and Melvin K. Cabatuan
7. Spectrum Survey in Singapore: Occupancy Measurements and Analyses; Md Habibul Islam, Choo Leng Koh, Ser Wah Oh, Xianming Qing, Yoke Yong Lai, Cavin Wang, Ying-Chang Liang, Bee Eng Toh, Francois Chin, Geok Leng Tan, and William Toh
8. Vietnam Spectrum Occupancy Measurements and Analysis for Cognitive Radio Applications; Vo Nguyen Quoc Bao, Le Quoc Cuong, Le Quang Phu, Tran Dinh Thuan, Nguyen Thien Quy, Lam Minh Trung

3.6.6 Oceania

A representative listing of measurement campaigns in Oceania is shown below:

1. A model for HF spectral occupancy in Central Australia; Percival, D.J., High Frequency Radar Div., Defense Sci. & Technol. Organ., Salisbury, SA, Australia ; Kraetzl, M. ; Britton, M.S.
2. A Quantitative Analysis of Spectral Occupancy Measurements for Cognitive Radio; Robin I. C. Chiang, Gerard B. Rowe, and Kevin W. Sowerby

3.7 Discussion and Conclusions

Many countries are now undertaking programs to determine spectrum occupancy and enacting rules to eventually support spectrum sharing. The spectrum occupancy data measured in multiple campaigns clearly indicates the potential for spectrum sharing – see for example the average spectrum occupancy observed in the IIT Spectrum Observatory campaigns in Chicago and NYC. Figure 4 contains additional notes indicating the services provided within each allocation; occupancy numbers indicated from the original publication have not been modified.

The study was based on early analysis of spectral occupancy in the Chicago and NYC regions. Since this data was captured and published, additional data, using sensing algorithms that allowed analysis at lower received signal levels has altered the reported occupancy of some allocations. For example, early studies of spectrum occupancy utilized higher received power level detection thresholds to determine if a given spectrum allocation (channel) has been active and the level at which activity has taken place. Additional data has been published indicating spectral occupancy based on lower thresholds. For example, the data presented in the Public Safety and Private Land-mobile portions of the UHF band (namely, portions of the 450-470MHz allocation) indicate cyclical, high occupancy use of public safety and public works spectrum with the highest rates indicted during incidents; levels of occupancy that exceeded 80%[11]. Similar factors occur in other spectrum allocations utilized by the Department of Defense and Federal users. While sharing of these bands cannot be ruled out, it has been suggested that services that are "Mission Critical" – expanded to define several critical service needs that affect and include human health, safety, and public protection – may require additional protection criteria be met and additional protective measures be implemented.

Some spectrum must be protected and, therefore, devoid of shared use either entirely or with additional criteria such as geographic and physical limitations (indoor use only; geographic restrictions, specified power limits, etc.) Fortunately, spectrum with these additional restrictions is quite limited; primarily consisting of spectrum such as that used for passive astronomy observations, certain satellite-based allocations such as Global Navigation Satellite System (GNSS) at L-band, and perhaps, at least initially, spectrum utilized for certain medical services (TV-37 in North America), and other discrete segments. Additional spectrum, such as that utilized by defense departments and federal systems operating on various allocations world-wide may also require protection although great strides are taking place to open portions of this spectrum for shared, dynamic use. Sub-bands of this nature will cause terrestrial spectrum occupancy surveys to appear underutilized. Additional protective regulatory action may be required to protect these necessary services although development of the art will undoubtedly open at least portions of restricted spectrum to dynamic shared use.

The average spectrum occupancy reported in measurement campaigns worldwide also follows the general trend in Figure 5; with differences in the distribution of channel/band utilization based on the local wireless communication services in place. While the average spectrum occupancy indicated would appear to support the viability of spectrum sharing in specific channel bands, the dynamic nature of spectrum utilization needs to be taken into account. Primary users (PUs) shall take precedence over Secondary users (SUs) at all times. If PU spectrum utilization requirements increase or interference from SUs becomes a dominant factor, then some and/or all SUs may be forced to back-off or relocate to a channel band where the SU is a primary user. Depending on the licensing approach taken, conflicts can be resolved either by the use of agile terminals – employing sensing to support Dynamic Spectrum Access (DSA) e.g. TVWS or the use of Licensed Shared Access (LSA) or Authorized Shared Access (ASA).

All approaches, licensed or unlicensed will require infrastructure support to a greater or lesser degree – from license grant/access management to metering service, blacklist management and interference monitoring/mitigation. Faced with a dramatic decrease in availability and prohibitive cost of spectrum for static allocation, wireless service providers will eventually roll out their preferred technical approach to spectrum sharing to address critical data bandwidth shortfalls in a cost effective manner.

11 IIT WiNCom Wireless Networks and Communications Research Center, 24 September 2013, http://www.cs.iit.edu/~mbilgic/seminar/pdfs/roberson_whoweare2013.pdf.

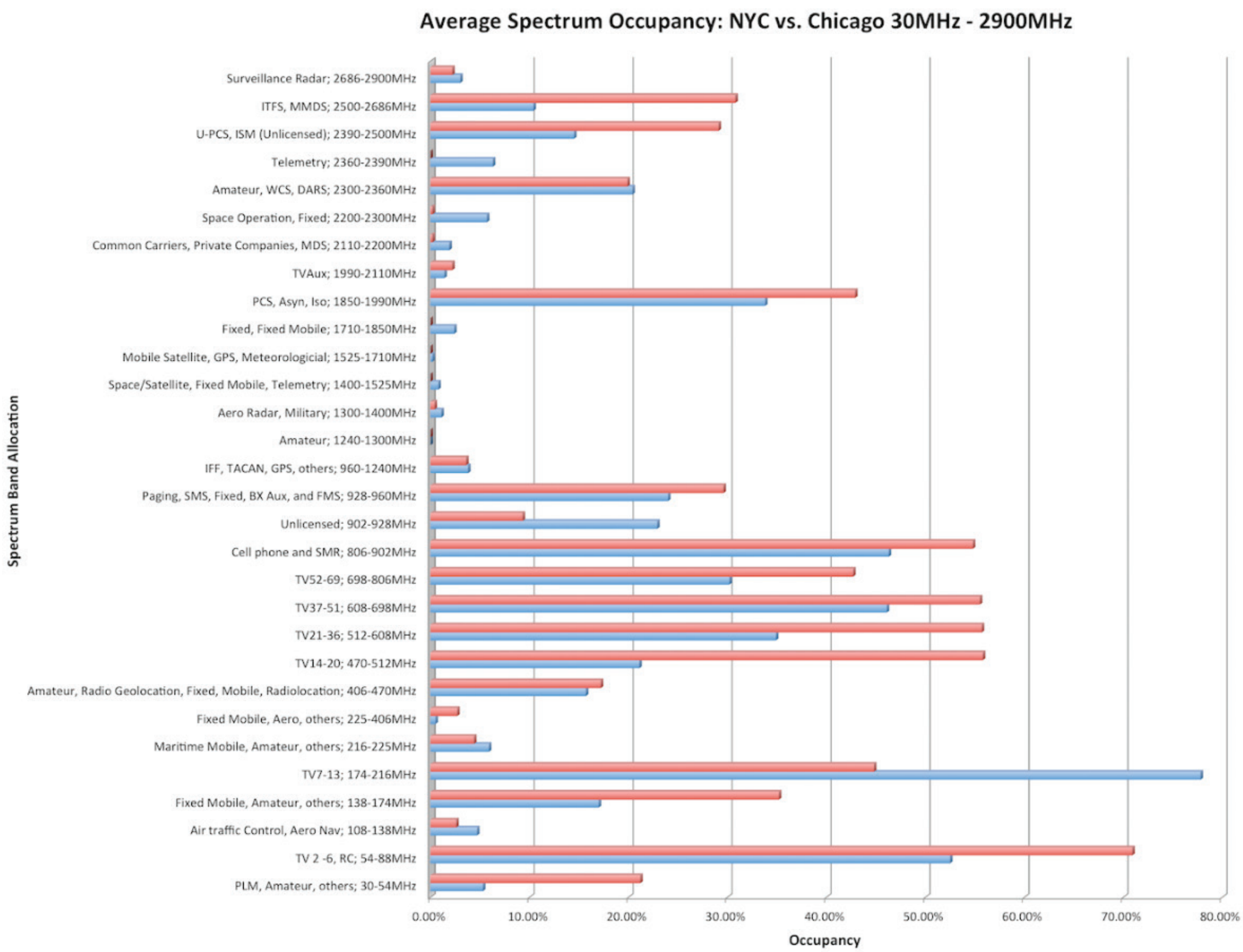

Figure 5: Average Spectrum Occupancy NYC vs. Chicago 30MHz – 2900MHz

4

Benefits of Spectrum Sharing

In December of 2010, the Wireless Innovation Forum published a report on "Quantifying the Benefits of Cognitive Radio" (WINNF-09-P-0012-V1.0.0)[12]. This document reports the results of an extensive survey performed by the Forum's Cognitive Radio Work Group (CRWG) on open and public cognitive radio (CR) literature. The intent of the report was to document the "hard numbers" that researchers and developers have reported so researchers and developers can better assess the value proposition of CR.

The report shows key benefits to dynamic spectrum sharing technology including:

- Improving spectrum utilization and efficiency
- Improving interoperability between legacy and emerging systems
- Improving link reliability
- Less expensive radios
- Extended battery life
- Extended coverage

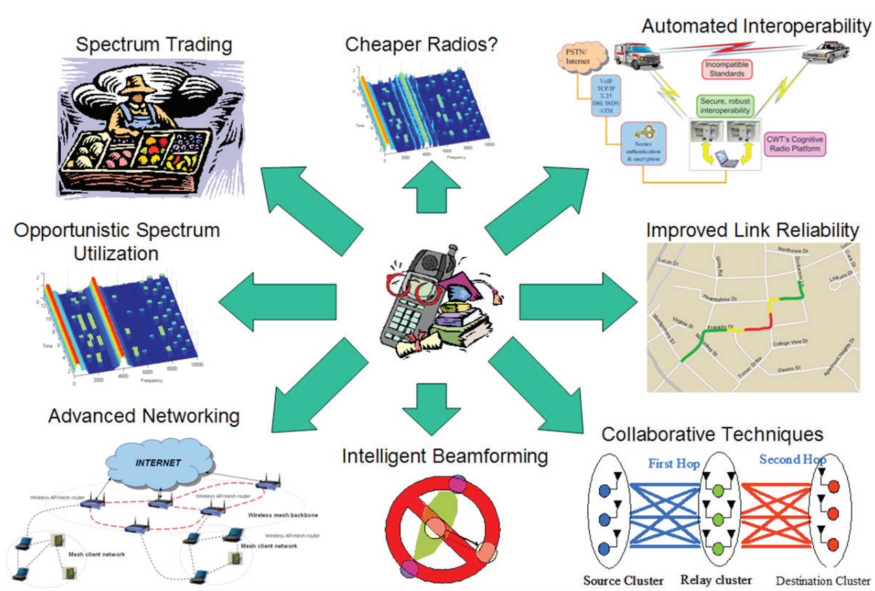

Figure 6: Cognitive radio is seen as enabling many new applications.[13]

12 http://groups.winnforum.org/d/do/3839

13 J. Neel, "Analysis and design of cognitive radio networks and distributed radio resource management algorithms," Figure 1.6, Virginia Tech, PhD Dissertation, Sep. 2006.

5

Regulation

Regulators allocate frequencies for all radio services based on the Radio Regulations[14] published by the International Telecommunications Union, the United Nations specialized agency based in Geneva. The Radio Regulations assign frequency bands for services including mobile, fixed links, radar, broadcasting, etc. Some services are assigned exclusive use of a band and most will share with others on a non-interference basis. However, a national regulator can vary its frequency allocations from the Radio Regulations, provided that there is no interference to services in neighboring countries or to international services.

The potential for spectrum sharing to improve spectrum efficiency and reuse has led several nations to investigate and implement legislation which encourages spectrum sharing among operators. Although typical implementations are rudimentary, limited in scope, or lack specificity when referring to spectrum sharing, they are serious steps toward large-scale, obstacle free spectrum sharing. The variety of approaches signifies the absence, internationally, of a cohesive spectrum sharing goal. At the same time, however, such diversity demonstrates the wide range of possible methods to legislate and encourage spectrum sharing. Viewed as a whole, these international movements suggest a positive direction for spectrum access legislation as more and more countries perceive it as a viable option for improving spectrum utilization.

Figure 7 Regulation of spectrum sharing around the world covered by this report at various levels.

14 ITU-R Radio Regulations 2012

This section provides a summary of regulations from national regulators supporting spectrum sharing.

5.1 ITU Region 1

5.1.1 European Commission

The European Commission develops radio spectrum policy with the assistance of the Radio Spectrum Committee (RSC), the Radio Spectrum Policy Group (RSPG) and the European Conference of Postal and Telecommunications Administration (CEPT). In March of 2012, the European Parliament and Council approved a first "Radio Spectrum Policy Programme" (RSPP) as a part of the Europe 2020 Initiative[15]. The program supports specific spectrum needs, including broadband, and outlines concrete actions to be taken by member states and the Commission, including leveraging the "digital dividend" realized in the digital TV transition in the 800 MHz band for communications in "sparsely populated areas," and making at least 1200 MHz available for wireless broadband services[16]. With this latter goal in mind, Article 4 of the RSPP explicitly calls for spectrum sharing:

> ***"Member States and the Commission shall, where appropriate, take measures to enhance efficiency and flexibility in particular through collective and shared use of spectrum in order to promote innovation and investment."***

In April of 2014, The Commission published a report to the European Parliament and Council on the implementation of this programme to date[17]. Efforts to facilitate spectrum sharing where outlined in two areas:

Unlicensed Spectrum (Spectrum Sharing Level 4B): the focus of the Commission with respect to unlicensed spectrum has been around short range devices (SRDs) including small cells. Steps have been taken to harmonize bands for SRDs, and to establish a regulatory environment conducive to small cell deployments.

Licensed Shared Access (Spectrum Sharing Level 2A): The Commission tasked the RSPG with developing an opinion on LSA, and that opinion was delivered in November 201318 19. The approach for LSA adopted by the RSPG is to allow additional users to access an incumbent's licensed spectrum with all parties having a known quality of service as defined by the rules. Many of the models considered are similar to the secondary markets ruling in the US outlined in section 5.2.5.3 of this report.

5.1.2 Kenya

The Kenyan government has created a special task force of ten members to study possible implementations of spectrum sharing as operators prepare to roll out 4G networks. The latest reports indicate that new regulations would cover the 700MHz-800MHz band20. The March 2014 draft of the task force's study states that "Radio frequency spectrum sharing

15 http://ec.europa.eu/digital-agenda/en/radio-spectrum-policy-program-roadmap-wireless-europe
16 https://ec.europa.eu/digital-agenda/en/news/concrete-actions-radio-spectrum-policy-programme-rspp
17 http://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:52014DC0228&from=EN
18 http://rspg-spectrum.eu/_documents/documents/meeting/rspg29/rspg12-424_final-rfo_lsa.pdf
19 https://circabc.europa.eu/d/d/workspace/SpacesStore/3958ecef-c25e-4e4f-8e3b-469d1db6bc07/RSPG13-538_RSPG-Opinion-on-LSA%20.pdf
20 C. Wokabi, "Taskforce to explore 4G spectrum-sharing options," *Daily Nation*, 14 Dec 2013. http://mobile.nation.co.ke/business/Taskforce-to-explore-4G-spectrum-sharing-options/-/1950106/2112118/-/format/xhtml/-/ca5hv3/-/index.html

among various services and users is to be encouraged in order to satisfy the growing needs for spectrum resources." However, the study mentions no recommendations on how to implement or encourage spectrum sharing[21].

5.1.3 South Africa (Spectrum Sharing Level 2A)

On 7 April 2014, the South African government approved the Electronic Communications Amendment Act of 2014 which allows for secondary trading of spectrum among licensees. Such trading, however, must receive approval from the Independent Communications Authority of South Africa (ICASA), which has 60 business days to approve an agreement[22]. The legislation is somewhat vague and it does not clarify whether spectrum sharing is a type of the permitted spectrum trading[23]. The date when the legislation comes into effect has not yet been announced by the South African Minister of Communications.

Further Reading:

[1] "Electronic Communications Amendment Act," *Government Gazette - Republic of South Africa*, 07-Apr-2014. http://www.ellipsis.co.za/wp-content/uploads/2014/01/Electronic-Communications-Amendment-Act-1-of-2014.pdf

5.1.4 United Kingdom (Spectrum Sharing Level 3A)

5.1.4.1 Introduction

UK frequency allocations are published in the UK Frequency Allocation Table (FAT)[24]. Ofcom, the UK regulator, has been considering DSA since around 2008. Initially the work was research based[25] and considered whether sensing could be used, finally concluding that this was not possible. Since 2010 Ofcom has published a series of consultation documents[26] as it moves toward enabling DSA to the TV bands. With the digital switchover clearing part of the TV UHF spectrum, Ofcom is proposing to allocate the 600 MHz band (550 – 606 MHz) for use by white space devices. and at the time of writing was predicting that it would complete the process by 2014, however the 700 MHz band (694 – 790 MHz) is likely to gain an international assignment to mobile broadband agreement at the 2015 Worldwide Radio Conference. This could result in Ofcom having a further review of the 600 MHz band.

Ofcom adopted the ETSI Harmonised Standard as the preferred device standard for its TV White Space (TVWS) pilot trials[27] in 2014.

21 Republic of Kenya Ministry of Information, Communications and Technology, "Wireless Broadband Spectrum Policy Guidelines - Draft." Mar 2014. http://www.information.go.ke/wp-content/uploads/2014/03/DraftSpectructionPolicy.pdf

22 "Electronic Communications Amendment Act 2014," *Ellipsis*. http://www.ellipsis.co.za/electronic-communications-amendment-act-2014/

23 T. Youell, "South Africa considers secondary trading for spectrum," *PolicyTracker*, 16 Aug 2013. http://www.policytracker.com/headlines/south-africa-considers-secondary-trading-for-spectrum/

24 UK Frequency Allocation Table

25 See http://stakeholders.ofcom.org.uk/market-data-research/other/technology-research/research/emerging-tech/cograd/ and other research papers on the Ofcom website.

26 See TV white spaces - A consultation on white space device requirements which references earlier work, presentation at http://stakeholders.ofcom.org.uk/binaries/consultations/whitespaces/annexes/workshop.pdf, and Ofcom statement on securing long term benefits from scarce low frequency spectrum (November 2012), and Ofcom consultation on the award of the 600 MHz spectrum band (February 2013), with the consequent statement Ofcom statement on the award of the 600 MHz spectrum band (July 2013), and Ofcom consultation on the future role of spectrum sharing for mobile and wireless data services (August 2013), and continuing publications.

27 Ofcom TVWS Pilot Trials

5.1.4.2 An approach based on allowed power levels

One of the key innovations put forward by Ofcom was that, rather than allowing white space access on a particular set of power levels, that the allowed power level could be variable and could be returned along with each free channel. So a white space device questioning the database would get back a set of channels with each channel having a maximum allowed power level associated with it. This should allow greater white space access since, in the case where the "full" power levels were just too high to be allowed, the database could return a lower power level and devices could still make some use of the spectrum. This also overcomes blanket restrictions such as the preventing of operation on channels adjacent to TV transmissions by returning a lower power level for these channels.

5.1.4.3 Multiple co-existence curves

With the allowed power levels being calculated dynamically on a pixel-by-pixel basis and depending on the licensed use in the vicinity, there is much more that can be done to maximize the availability of the TV white space. This includes:

1. taking into account the emission mask of the white space device,
2. taking into account the propensity of white space waveform to interfere with licensed usage,
3. making use of knowledge about the application in determining minimum coupling loss and similar, and
4. taking into account the licensed power levels where the protection ratio varies with power level.

The first three of these are specific to the technology. For example, a Weightless technology would have a particular emissions mask as specified in the Weightless Specification. The tolerance of TV receivers to its particular transmission waveform could have previously been measured by a regulator or test house as part of any regulatory type-approval process. The application space for machine to machine (M2M) might be understood not to generally include devices that did not have directional antennas, were not mounted on outside walls of buildings and only transmitted very irregularly. Whenever a Weightless base station sent an enquiry to the database it could be instructed to look up these values and calculate maximum allowed power levels accordingly.

The advantages of this approach are access to much more spectrum. The disadvantages are even more complex. The database now needs to maintain information about multiple technologies and this information needs to be certified and provided as part of a type-approval process. There may be tens or hundreds of combinations of technology, implementation and applications all of which may need to be maintained across multiple databases. This also makes pre-calculation of database output more difficult, increasing the real-time calculation needed. But broadly, computation is cheap whereas spectrum is expensive and it seems logical to make use of whatever approaches can be found to maximize the availability of white space.

5.1.4.4 Narrowband and wideband differences

The two key licensed users of TV white space have systems with quite different bandwidths. TV transmissions are broadband – 6MHz in the US, 8MHz in Europe and a mix of this elsewhere. Wireless microphones have a bandwidth of around 100kHz. White space devices might also have differing bandwidths. While the broadband systems tend to occupy as much of a channel as possible, systems like Weightless operate a mix of a broadband downlink and multiple narrowband uplinks, each being around 128kHz wide.

Regulators have given consideration to bandwidth when specifying allowed power levels. The concern is that if the bandwidth were unspecified it might be possible to abuse this. For example, were a power of 30dBm (1W) allowed when averaged across an 8MHz channel, this could be delivered as 49dBm in 100kHz and nothing in other channels.

Ofcom concluded that there should be two power levels provided to the device, one measured across the entire 8MHz channel and another across any 100kHz part of that channel. Broadly, the 8MHz level would be calculated based on interference to TV receivers and the 100kHz level to interference for wireless microphones. A device would need to meet both limits. Key is that there is no pre-determined relationship between them. For example, if there were no wireless microphones in a white space coverage area then the 100kHz power might be quite high relative to the 8MHz power.

This flexibility is important to technologies like Weightless where using narrowband uplink transmissions helps enable devices to operate with very low transmit powers.

In principle, using narrowband channels could increase the risk of aggregation. If a device used as much power in a narrow band as would be allowed if it were broadband, and if there were multiple devices in the same area, then the total interference could be higher. How much this increases the risk is unclear – initial assessment would suggest the risk still remains low. Regulators can either take a risk adverse approach and allow a margin for this, or can monitor the situation and if either evidence or understanding of deployment scenarios suggests that action is needed then they can modify the responses returned by the database.

5.1.4.5 Using declared distances to nearest TV for professional install

Ofcom decided to take different approaches to fixed and mobile equipment. In particular, they observed that where a device was fixed and was installed by a professional then there was additional information that could be used to determine the Minimum Coupling Loss (MCL). Broadly, this approach is envisaged for base stations, although it could also be applied to some terminals.

For a base station, optionally the installer could measure the distance to the nearest building and declare this to the database. This measurement could be exact or as simple as "more than 50m." This distance can then be used in determining the MCL. Since the MCL is often the constraining factor on the output power levels that can be used, this provides a level of flexibility. Network operators can then select base station sites partly on the basis that they are some distance from any buildings and hence gain the ability to use a higher transmit power. There is the potential for buildings to subsequently be built closer to the base station but it was decided to deal with this when interference was reported.

It is also then possible to take into account antenna radiation patterns, so a network operator might choose to use a lower gain antenna in the direction of buildings. Again, this would need to be registered with the database.

This does then require a process for ensuring that the declaration of distance is appropriately policed. Ofcom envisage that installers would need to have some level of accreditation in order to demonstrate their competence. There would also need to be some sanction in the cases where the operator transgressed. This is difficult territory for regulators who may not have the legal powers to readily implement the simplest scheme. At the time of writing Ofcom were still exploring the mechanics of quite how this would be implemented.

5.1.4.6 Changing path loss models for short distances

Another area linked to MCL and propagation loss is to re-assess whether the propagation models that are currently used are appropriate for DSA analysis. This is particularly the case when distances are short – less than 1km. Conventional propagation models typically predict the most likely propagation loss and then assume a distribution of values around this level. The distribution is often assumed to be log-Normal (that is, Normally distributed when shown on a logarithmic scale). These distributions are symmetrical so there is an equal likelihood of the pathloss being 3dB greater than predicted and it being 3dB less than predicted. Such models have been widely used for long-range propagation and generally shown to be approximately correct.

However, when the range is short, the pathloss model often makes use of free-space propagation where it assumes a direct line-of-sight exists between the transmitter and receiver. In this case, there is little scope for the pathloss being less than predicted since this would require some form of focussing of waveforms or constructive reflections. However, there is much scope for it being greater than predicted in the case where there are obstructions between the transmitter and receiver. So it might be imagined that a distribution would be skewed around the predicted value. For example, it might have a log-Normal distribution with a σ of 5dB on the upper (greater pathloss) side and a log-Normal distribution with a} of 1dB on the lower (less pathloss) side. There is little in the way of measurement work to confirm this but logic would suggest it to be appropriate.

If a symmetric distribution is adopted, then generally far too great a probability is assigned to a low pathloss occurring. But this is exactly the situation that leads to the worst-case interference scenario and hence the model over-predicts the likelihood of interference and unnecessarily restricts white space access.

While the Ofcom work did not lead to any learned publications which could definitively set out the distributions that should be used around the predicted pathloss values where distances were short, it did clearly demonstrate that using a conventional approach was hugely conservative.

5.1.4.7 The September 2013 co-existence consultation

In September 2013 Ofcom published a detailed consultation[28] into co-existence parameters for white space devices. In the consultation Ofcom noted that much previous work had been conservative and that a more balanced approach would be taken toward determining appropriate power levels. Key elements in the consultation were:

- A cap on the maximum transmitter power of 36dBm/8MHz, bringing the UK into alignment with the US.
- Protection will not be afforded to indoor reception or to reception of transmitters other than the preferred one. In particular, not protecting indoor reception is of critical importance to white space usage as otherwise the very small coupling losses prevent most usage.
- Rather than measuring the TV interference as a reduction in location probability it will be measured as an increase in noise power of 1dB. This is equivalent to a reduction in location probability of around 7%, taking edge of cell location probability at 1% time from 70% to around 63%. The noise power approach is much simpler to calculate and does not require prior knowledge of Digital Terrestrial Television (DTT) planning criteria.
- A minimum distance of 10m from a White Space Device (WSD) to a Programme Making and Special Events (PMSE)device will be assumed when determining the coupling loss. A penetration loss of 7dB will apply where one device is indoors, the other outdoors and a loss of 14dB in the case both are indoors[29].
- Aggregation of interference from multiple WSDs will not be considered since the interference tends to be dominated by the closest WSD and also since WSDs will tend to back-off from multiple transmissions in the same location.
- Coupling loss between fixed ("Type A") WSDs and TVs is based on the environment (urban, suburban or rural) and the transmitter height. The worst case is 45dB for urban transmissions at 10m height, the best case 60dB for rural transmissions at 1.5m height[30]. For mobile ("Type B") devices the height is assumed at 1.5m outdoors. For larger heights the device is assumed indoors and a 7dB penetration loss added.
- Multiple charts are presented in the consultation showing estimated white space availability for various transmit powers and classes of emissions. These show that in most cases at least 95% availability of three or more channels can be achieved across the UK. Detailed protection ratios for 50 receivers were also provided.

At the time of writing this consultation had closed, but coexistence work was continuing in Ofcom's technical working groups.

28 See Ofcom consultation "TV white spaces: approach to coexistence," September 2013,

29 This effectively assumes they are in different buildings or different parts of the same building.

30 See Table 4.1a of the annex to the consultation.

Further Reading

1)https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/287994/UK_Spectrum_Strategy_FINAL.pdf.

5.2 ITU Region 2

5.2.1 Brazil (Spectrum Sharing Level 2A)

In 2008, to promote development of cellular networks, the National Telecommunications Agency of Brazil (Anatel) issued four 3G licenses per geographic service area. To promote efficient use of resources, the licenses allow infrastructure sharing, including spectrum sharing. However, the 3G auction rules identify spectrum sharing specifically as a method of bringing coverage to areas that are either rural or remote[31]. Although this purpose is not listed as a hard requirement, since any spectrum sharing between operators must receive specific prior approval from Anatel, it may be used as a basis to block spectrum sharing agreements. Thus, 3G spectrum sharing has limited application in Brazil at this time.

Anatel also permits spectrum sharing case-by-case for LTE services. In 2013, Anatel began drafting regulation that would permit spectrum sharing without requiring operators to get independent approval. A first draft has been completed and was available for public review until June 1, 2014. The proposal plans to allow spectrum sharing between Television and 4G operators in the 700MHz band, which spans from 698 to 806 MHz. The 700MHz auction was scheduled to take place in August 2014[32].

Further Reading:

[1] "ATDI Report Demonstrates That LTE & TV Services Can Coexist in Brazil | ATDI," *ATDI*, 17-Jan-2014. http://www.atdi.co.uk/big-country-big-plans-2/

[2] *GSMA*, "New GSMA Report Demonstrates That LTE & TV Services Can Coexist in Brazil | Newsroom," 17-Jan-2014. http://www.gsma.com/newsroom/gsma-report-lte-television-brazil/.

5.2.2 Canada

Canada, like other countries, is working to provide additional spectrum for mobile services. The "Spectrum Policy Framework for Canada" provides general guidance on flexibility in regulatory practices to achieve this objective, and toward that end, Canada has been exploring several Spectrum Sharing alternatives[33]. Information on these activities can be found through the following references:

1. Licensing Framework for Broadband Radio Service (BRS) - 2500 MHz Band (2014), http://www.ic.gc.ca/eic/site/smt-gst.nsf/eng/sf10726.html, see paragraphs 220-234.
2. Licensing Framework for Mobile Broadband Services (MBS) - 700 MHz Band (2013), http://www.ic.gc.ca/eic/site/smt-gst.nsf/eng/sf10572.html, see paragraphs 197-202.
3. Commercial Mobile Spectrum Outlook (2013), http://www.ic.gc.ca/eic/site/smt-gst.nsf/eng/sf09444.html, see Sections 2.4, 4.2.2, 4.2.5 and 4.2.6

31 ICT Regulation Toolkit, "5.4 Spectrum Sharing," http://www.ictregulationtoolkit.org/5.4.

32 T. Youell, "Brazil's broadcasters question 700 MHz study," *PolicyTracker*, 18 Feb 2014. http://www.policytracker.com/headlines/spectrum-policy-drives-3g-take-up-in-guatemala-and-el-salvador/

33 http://www.ic.gc.ca/eic/site/smt-gst.nsf/eng/sf08776.html

4. Study of Future Demand for Radio Spectrum in Canada 2011-2015, http://www.ic.gc.ca/eic/site/smt-gst.nsf/eng/sf10253.html, see Section 6.11.2 for sharing related to military services
5. Framework for Mandatory Roaming and Antenna Tower and Site Sharing, http://www.ic.gc.ca/eic/site/smt-gst.nsf/eng/h_sf10290.html
6. Framework for the Use of Certain Non-broadcasting Applications in the Television Broadcasting Bands Below 698 MHz, http://www.ic.gc.ca/eic/site/smt-gst.nsf/eng/sf10493.html

5.2.3.Guatemala (Spectrum Sharing Level 2A)

In 1996, Guatemala converted spectrum access rights to a free market system, where any individual or other entity could purchase a Frequency Use Title (TUF) for a given bandwidth in a given location. Each TUF allows an operator to use its assigned spectrum in any manner that does not interfere with other operators. Each private entity has full right to subdivide, sell, lease, and aggregate their TUF to other entities. There are no known instances of TUF holders implementing spectrum sharing to improve spectrum utilization. However, the almost complete liberalization of the market suggests excellent opportunity to investigate applications of spectrum sharing in Guatemala[34].

Further Reading:

[1] M. Franklin, "Guatemala: spectrum trading pioneer starts to see the drawbacks," *PolicyTracker*, 26-Jan-2006. http://www.policytracker.com/headlines/guatemala-spectrum-trading-pioneer-starts-to-see-the-drawbacks/

[2] M. Franklin, "Liberalisation pioneer fails to close the legal loopholes," *PolicyTracker*, 21-Apr-2006. http://www.policytracker.com/headlines/liberalisation-pioneer-fails-to-close-the-legal-loopholes/

5.2.4 Mexico

In 2013, to reform the telecommunications sector, Mexico established the Instituto Federal de Telecomunicaciones (IFT) with power over spectrum assignment, coverage conditions, and competition rules for operators. The IFT is required to deploy a public sector LTE telecommunications network which shares its services wholesale to resellers and network operators. Network deployment is scheduled to begin in 2014 and be completed by 2018. In addition to any available state-owned infrastructure, this network is required to exploit the 90MHz available in the 700MHz band, as laid out according to the Asia-Pacific Telecommunity band plan. All aspects of the network, including spectrum, must be managed with infrastructure sharing as a first principle[35]. The model faces great criticism from network operators: chief of legal and regulatory affairs at telecom Etisalat, Kamal Shehadi, claims that the monopoly will stifle innovation in mobile networks. On the other hand, Ernesto Flores-Roux, consultant for the Mexican government, claims that with competing networks in different bands, there would not be a monopoly, and that innovation is still possible in the 850MHz band because it will remain with the private sector[36]. More details of how the wholesale network will share its infrastructure are to be determined as the network development begins.

34 D. Standeford, "Spectrum policy drives 3G coverage in Guatemala and El Salvador," *PolicyTracker*, 28 Sep 2011. http://www.policytracker.com/headlines/spectrum-policy-drives-3g-take-up-in-guatemala-and-el-salvador/

35 E. Flores-Roux, "Mexico's Spectrum Sharing Model." 12 Mar 2014. http://broadbandasia.info/wp-content/uploads/2014/03/efloresroux-delhi-2014.pdf

36 T. Youell, "Operators doubt logic of Mexico's 700 MHz wholesale network," *PolicyTracker*, 04 Apr 2014. http://www.policytracker.com/headlines/mexico-to-build-worlds-first-government-wholesale-lte-network-in-the-700-mhz-band/

5.2.5 United States

5.2.5.1 Introduction

Regulation of spectrum sharing in the United States is often times more complex than in other countries because spectrum is managed by multiple regulatory agencies (see Figure 7)[37]. Through the Communication Act of 1934, the United States Congress established the Federal Communications Commission (the FCC or "Commission") as an independent body with broad powers to regulate both wireline and wireless communications for non-Federal use including commercial, private, and state and local government use. Through the same act, Congress reserved for the President of the United States the authority to assign operating frequencies for Federal government. In 1978, the President issued an Executive Order effectively delegating these powers to the newly established National Telecommunications and Information Administration (NTIA) operating within the Department of Commerce and led by the Assistant Secretary of Commerce for Communications and Information. Congress later codified the functions defined in this order in the National Telecommunications and Information Administration Organization Act, making the delegation permanent.

The regulation of spectrum is managed differently by the FCC and NTIA. Regulations from the FCC are largely created through a rule making process[38]. For each new rule, a docket is opened to act as an electronic file for all the rule making documents issued. Once a docket is opened, a notice of public rulemaking (NPRM) can be released, defining the need for and the text of the proposed rule to allow for public comment. Comments and reply comments (comments about the comments) are reviewed, and the Commission can then choose to leave the docket open, issue a further notice of proposed rule-making with an amended proposal, or issue a final rule, or Order. The Commission may also release a Notice of Inquiry or other Public Notice in support of the Rulemaking Process. The FCC's rules and regulations are in Title 47 of the Code of Federal Regulations (CFR), which are published and maintained by the Government Printing Office. Parties disagreeing with the final rules may issue a petition for reconsideration or seek court review of the decision. The FCC is supported in this rule making process through a Technological Advisory Council (TAC), which is comprised of leading experts and is chartered to help the Commission keep abreast of current innovations and understand relevant technologies[39].

Spectrum management at NTIA follows a different model. Policies and procedures for assigning federal spectrum within the United States are established by NTIA's Office of Spectrum Management (OSM)[40]. To help facilitate this task, OSM chairs the Interdepartmental Radio Advisory Committee (IRAC) consisting of representatives from 19 federal government agencies who advise the NTIA on policies and regulations for the use of federal spectrum[41]. OSM coordinates with the IRAC to set policy for the assignment of spectrum, the results of which are published in the NTIA "Manual of Regulations and Procedures for Federal Radio Frequency Management," also known as the "Redbook"[42]. In addition to the IRAC, OSM receives support in this area from the Commerce Spectrum Management Advisory Committee (CSMAC), comprised of government and industry experts chartered to advise NTIA on spectrum management policy[43].

The Communications Act of 1934 act does not allocate exclusive use of specific bands for Federal and non-Federal use, so all allocations stem from coordination and agreement between the FCC and NTIA. To help in this process, The FCC appoints a representative to act as a liaison between the IRAC and the Commission. Through this coordination, 54.2% of spectrum below 3.1 GHz in the United States is already shared, with 31.7% and 14.1% allocated respectively to the private

37 http://www.ntia.doc.gov/book-page/who-regulates-spectrum
38 http://www.fcc.gov/encyclopedia/rulemaking-process-fcc
39 http://www.fcc.gov/encyclopedia/technological-advisory-council
40 http://www.ntia.doc.gov/office/OSM
41 http://www.ntia.doc.gov/page/irac-functions-and-responsibilities
42 http://www.ntia.doc.gov/page/2011/manual-regulations-and-procedures-federal-radio-frequency-management-redbook
43 http://www.ntia.doc.gov/files/ntia/publications/csmac_2013_charter.pdf

sector and government on an exclusive basis[44]. Until recently, most sharing has been through static allocations, however this is changing, and new regulations are being looked at for federal and non-federal use to utilize more dynamic sharing to improve efficiency to free spectrum for new applications. The remainder of this section will explore existing and emerging regulations related to these new dynamic spectrum sharing regulations, with a focus on the technical details of the defined policies and rules.

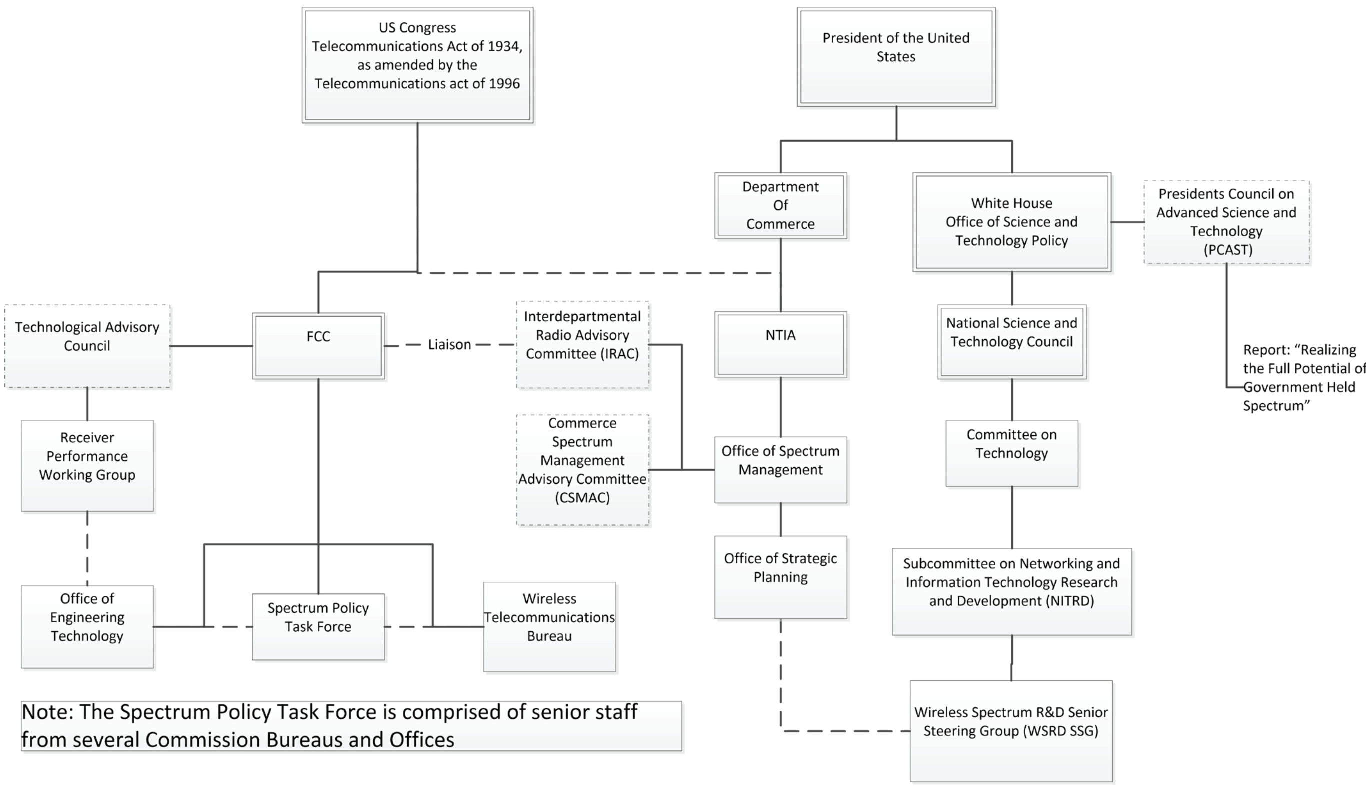

Figure 8: Relationships between organizations regulating and managing spectrum in the United States.

5.2.5.2 Managing Spectrum Sharing Among Federal Users (Spectrum Sharing Level 1)

Frequency sharing is assumed for federal users, and the Redbook specifically states:

"Sharing of frequencies is necessary for the fullest utilization of the radio spectrum. This may entail the acceptance of some interference but does not contemplate requiring the acceptance of harmful interference."

With that in mind, Chapter 8 of the Redbook defines the specific procedures followed for the coordination and assignment of frequencies[45]. In summary:

- Each federal agency evaluates telecommunications needs on a mission by mission basis. As a part of this evaluation, agencies perform technical studies, select potential frequencies for each mission and coordinate with other agencies

44 http://www.ntia.doc.gov/book-page/how-spectrum-shared
45 http://www.ntia.doc.gov/files/ntia/publications/redbook/2013/8_13.pdf

as necessary, with a requirement to neither cause harmful interference to nor receive harmful interference from other authorized users, as outlined in Redbook Chapter 10[46].

- Once this evaluation is complete, the agency files an application with the NTIA Office of Spectrum Management for consideration of the Frequency Assignment Subcommittee (FAS) of the IRAC. Preparation of these applications is outlined in chapter 9 of the Redbook[47], and includes requirements for technical data on transmit and receive equipment, geolocation information, application descriptions, and other usage information. Applications can request a regular, or permanent assignment, a temporary assignment, a trial assignment or a group assignment.
- The FAS considers applications and takes action within the established policy guidelines. Principles followed by the FAS in frequency assignment include frequency sharing, planned frequency utilization and the justification for frequency assignments.

Frequency assignments are made with a specific geographic location, a specific service area, and with performance requirements levied against stations in a close geographic proximity. If multiple assignments are made in the same area, priority access is generally given to the assignment made first. Other frequency assignment regulations defined in the Redbook take into account type of service and band of operation. Under these rules, OSM processes between 8000 and 10,000 assignment actions each month while maintaining a database of over 400,000 assignment entries[48]. On 11 April 2014, the NTIA published a new online resource detailing these assignments and use[49].

One important item to note: the sharing of spectrum between federal and non-federal users discussed later in this section is facilitated through this same process. The FCC, through their IRAC liaison, files frequency assignment applications for non-federal use of shared bands, and in cases where operation in non-federal bands that may impact federal spectrum use. Processing of the application then follows the standard course.

5.2.5.3 Early Regulations Supporting Non-Federal Spectrum Sharing

A key element of the 1934 act, as amended, directs the Commission to "generally encourage the larger and more effective use of radio in the public interest" and to seek to promote "efficient and intensive use of the radio spectrum"50. In 2000, the FCC began looking at new models to achieve these objectives with a move toward higher levels of spectrum sharing for non-federal users through two early rulemakings: one on software defined radio and the other on secondary markets. In 2002, the Commission took these actions a step further in forming the Spectrum Policy Task Force. This task force was made up of senior staff and chartered to "provide specific recommendations to the Commission for ways in which to evolve the current "command and control" approach to spectrum policy into a more integrated, market-oriented approach that provides greater regulatory certainty, while minimizing regulatory intervention" and "Assist the Commission in addressing ubiquitous spectrum issues, including, interference protection, spectral efficiency, effective public safety communications, and implications of international spectrum policies"51. Through this task force, a host of other proceedings advanced spectrum sharing, including an early proceeding on smart radio systems. This section will explore these early regulations.

FCC Rule Making on Software Defined Radio (Docket 00-47)

In March of 2000, the FCC issued a notice on inquiry seeking comment on a variety of issues related to software defined radios (SDR)[52]. A key element of this notice was an exploration of several spectrum sharing scenarios that could be enabled

46 http://www.ntia.doc.gov/files/ntia/publications/redbook/2013/10_13.pdf
47 http://www.ntia.doc.gov/files/ntia/publications/redbook/2013/9_13.pdf
48 http://www.ntia.doc.gov/book-page/national-telecommunications-and-information-administration
49 http://www.ntia.doc.gov/other-publication/2014/federal-government-spectrum-compendium
50 http://transition.fcc.gov/Reports/1934new.pdf
51 http://transition.fcc.gov/sptf/
52 http://transition.fcc.gov/Bureaus/Engineering_Technology/Notices/2000/fcc00103.txt

by SDR, allowing a lessee to reconfigure a radio to meet with the requirements of a specific band manager at a specific moment in time. Twenty-four parties filed comment on this NOI, and in December of 2000 the FCC followed with a Notice of Proposed Rulemaking[53]. The NPRM proposed a regulatory definition of SDR and rules for SDR equipment authorization. Through the NPRM, the Commission recognized the potential for SDR to increase spectrum efficiency, but concluded that no additional rules were required at that time with respect to this capability. The Commission later went on to issue a Report and Order, building on the 14 comments and eight reply comments to modify the proposed SDR definition and to finalize voluntary authorization requirements[54].

Elimination of Barriers to the Development of Secondary Markets (Docket 00-230) (Spectrum Sharing Level 2A)

In November of 2000, the FCC issued a Notice of Proposed Rulemaking on "Promoting the Efficient Use of Spectrum through Elimination of Barriers to the Development of Secondary Markets"[55]. Through this NPRM, the Commission recognized that spectrum may be being used inefficiently, especially in rural areas, and given the increased demand for spectrum, sought ways to encourage license holders to lease underutilized spectrum on a temporary basis. Concurrent with this NPRM, the Commission also issued a policy statement outlining its long term principles for encouraging the development of such secondary markets[56].

A key issue that the NPRM tried to address was clearly defining who was responsible should harmful interference occur under the defined scenarios. In addressing this issue, the NPRM introduced the concept of a "band manager," which is a class of licensee specifically authorized to lease unused spectrum. The NPRM also proposed a database approach for band managers to utilize in managing secondary users, concluding that "the private sector is better suited both to determine what types of information parties might demand, and to develop and maintain information on the licensed spectrum that might be available for use by third parties."

Thirty-seven parties commented on this NPRM and 21 filed reply comments. Based on these comments, in 2003 the FCC issued a Report and Order and Further Notice of Proposed Rulemaking[57]. The Order established two options for use in secondary markets:

- A spectrum license holder may enter into an agreement with an entity wishing to lease spectrum without commission interaction. In doing so, the licensee must maintain legal responsibility for the leased spectrum. The licensee acts as the "Spectrum Manager" in this option, and may lease any or all of their licensed spectrum in any geographic area for any length of time they wish. Technical and interference related rules associated with the license still apply, and the licensee is liable for any violations.
- A streamlined process for a licensee to transfer control to an entity wishing to lease the spectrum. Referred to as de facto transfer leasing, the lease can apply to any amount of spectrum in any geographic area and for any period of time. All the original service rules and policies apply, however for the period of the lease, the leasing entity is the responsible part and is liable for any violation.

In addition, the Commission issued a second NPRM seeking comment on issues fundamental to the development of secondary markets. Questions contained in this NPRM included what additional steps the commission needs to take, whether there will need to be a clearing house mechanism to provide real time information for "opportunistic" devices, and what role the commissions should take, if any, in regulating such a clearing house.

53 http://transition.fcc.gov/Bureaus/Engineering_Technology/Notices/2000/fcc00430.pdf
54 http://transition.fcc.gov/Bureaus/Engineering_Technology/Orders/2001/fcc01264.pdf
55 http://hraunfoss.fcc.gov/edocs_public/attachmatch/FCC-00-402A1.pdf
56 http://hraunfoss.fcc.gov/edocs_public/attachmatch/FCC-00-401A1.pdf
57 http://hraunfoss.fcc.gov/edocs_public/attachmatch/FCC-03-113A1.pdf

The commission received five petitions for reconsideration on the order, along with 21 comments and 10 reply comments on the NPRM. In July of 2004, the commission responded with a second Report and Order, Order on Reconsideration, Second Further Notice of Proposed Rule Making (NPRM)[58]. In summary, the order:

- adopted immediate approval procedures for certain categories of de facto transfer leasing agreements and streamlined the procedures for establishing a short term de facto lease,
- clarified policies related to "smart" or "opportunistic" use technologies, including reinforcing that the rules allow for dynamic forms of spectrum leasing and that licensees and those entities that are leasing their spectrum may share use of the same spectrum on a non-exclusive basis for the term of the lease, and
- established a new type of secondary market that facilitates the development of a private commons in licensed spectrum, allowing groups of licensees or lessee to make spectrum available to a group of users that do not use the licenses or lessees network infrastructure.

The second Further NPRM sought comment on ways in which new technologies could make opportunistic use of licensed spectrum, including types of uses of opportunistic spectrum, and examples of private commons and ways to improve the private commons model. Only three comments were received, and so in April 2007, the Commission issued a third report and order that reaffirmed the existing report and order without change[59].

FCC Rule Making on "Smart Radio" Systems (Docket 03-108) (Spectrum Sharing Level 2A)

In May of 2003, the FCC Office of Engineering and Technology (OET) hosted a workshop exploring the use of cognitive radio technologies to enable more efficient use of spectrum[60]. In December 2003, the FCC followed up on this workshop by launching a Notice of Public Rulemaking on "Facilitating Opportunities for Flexible, Efficient, and Reliable Spectrum Use Employing Cognitive Radio Technologies"[61]. Through this NPRM, the commission sought comment on all issues related to cognitive radio technology, with a specific focus on:

1. Allowing unlicensed devices to operate in higher power levels in rural areas
2. Allowing unlicensed devices to operate at higher power levels in bands with limited spectrum use
3. Enabling spectrum leasing, including:
    a. The ability of cognitive radio to support/enable for interruptible spectrum leasing, allowing a lessor to take back spectrum from a lessee,
    b. Applicability of interruptible spectrum leasing models to allow secondary commercial use of public safety spectrum
4. Dynamically coordinating spectrum sharing, allowing ad-hoc sharing of licensed spectrum
5. Facilitating interoperability between communications systems, especially first responder public safety communications systems
6. Forming ad-hoc or mesh networks with the ability to self heal

The NPRM also sought comment on proposed rule changes allowing automated frequency selection for unlicensed devices, allowing manufacturers to build devices that can operate worldwide when unlicensed frequency bands are not harmonized.

58 http://hraunfoss.fcc.gov/edocs_public/attachmatch/FCC-04-167A1.pdf
59 http://apps.fcc.gov/ecfs/proceeding/view?z=g9mf5&name=00-230
60 http://hraunfoss.fcc.gov/edocs_public/attachmatch/DOC-234600A1.pdf
61 http://hraunfoss.fcc.gov/edocs_public/attachmatch/FCC-03-322A1.pdf

Through the associated Order, Docket 00-47 was closed, and with the further evolution of the regulation of SDR now falling under a combined SDR/CR docket. The NPRM also revisited equipment authorization for SDRs, noting that in the 2 years since the rules were passed, no manufacturers had filed applications to certify an SDR, even though many of the devices certified by the FCC met the Commission's broad definition of SDR. With this in mind, the NPRM sought comment on whether it should become mandatory for manufacturers to declare certain types of equipment as SDR, rules on the types of security features that SDR's must incorporate, and the approval process for SDR's contained within modular transmitters.

The Commission received 56 comments and 14 reply comments to this NPRM and based on this issued a Report and Order in March 2005[62]. The report covered a wide range of cognitive radio topics, recognizing that both software defined radio and cognitive radio will continue to evolve over time. The report also described the technical requirements for interruptible spectrum leasing as follows:

1. The licensee must have positive control as to when the lessee can access the spectrum.
2. The licensee must have positive control to terminate the use of the spectrum by the lessee so it can revert back to the licensee's use.
3. Reversion must occur immediately upon action by the licensee unless that licensee has made specific provisions for a slower reversion time.
4. The equipment used by the licensee and the lessee must perform access and reversion functions with an extremely high degree of reliability.
5. The equipment used by the licensee and the lessee must incorporate security features to prevent inadvertent misuse of, and to thwart malicious misuse of, the licensee's spectrum

The commission did not adopt any particular technical model in this area, stating that this was best left to the licensee to be satisfied that the technical mechanism implemented meets with their requirements for reclaiming leased spectrum

Through the associated Order, the Commission broadened the definition of Software Defined Radio to include changes in software that could make a transmitter non-compliant with Commission emission rules. They also changed the equipment authorization rules to require that equipment in which the software controlling the radio frequency operating parameters is expected to be modified by a party other than the manufacturer must be certified as an SDR. Certification as an SDR remains optional for equipment that is not expected to be modified by a third party. In addition, the Order allowed certification of unlicensed transmitters that are capable of operating outside of US unlicensed frequency bands, provided that they incorporate automatic frequency selection mechanisms to ensure they operate only on allowed frequencies inside the United States.

5.2.5.4 Early Regulation to Facilitate Spectrum Sharing Between Federal and Non-Federal Users

Building on these earlier rulings, the FCC began initiating proceedings in 2004 to enable spectrum sharing between federal and non-federal users. Two rulings are of significant interest: the 5 GHz U-NII ruling and the 3650 to 3700 MHz band ruling. Regulations from these proceedings are addressed below.

FCC 5GHz U-NII Rulemaking (Docket 03-122) (Spectrum Sharing Level 3A)

Prior to 2002, Unlicensed National Information Infrastructure (U-NII) devices were permitted to operate in the US over a total of 300 MHz of spectrum spread across the 5 GHz band. The majority of U-NII devices operating in this band

62 http://hraunfoss.fcc.gov/edocs_public/attachmatch/FCC-05-57A1.pdf

supported the IEEE 802.11a standard, and in January of 2002, the Wireless Ethernet Compatibility Alliance (WECA, now the WiFi Alliance) petitioned for rulemaking to provide an additional 255 MHz of spectrum for use by these types of devices in the 5470 to 5725 MHz band. In response to this petition, 17 comments and 10 reply comments were filed, and upon reviewing these comments, the FCC issued a Notice of Public Rulemaking in May of 2003[63].

In the NPRM, the FCC agreed with WECA that current allocation was insufficient for growth. However, the 5350 to 5650 band was currently allocated to radio location and used by US Department of Defense (DoD) for a number of radar systems, including systems used for national security. The DoD was concerned that U-NII devices would cause interference to its radar systems, and therefore asked that if this petition were granted, its radio location services be upgraded from secondary to primary status in this band.

In addition, NTIA working with the FCC, NASA and the DoD reached the following agreement on International Telecommunications Union World Radiocommunications Conference 2003 (WRC-03) Agenda Item 15 to establish an international recommendation that:

1. Radiolocation service in the 5350 to 5650 MHz band be upgraded to primary status
2. An allocation be added in the 5350 to 5460 MHz band for Space Research Services (SRS) and in the 5460 to 5560 for SRS and the Earth Exploration Satellite Service (EESS)
3. A mobile allocation be added to the 5150 to 5350 MHz and 5470 to 5725 MHz bands
4. U-NII or HiperLAN users in the 5250 to 5350 MHz and 5470 to 5725 MHz bands be required to employ dynamic frequency selection (DFS) using a listen-before-transmit mechanism with the following detection thresholds: -64 dBm for devices that operate with an Effective Isotropic Radiated Power (EIRP) of between 200 mW and 1 W and -62 dBm for devices that operate with an EIRP of less than 200 mW.

Based on this agreement, through the NPRM the Commission sought comment on proposals to upgrade affected federal government radiolocation service to primary status, to upgrade the affected non-Federal government radio location services, primarily used for weather radar, to co-primary status, to add primary Federal Government and secondary non-federal government allocations for SRS and EESS, and to allow U-NII devices to operate as per the WECA petition on a non-interference basis

Technical requirements for unlicensed operation proposed in the NPRM were as follows:

- 1 Watt EIRP peak
- Devices operating in the 5250 to 5350 MHz and 5470 to 5725 MHz bands employ DFS to monitor spectrum and determine if radar signals are present (listen before talk) with detection thresholds as per the WRC-03 agreement. In addition, the Commission sought comment on:
    - ◊ A proposed correction factor for devices with under 1 MHz BW
    - ◊ The minimum number of radar pulses and observation time for reliable detection
    - ◊ A proposal that devices operating under control of a central controller or master not be required to have DFS, proposing that only the master be required to have DFS capability
    - ◊ As U-NII devices in the 5250 to 5350 MHz band currently operate without DFS capability, the Commission proposed establishing a transition period

The commission also sought comment on a proposal to require devices operating in the 5470 to 5725 MHz band employ Transmit Power Control (TPC) to further protect EESS and SRS operations. The Commission's proposal was

63 http://hraunfoss.fcc.gov/edocs_public/attachmatch/FCC-03-110A1.pdf

that the power level be reduced by 6dB when triggered, and requested comment on a suitable trigger. The Commission also requested comment on whether TPC was required for devices that operate at less than 500 mW EIRP. Finally, the Commission requested comments on test procedures necessary to ensure compliance with the DFS and TPC requirements/

Twenty-nine comments and 12 reply comments were filed in response to this NPRM, and the Commission quickly followed up to issue a Report and Order in November of 2003[64]. Through this order, the Commission established rules to make the 255 MHz requested by the WECA available in the 5470 to 5725 MHz band for unlicensed National Information Infrastructure (U-NII) devices. As a part of this ruling, the FCC upgraded federal and non-federal radiolocation services to primary status as proposed, and added primary federal and secondary non-federal government allocations for SRS and EESS. The commission declined to adopt a specific mobile allocation, and instead chose to treat devices equally as unlicensed intentional radiators, allowed to operate on a non-interfering basis.

On the technical side, the Report and Order adopted the power requirements and DFS requirements as proposed. The order exempted remote devices under control of a central controller from the DFS requirement, but did not exempt controller or master devices. The Order required Transmit Power Control for devices operating at power levels of greater than 500 mW. In doing so, the Commission declined to provide a triggering mechanism, but rather asked that applicants seeking equipment authorization for U-NII devices provide a statement in the certification application explaining how they comply. Finally, the Order provided an interim test procedure to allow immediate certification.

This Order was followed in June 2006 with a Memorandum Opinion and Order clarifying the rules for TPC and providing a revised test procedure for determining DFS compliance[65]. Then, in 2013, the Commission issued a new NPRM (Docket 13-49) proposing an additional 100 MHz bandwidth in the 5 GHz band for U-NII devices. This was followed by an Order in April of 2014 allocating this new bandwidth as a part of the regulations[66].

FCC 3650 MHz Rule Making (Docket 04-151) (Spectrum Sharing Level 4A)

The Omnibus Budget Reconciliation Act passed by the US Congress in 1993 required the US Secretary of Commerce to identify at least 200 MHz of spectrum allocated for use by the Federal Government agencies to be transferred to the private sector. NTIA released a final report on reallocation in 1995, identifying the 3650 MHz band for transfer on the condition that government radiolocation stations in two locations continue to operate in that band and that spectrum in the adjacent 3600 to 3650 MHz band continue to be used for high power radar. In 1998, the Commission issued an NPRM (Docket 98-237) proposing to allocate the 3650 band for non-government fixed service on a primary basis. In 2000, the FCC issued an associated Report and Order that allocated 3650 MHz band to fixed and mobile terrestrial services on a co-primary basis, but to protect grandfathered fixed satellite service (FSS) earth stations and radio location operations operating on a primary basis. This order limited mobile service allocation to base station use only and established that new FSS earth stations were only allowed to operate in the band on a secondary basis. The commission received four petitions for reconsideration, requesting that FSS be returned to full allocation and deleting the fixed service and mobile service allocations. Concurrent with issue of 3650 MHz allocation Report and Order, the Commission issued a 3650 Service Rules Second NPRM. In response to this NPRM, the FCC received 17 comments and seven reply comments. Comments submitted on behalf of telecommunications providers serving rural areas and internet service providers who provide wireless internet to their customers were interested in licensed terrestrial services. FSS providers submitted comments that licensed fixed and mobile services would cause interference.

Later, in December 2002, the Commission issued an Unlicensed Spectrum Notice of Inquiry (Docket 02-380). This inquiry sought to assess the feasibility of releasing additional spectrum for unlicensed use below 900 MHz (TV Bands) and

64 http://hraunfoss.fcc.gov/edocs_public/attachmatch/FCC-03-287A1.pdf
65 http://hraunfoss.fcc.gov/edocs_public/attachmatch/FCC-06-96A1.pdf
66 http://transition.fcc.gov/Daily_Releases/Daily_Business/2014/db0401/FCC-14-30A1.pdf

in the 3 GHz band). The inquiry specifically sought comment on whether unlicensed devices could operate in these bands at higher power levels than was previously allowed, and asked whether licensed and unlicensed devices should be allowed to operate in unused portions of the spectrum on a non-interfering basis.

A number of commenters supported the ideas proposed by the commission, however numerous comments were also received from those incumbent licensed users in these bands with mixed opinions on whether such operation would cause interference, especially when operating in band adjacent to those supporting licensed operation (adjacent band interference).

With this as background, in April of 2004, the FCC issued a Notice of Public Rulemaking[67]. Through this NPRM, the Commission deferred comment on petitions for reconsideration defined above, and instead sought comment on whether new FSS stations could operate in band on a co-primary basis using smart/cognitive radio technologies. The also sought comment on a proposal to delete fixed service and mobile service allocations in favor of unlicensed operation and sought comment on proposed fixed and non-fixed unlicensed operation as follows:

- Fixed Operation
  - ◊ Primary use will be to provide wireless broadband connectivity by wireless internet service providers (WISPs) in rural areas
  - ◊ Certified professional installer would be required to ensure fixed unlicensed devices operate in a manner that will avoid causing interference with FSS earth stations
  - ◊ Maximum allowed EIRP of 25 Watts, with comment sought on the proposed use of sectorized or scanning spot beam antennas
  - ◊ Fixed devices would be prohibited from operating within protection zones defined as 180 km within +/-15 degrees of the FSS antenna main-beam azimuth and 25 km otherwise
- Non-fixed Operation
  - ◊ Maximum allowed EIRP of 1 watt
  - ◊ DFS like listen before talk function required, with power to be adjusted based on detected FSS receiver signal strength.
    - Device prohibited from transmitting if detects an uplink signal greater than -76dBm in a 1 MHz bw.
    - Device must lower EIRP to 500 mW if FSS signal strength of between -79 and -82dBm is detected
    - Device must lower EIRP to 250 mW if FSS signal strength of -76 and -79 dBm is detected

The NPRM also proposed to prohibit operation by unlicensed devices within 8 km of the US/Mexico border and proposed to require all unlicensed devices to broadcast identification information at regular intervals. Through the NPRM, the Commission also sought comment on the use of geolocation or a dedicated FSS beacon signal to protect incumbents and sought comment on options for licensed use or combinations of licensed and unlicensed use.

The Commission received responses to this NPRM from more than 100 parties. In March of 2005 they followed up with a Report and Order and Memorandum Opinion and Order[68]. Through this Order, the FCC maintained the existing FSS and fixed service allocations established in the 2000 Order and removed the base station only restriction on the mobile service allocations. The Order established that the fixed service and mobile service access would be through non-exclusive nationwide licensing in lieu of the unlicensed scheme discussed in the NPRM. The Order also allowed new FSS earth stations but limited them to secondary status.

67 http://hraunfoss.fcc.gov/edocs_public/attachmatch/FCC-04-100A1.pdf
68 http://hraunfoss.fcc.gov/edocs_public/attachmatch/FCC-05-56A1.pdf

The Order required that licensees cooperate to avoid harmful interference, and to facilitate this required that they register their fixed and base stations in a common database. The Order further required a contention based protocol to manage interference in the shared spectrum, but did not specify the protocol, and left this to industry standards bodies. Fixed station power was limited to 25W EIRP in any 25MHz band, and mobile station power was limited to 1W EIRP over the same bandwidth.

In response to this order, the Commission received eight petitions for reconsideration, with 160 oppositions, replies or comments to those petitions. After consideration, in June 2007, the FCC issued another Memorandum Opinion and Order reaffirming the non-exclusive licensing and retaining the requirement for contention based protocols, but clarified that the rules allow for the certification of a variety of different protocols and contention avoidance mechanisms [69]. This included unrestricted protocols such as listen before talk, or restricted protocols which can only prevent interference from other devices utilizing the same protocol. To avoid contention between these types of devices, the Order limited devices using restricted protocols to the lower 25 MHz of the band. No other reconsideration of power levels or other petition items occurred.

5.2.5.5 Unlicensed Operation in the TV Broadcast Bands (Docket 04-186) (Spectrum Sharing Level 3A)

As part of the Docket 02-380 Notice of Inquiry, the FCC also asked questions concerning the unlicensed use of unused spectrum below 900 MHz. Comments received from wireless technology suppliers and wireless internet service providers generally support the concept, however television broadcasters expressed concerns that the technology to determine if a television station is active in a specific location and the ability to quickly change frequency is unproven. Based on these comments, in May of 2004, the FCC issued a Notice of Public Rulemaking with a stated goal to enable wireless internet service providers to offer expanded services by allowing unlicensed operation in the broadcast television spectrum at locations where that spectrum is not being used[70]. The hope was that such operation would also provide synergy between WISPs and traditional broadcast operations to offer broadcasters the opportunity to provide additional services.

The approach taken by the FCC through the NPRM was to ensure no harmful interference to authorized users of spectrum by requiring "smart radio" technology be used to identify unused TV channels in a specific geographic area. Two types of operations were proposed by the FCC:

1. **Personal/Portable Devices**: Personal/portable devices were envisioned by the FCC to be used as WiFi like cards in home computers and for in-home local area networks. For these types of devices, the commission proposed that interference could be prevented through the use of a control signal sent by TV transmitters in the vertical blanking interval of a standard TV signal. Transmission of this control signal was voluntary, and parties could receive compensation for transmitting. The control signal would be current on a 24 hour cycle. For personal/portable devices, a TV channel would only be considered vacant if no portion of the service area of an authorized station assigned to use that channel was within the service area of the station transmitting the control signal. Transmit power for these devices was limited to 100 mW, with antenna gain limited to 6 dBi.
2. **Fixed Access Devices**: Fixed access devices were envisioned by the FCC to be used for commercial services. The Commission proposed that for these devices, interference would be prevented through the use of geolocation information. The location of the device would be set with 10 meter accuracy using a GPS or certified professional installer to establish and set the location. Once the location was set, the device would access a database, provide its location and retrieve information to calculate what channels are available in its area. Once a frequency of operation was selected by a device, the

69 http://hraunfoss.fcc.gov/edocs_public/attachmatch/FCC-07-99A1.pdf
70 http://hraunfoss.fcc.gov/edocs_public/attachmatch/FCC-04-113A1.pdf

Commission proposed that the device register with a separate database indicating its operating frequency and location. Through the NPRM, the commission proposed that for these types of devices, transmit power would be limited to 1 Watt with antenna gain limited to 6 dBi. The Commission also proposed that higher antenna gains could be allowed at lower power levels. The Commission also proposed that devices periodically transmit a unique ID to identify a transmitter if harmful interference was occurring.

The Notice made no specific proposals on spectrum sensing to detect active TV signals, but sought comment on spectrum sensing technologies, including levels that must be detected and ways of dealing with the hidden node problem that occurs when the TV signal is blocked from the sensing device but not from a TV receiver in range of the unlicensed wireless transmitter.

Technical criteria for determining when a TV channel would be considered vacant were established in the NPRM through the use of protected contours defining service areas based on service types (analog TV, digital TV, low power TV, TV boosters, etc.) with defined propagation curves. The Notice proposed desired to undesired signal protection ratios based again on service type, channel separation (co-channel or adjacent channel) and propagation curves. The NPRM proposed that calculations would be made to determine if operation within a specific location would create an undesired signal strength from the unlicensed device within the service area that is too high.

The NPRM proposed to allow operation in all channels except:

- Channels 2 to 4
- Channel 37, which was being used for radio astronomy
- Channels 52 to 69, which were being reallocated in the digital TV transition
- Channels 14 to 20 where used for Public Safety, Public Land Mobile Radio Service (PLMRS) and Commercial Mobile Radio Service (CMRS)

Through the NPRM, the Commission also sought additional comment on interference with wireless microphones, security, compliance and enforcement, testing and the need for voluntary standards.

The commission received numerous comments and reply comments to this NPRM. WISPs, manufacturers of unlicensed TV Band Devices (TVBDs) and potential users of TVBDs all expressed support for the proposals. Broadcasters and other licensed incumbents expressed strong concerns as to whether unlicensed devices could in fact operate without causing interference. Several comments were also received from multiple parties who felt that the operations of TVBDs should be licensed.

Upon reviewing these comments, the Commission issued a First Report and Order and Further Notice of Proposed Rulemaking in October of 2006[71]. Through this order, the Commission concluded that allowing low power devices to operate in the TV band in frequencies that are not used could have significant benefits for the public by enabling the development of new wireless devices, systems and services. The Commission also reiterated its belief that properly regulated devices could operate in the TV bands without causing interference, however based on comments received, the Commission concluded that it needed more data to set those regulations. With this in mind, the Commission ordered the FCC OET to test the interference rejection capabilities of Digital Television (DTV) receivers and test the interference potential of low power devices, including field tests, plus other tests as required to ensure whatever regulations were adopted would adequately protect incumbents.

71 http://hraunfoss.fcc.gov/edocs_public/attachmatch/FCC-06-156A1.pdf

In addition, through the Further NPRM, the FCC sought comment on a numbers of questions raised from the previous notice:

- **Licensed versus unlicensed operation**. The Commission's belief was that unlicensed operations may be better able to dynamically adapt to a shifting spectrum environment characterized by low power operation. Unlicensed operation may be better suited to rural areas and may better promote technical innovation. The Commission recognized, however, that licensed operation may provide better incentives to operators to invest, and therefore sought comment on these tradeoffs.
- **Spectrum sensing and other technical requirements.** The Commission noted that in the comments to the original NPRM, no party provided sufficient technical information on the use of spectrum sensing for rules to be established. The Commission reiterated that technical rules are necessary if sensing devices are to be used to ensure that such devices adequately sense incumbents. As such, the Commission sought comment on the following proposal for sensing TV band signals, modified from the radar signal sensing rules adopted for the 5 GHz U-NII band:
  - ◊ Detection threshold of -116 dBm (based on work of 802.22) as well as factors that may affect this threshold such as number of false positives, antenna height, and addressing the hidden node problem through technologies such as distributed sensing or sensing in combination with geolocation information.
  - ◊ Devices will sense before occupying a channel and then periodically recheck the channel, with a proposed recheck period of every 10 seconds, with sensing only required in the adjacent channels during recheck.
  - ◊ The commission also raised a number of questions on which it sought comment such as whether the sensing bandwidth should be regulated, and whether antenna gain should be limited to 0 dBi as proposed by 802.22.
- **Transmit power control**. The commission proposed to use the same transmit control levels as the 5 GHz U-NII rules and sought comment on whether this was sufficient, whether a wider range was possible, and whether to allow for adjusting the sensing detection threshold as transmit power decreases.
- **Master/Client Operation**. The Commission sought comment on a proposal to allow fixed operation under a master/client model.
- **Spectrum Sharing and Coexistence**. The Commission sought proposals on ways in which spectrum could be shared among potential users in an equitable manner, such as establishing a time period in which a terminal can occupy a band before releasing and reacquiring.
- **Geolocation Database Approach**. The Commission sought expressions of interest for those wishing to maintain a database, and sought comment on determining the location (GPS, professional installer, or other), on qualifications of installers and addressing wireless microphones that may not be in the database.
- **Control signal approach**. The Commission sought comments from potential database providers who may provide a control signal as to the business model for providing such a control signal, regulatory approach to be taken with a control signal, the selection of database providers by the Commission, issues regarding access and control of the database, and the format and content of control signal.
- **Operation on channels 14 to 20 and 2 to 4.** The Commission sought comment of whether fixed devices operating in channels 14 to 20 where PLMRS/CMRS services not being used could impact public safety. They also sought comment on how much longer consumers would be using channels 2 to 4 to connect TV interface devices (VCR's, Gaming Systems, etc.) to TVs.

Through the Further NPRM the commission sought comment on a host of other issues, including the relationship between technical requirements and the types of applications that will be developed to operate in TV bands, out of band emission and interference limits, the potential for direct pickup interference and receiver desensitization, methods of certification of TVBDs, and use of TVBDs along the Canada and Mexico borders.

In response to the Order, in Dec of 2006 the Office of Engineering and Technology invited submittal of prototype devices for initial testing72. Two prototype devices were provided for testing, which focused on "detect and avoid" or "listen before talk" strategies using spectrum sensing. The test results from this initial testing were released in July of 2007, concluding that73:

"… sample prototype White Space Devices submitted to the Commission for initial evaluation do not consistently sense or detect TV broadcast or wireless microphone signals. Our tests also found that the transmitter in the prototype device is capable of causing interference to TV broadcasting and wireless microphones."

A separate report on direct interference testing of three consumer DTV receivers showed that such interference was possible at relatively low power levels[74].

In August of 2007, OET held a meeting with interested parties to review the test results and define a way forward[75]. Based on the outcome of this meeting, the Commission announced a second phase of testing beginning in January of 2008 following a revised test procedure[76 77 78]. In July of 2008, the Commission also initiated field trials of TV White Space Devices[79]. Results of the Phase II testing were published in October 2008, with conclusions summarized as follows[80]:

1. All devices were able to reliably detect a clean DTV signal on a single channel, however results varied in a noisy real world environment.
2. Signals in adjacent channels degraded detection capability in channel.
3. All devices were able to detect wireless microphones when no other signals were present. TV signals in adjacent channels degraded performance in detecting wireless microphones to the point that it was no longer reliable.
4. In most cases, devices correctly reported occupied channels in field tests, but there were some errors and high false alarm rates.
5. The use of a geolocation database in combination with sensing was 100% reliable in detecting DTV.
6. Wireless microphone field tests failed in that false alarms eliminated all bands or when sensitivity was adjusted indicated channels were available when in fact they were not.
7. Under certain conditions, direct pickup was possible.

Based on these results, in November of 2008 the Commission issued a Second Report and Order and Memorandum Opinion and Order[81]. Through this order, the Commission continued to allow for both fixed and personal/portable devices, however they modified the original proposed rules to require that devices, except personal/portable devices operating in client mode, access a geolocation database over the internet. The rules also required that all devices employ spectrum

72 http://hraunfoss.fcc.gov/edocs_public/attachmatch/DA-06-2571A1.pdf
73 http://hraunfoss.fcc.gov/edocs_public/attachmatch/DOC-275666A1.pdf
74 http://hraunfoss.fcc.gov/edocs_public/attachmatch/DOC-275668A1.pdf
75 http://hraunfoss.fcc.gov/edocs_public/attachmatch/DA-07-3571A1.pdf
76 http://hraunfoss.fcc.gov/edocs_public/attachmatch/DA-07-4179A1.pdf
77 http://hraunfoss.fcc.gov/edocs_public/attachmatch/DA-08-118A1.pdf
78 http://hraunfoss.fcc.gov/edocs_public/attachmatch/DA-08-118A2.pdf
79 http://hraunfoss.fcc.gov/edocs_public/attachmatch/DA-08-1635A1.pdf
80 http://hraunfoss.fcc.gov/edocs_public/attachmatch/DA-08-2243A3.pdf
81 http://hraunfoss.fcc.gov/edocs_public/attachmatch/FCC-08-260A1.pdf

sensing as a further means of minimizing potential interference, but the database will be the controlling mechanism as test results showed that more developmental work was needed before spectrum sensing can be the principal means of identifying unoccupied channels. The rules also established that fixed devices were prohibited from operating in adjacent channels, fixed devices must register with the database to provide FCC ID, location and responsible party information, and that wireless microphones could be registered in the database for protection. Through this order, The Commission eliminated the control signal option for determining available channels, but agreed to revisit if economics or other circumstances make it more favorable. No regulation was established for coexistence of TVBDs.

Other technical requirements established for fixed and personal portable devices are summarized as follows:

- Fixed Devices
  - ◊ Maximum transmit power of 1W, with 4W maximum EIRP. For antennas with gains above 6 dBi, the transmit power must be reduced so that EIRP does not exceed 4 W
  - ◊ Should use Transmit Power Control to limit maximum power where possible
  - ◊ Allowed to communicate with other fixed devices and personal portable devices
  - ◊ Must incorporate geolocation capability or have location set by professional installer
  - ◊ Antennas must be mounted outdoors, height limited to 30m
  - ◊ Sensitivity of spectrum sensing set at -114 dBm, 6 MHz detection BW for TV, 200 Khz detection bw for wireless microphone. Sensing antenna must be at least 10 M above ground, and sensed devices identified must be reported back to database
  - ◊ Must transmit identifying information, following a standard to be established by the industry
- Personal Portable Devices
  - ◊ 100mW maximum EIRP, except when operating adjacent to a TV station or licensed station within the protected coverage area, in which case limited to 40 mW. Power should typically be adjusted to less than the maximum permitted power when possible.
  - ◊ Two modes
    - Mode I – client that is controlled by a fixed device or a personal portable device operating in Mode II
    - Mode II – determines available channels from internal geo-location/database access. Can act as a master to a mode I device in a Master Client link
  - ◊ Both modes must establish location each time they are activated, and must re-verify their location each time they detect they have moved. Mode II devices must not transmit if location unknown.
  - ◊ Sensitivity of spectrum sensing set at -114 dBm, 6 MHz detection BW for TV, 200 KHz detection bw for wireless microphone.

The Order established that all fixed devices and Mode II personal portable devices are allowed to operate in Master Mode. Each network would have at least 1 master, and a master was allowed to transmit without receiving an enabling signal from any other device. A personal portable device communicating with a fixed master was required to use channels and frequencies as directed by the fixed device. If a fixed device does not have direct connection to the internet, and has not initialized and registered with the database system, then it can communicate to another TVBD that does have a connection and is registered over a channel that device is using. That link must then be used to register with the database and receive a list of channels for use. Finally, a Mode I personal portable device that does not have geolocation capability can listen for and then communicate with a Mode II or Fixed device over a channel that device has already used. The Mode II device must then immediately obtain a list of channels.

Channel of operation were defined in the Order as originally proposed by the Commission, with the addition of Channel 2. Operation was also allowed in channels 14 to 20 but must avoid interference with PLMRS/CMRS and offshore radio telephone service. For all devices, out of band emissions in the first adjacent channel limited to a level of 55dB below the power in the channel they occupy measured in a 100hHz bandwidth.

The Order also established that the database system for fixed stations and Mode II personal portable devices would be managed by database administrators selected by OET. The database requirements established are summarized as follows:

- Databases will be privately owned and operated service, with database service providers allowed to charge fees for registration of fixed devices and to provide available channels to all devices.
- More than one entity may be authorized to operate as a TV bands database provider, with final decision based on expressions of interest.
- Database providers must share registration information with each other and with the commission.
- Fixed and Mode II TVBDs must resync with the database at least once per day, and after a one day grace period, must stop transmitting.
- Database administrator not required to resolve claims of interference from TVBDs.
- Services must be made available by database providers to all TVBD's on a non-discriminatory basis.

The Order established that the FCC would be the certifying authority for TVBDs and databases, and established a proof of performance standard to allow certification of sensing only devices that demonstrate the capability to detect protected services with a high level of accuracy.

The commission received 17 Petitions for Reconsideration in response to this NPRM and following review and analysis issued a Second Memorandum Opinion and Order in September of 2010[82]. Major changes to the rules above made by the commission in addressing the petitions are as follows:

- TV Band Devices
    - ◊ Eliminated the requirement that TVBDs support sensing, and allowed database only solutions. In doing so, the Commission stated that they continue to believe that sensing will evolve, that sensing has promise, and left open the possibility of sensing only devices. The Commission also allowed sensing to be used on a voluntary basis.
    - ◊ Added a requirement that Mode I devices must either receive a special signal from a mode II or fixed device providing a current list of available channels once per minute, or must contact the mode II or fixed device once per minute to re-verify/reestablish channel availability.
    - ◊ Modified the rules for transmit antenna height of a fixed device to be height above average terrain (HAAT), and restricted fixed devices from operating in locations where the ground HAAT is greater than 75m. The commission established that HAAT would be calculated by the database provider.
    - ◊ Ground HAAT to be calculated by the database.
    - ◊ Established Power Spectral Density Limits on conducted output power of 16.7 mW (12.2 dBm) for fixed devices, 1.67 mW (2.2 dBm) for personal/portable devices, .7 mW (-1.8 dBm) for personal portable in adjacent channels all in 100 kHz BW.
    - ◊ Modified the out of band emissions limit.

82 http://hraunfoss.fcc.gov/edocs_public/attachmatch/FCC-10-174A1.pdf

- Databases
  - ◊ Imposed security measures, requiring that TVBDs shall only be capable of contacting databases operated by administrators designated by the Commission, that the database must not provide channel information to uncertified TVBDs, and that communication between TVBDs and Database be secure. The Commission did not require specific technologies to meet these requirements.
  - ◊ Require that all database information required by the commission be publically available. In doing so, the Commission stated that public disclosure was not required, and that data not required by the commission that database administrators keep does not have to be disclosed
  - ◊ Mandated that information on TV stations in Canada and Mexico border areas be included in the database
- Protection Criteria
  - ◊ Expanded protection for certain radio astronomy receive sites
  - ◊ Established that two channels between 14 and 51 would be reserved in all markets nationwide for wireless microphones
  - ◊ Disallowed unlicensed wireless microphone and other low power auxiliary devices operating without a license to be registered in the database, stating that these devices will not be afforded protection from interference from TV band devices on channels were TV band devices are allowed to operate
  - ◊ Established that operators of licensed low power auxiliary stations including wireless microphone may register their site directly with one of the designated database administrators
  - ◊ Established that entities operating or otherwise responsible for the audio systems of major events where large numbers of wireless microphones will be used may request a registration of the event
  - ◊ Maintained the ruling that fixed TVBD must not operate co-channel within 1 km of low power auxiliary stations entered in the database, but amended rules to require that Mode II Personal Portable devices not operate within 400 meters of a low power auxiliary stations entered in the database

Other rules clarifications were also made. Five petitions for reconsideration were made on this second order, and following review and analysis, the Commission issued a Third Memorandum Opinion and Order in April of 2012[83]. The only changes made by the commission in this Order were to modify HAAT to 250 meters, with associated modifications to separation contours, and to set a fixed adjacent channel emission limit of 72.8 dB below the maximum power limit for each type of device. Other petitions were declined.

In compliance with these orders, the FCC OET began accepting applications for white space database administrators[84]. To date, 10 organizations have been designated as database administrators, and four have databases that have been approved for operation:

Organization	Status
Google	Designated Database Administrator, Database Approved
Keybridge Global	Designated Database Administrator, Database Approved
Spectrum Bridge	Designated Database Administrator, Database Approved
iconectiv	Designated Database Administrator, Database Approved
Comsearch	Designated Database Administrator, Database Approval Pending
LS Telecom	Designated Database Administrator, Database Approval Pending

83 http://hraunfoss.fcc.gov/edocs_public/attachmatch/FCC-12-36A1.pdf
84 http://apps.fcc.gov/ecfs/proceeding/view?name=ET%252004-186

Microsoft	Designated Database Administrator, Database Approval Pending
Airity	Designated Database Administrator
Frequency Finder	Designated Database Administrator
Neustar	Designated Database Administrator

The Commission has also published a compliance guide for TV Band devices and a guide for Database Administrators[85] [86].

One final note on this topic: In February 2012, Congress directed the FCC to hold a reverse auction, or incentive auction, which freed up broadcast spectrum for use by cellular operators "by encouraging <broadcasters> to voluntarily relinquish spectrum usage rights in exchange for a share of the proceeds from an auction of new licenses to use the repurposed spectrum"[87]. If successful, these incentive auctions, which are currently scheduled for 2015, will necessarily reduce the amount of white space that is available in the TV broadcast bands, and as such, further regulatory changes may be required in this proceeding.

5.2.5.6 500 MHz Broadband Initiative

In June 2010, the President of the United States issued an executive memorandum on "Unleashing the Wireless Broadband Revolution"[88]. This memorandum recognized that "America's future competitiveness and global technology leadership depend, in part, upon the availability of additional spectrum," and that "We can also unlock the value of otherwise underutilized spectrum and open new avenues for spectrum users to derive value through the development of advanced, situation-aware spectrum-sharing technologies." Through this memorandum, the President directed the Secretary of Commerce, working through the NTIA, to collaborate with the FCC and other federal agencies to make 500 MHz of federal spectrum available for non-federal use within a 10 year time frame. In support of this initiative, NTIA undertook a fast track review of the 1675 to 1710 MHz band, 1755 to 1780 MHz band, 3500 to 3650 MHz band, 4200 to 4220 MHz band and 4380 to 4400 MHz to determine the near term viability of non-federal broadband access within the 10 year time frame[89]. Through this study, NTIA identified the 1675 to 1710 MHz bands and the 3550 to 3650 MHz bands as early candidates for commercial use. They also identified several additional bands that may be viable, but required further study. In response to this report, in March of 2011 the FCC issued a Notice of Inquiry under Docket 10-123 seeking comment on the proposed bands, noting that the 3550 to 3650 MHz band was already shared for WiMAX as federal operations were geographically limited[90].

In the meantime, the President's Council of Advisors on Science and Technology (PCAST) was preparing a report on "Realizing the Full Potential of Government-Held Spectrum to Spur Economic Growth"[91]. This report, published in 2012, had a number of key findings related to the 500 MHz Initiative, the first of which was that "clearing and reallocating Federal spectrum is not a sustainable basis for spectrum policy." The report cited as an example the March 2012 report by NTIA entitled "An Assessment of the Viability of Accommodating Wireless Broadband in the 1755 to 1850 MHz Band"[92]. The report indicates that this band is currently used for fixed point to point microwave systems, military tactical radio relay, air combat training systems, precision guided munitions, tracking and telemetry, video surveillance and UAVs. Moving these

85 http://www.fcc.gov/document/part-15-tv-bands-devices
86 http://www.fcc.gov/encyclopedia/white-space-database-administration
87 http://www.fcc.gov/topic/incentive-auctions
88 http://www.whitehouse.gov/the-press-office/presidential-memorandum-unleashing-wireless-broadband-revolution
89 http://www.ntia.doc.gov/report/2010/assessment-near-term-viability-accommodating-wireless-broadband-systems-1675-1710-mhz-17
90 http://www.fcc.gov/document/spectrum-task-force-requests-information-frequency-bands-identified-ntia-potential-broadban
91 http://www.whitehouse.gov/sites/default/files/microsites/ostp/pcast_spectrum_report_final_july_20_2012.pdf
92 http://www.ntia.doc.gov/files/ntia/publications/ntia_1755_1850_mhz_report_march2012.pdf

systems to other spectrum to allow dedicated use by non-federal users is estimated to cost approximately $18 billion over 10 years. The PCAST reports that the last successful auction of 90 MHz in 2006 yielded only $13.7 billion in revenue, bringing into question the business case for clearing the 1755 MHz band.

PCAST offered an alternative view instead, recommending a Federal spectrum architecture where "the norm for spectrum use should be sharing, not exclusivity." The report urged the President to issue a new memorandum directing the Secretary of Commerce to find 1000 MHz for sharing, building on a number of elements including the following:

1. Spectrum should not be fragmented for use, but allocated in as large of frequency bands as possible. These bands should not be allocated for the use of specific technologies, but rather be technology neutral allowing the greatest possible flexibility in use.
2. Spectrum should be managed via a Spectrum Access System (SAS), similar to the white space database but with additional features and capabilities.
3. Access to shared spectrum should take a 3 tier approach:
    a. Protected non-exclusive use by primary users.
    b. Protected, non-exclusive access for certain priority secondary users so long as they do not interfere with primary users.
    c. General authorized access for all other devices. Such access is not protected, and must not interfere with primary users or priority secondary users.
4. Spectrum management should include not only transmission characteristics but also receiver characteristics, recognizing that receiver performance will increasingly impact the ability of spectrum to be shared as poor receiver design will increase the likelihood that the receiver will receive harmful interference from adjacent channel or co-channel transmitters.

A host of regulatory activities evolved in response to this report, some of which are presented in this section.

TAC White Paper NOI (Docket 13-101)

In June 2013, the FCC OET opened a new docket and issued a public notice inviting comments on a white paper prepared by the FCC TAC entitled "Interference limits policy – the use of harm claim thresholds to improve the interference tolerance of wireless systems[93] [94]. The basic premise of this white paper is that instead of regulating receiver performance to improve the efficient use of spectrum, the FCC should focus on establishing in-band and out-of-band interfering signal levels at a specific location and time that a radio system must be able to tolerate before it can claim it is experiencing harmful interference. This threshold becomes an entitlement for the licensee, and manufacturers are then left to determine how to build receivers that can tolerate these levels when operating under the license. There are multiple advantages stated for this approach, including that:

- the approach allows clarity on levels of protection when multiple technologies occupy the same or adjacent bands, and
- the approach provides a vehicle for incentivizing better receiver performance over time through a roadmap of negotiated adjustments in the harm claim threshold for a specific license.

Through the public notice, the FCC invited comment on the viability of the approach, requested information on other policy approaches that could be taken, requested comment on the relationship between harm claim thresholds and receiver

93 http://apps.fcc.gov/ecfs/document/view?id=7022305447
94 http://transition.fcc.gov/bureaus/oet/tac/tacdocs/WhitePaperTACInterferenceLimitsv1.0.pdf

performance, suggested incentives for improving receiver performance, and the formation of multi-stakeholder organizations called for in the white paper to develop the technical parameters and methods for implementing interference policy.

Additional action on this docket was still pending at the time of this writing, however a related request for information did occur under docket 12-354 as discussed in the next section.

3.5 GHz CBS NPRM (Docket 12-354) (Spectrum Sharing Level 3B)

In November 2010, the FCC issued a Notice of Inquiry on Dynamic Spectrum Access Technologies (Docket 10-237), as a means of building a record on current state of dynamic spectrum sharing technologies[95]. Building on this background, in December 2012, the FCC issued a Notice of Proposed Rule Making proposing the creation of a Citizen's Broadband Service (CBS) in the 3550 to 3650 MHz band[96]. These bands are currently used by the military for various radar systems and aeronautical radio navigation and for some fixed satellite services. The proposal focused on allowing the shared use of small cells and other devices to share access with these incumbent users, drawing upon the TV White Space proceedings as a model, and following the recommendations of the PCAST report:

- Three Tier Model: the commission proposed a 3 tier access model, and sought comment as follows:
    1. Incumbent Access: Authorized Federal users and grandfathered FSS would be granted primary access and protected from harmful interference through the use of the exclusion zones established in the NTIA fast track report based on an evaluation of high power WiMAX technology. The Commission sought comment on reducing the size of these exclusion zones established to something more appropriate given the focus on small cell use. The Commission also sought comment on allowing access by other tiers near incumbent users based on time, frequency and location of incumbent use of these bands and on the potential to modifying receiver performance to mitigate interference issues for FSS.
    2. Priority Access (PA): Users with critical QoS needs, such as hospitals, utilities and public safety entities, would be granted a measure of interference protection when operating on a non-exclusive basis inside of "Priority Access Zones." The Commission proposed that 50MHz of the band would be allocated to Priority Access Use, and stated explicitly that within these zones, priority access users must provide interference protection to and accept interference from Incumbent Access users. The Commission proposed that Priority Access Users would be licensed by rule, allowing individuals, organizations and services providers with automatic authorization to deploy small cell systems. The Commission sought comment on, among other things, whether such Priority Access should be allowed, whether safety of life applications should be permitted in this tier, and the proposed license by rule versus unlicensed operation.
    3. General Authorized Access (GAA): GAA users would operate without protection, and must provide interference protection to and accept interference from Incumbent Access and PA users. GAA Users would be allowed to operate in both "Priority Access Zones" and GAA zones on a non-exclusive basis and would also be licensed by rule.
- Design of the Spectrum Access System. Building from the TV White Space proceedings, the Commission sought comment on whether the government, a commercial entity, or a public private partnership should manage the SAS, and if a commercial entity was used, whether the commission should select a single database administrator or allow multiple administrators. The commission also sought comment on the requirements for registration with the database, and on a number of security issues including the management of classified and unclassified data, cross domain access, and techniques to manage sensitive but unclassified federal information. Finally, the Commission

95 http://apps.fcc.gov/ecfs/document/view?id=7021025483
96 http://www.fcc.gov/document/enabling-innovative-small-cell-use-35-ghz-band-nprm-order

sought comment on whether data within the database be available for public inspection.

- CBS Devices. The Commission sought comment on the proposal that all CBS devices include geolocation technology, on power levels for priority access and GAA devices for fixed base station and mobile station operation, and whether lower power should be allowed near or within an exclusion zone versus outside of an exclusion zone. The Commission also sought comment on HAAT and minimum/maximum emission bandwidth, and allowances for out of band emissions
- Geographic Area Exclusion. The commission sought comment on the Geographic Exclusion area defined in the NTIA fast track report based on high power WiMAX models.
- Other Related Items. The commission also sought comment on a whole host of other items, including equipment authorization, receiver protection, spectrum sensing, and indoor use only models. The Commission also sought comment on whether the proposal should be extended to the 3.65 to 3.70 GHz band, and alternative 2-tier schemes based on the European Authorized Shared Access/Licensed Shared Access models. Public notice seeking comment on licensing models and technical requirements.

In follow up to this NPRM, the FCC Wireless Telecommunications Bureau and Office of Engineering Technology hosted a workshop on the proposed SAS in January of 2014[97]. In parallel with this activity and based on a review of the record from the NPRM, the Commission issued a Public Notice soliciting further comment on alternative licensing proposals inspired by suggestions made by the commenters to the original NPRM[98]. Through this Public Notice, the Commission sought to explore whether Priority Access should be made open to a broader class of users, including commercial users, allowing some level of assured access beyond the critical access users defined in the NPRM. Expanding on this, the Commission sought comment on licensing Priority Access by auction, to include proposed licensing term as well as the geographic, temporal and frequency dimensions associated with such licenses. The Notice also sought comment on a defined floor proposed for GAA spectrum availability, allowing GAA access to unused priority access bandwidth, managed by the SAS, to maximize dynamic use of unutilized spectrum, and a proposal to allocate a portion of the priority access bandwidth for the critical users defined in original NPRM. Through the Notice, the commission sought comment on technical implementation issues, including limiting the maximum power to 24 dBm with maximum antenna gain of 6 dBi for a composite 30 dBm EIRP, and how to facilitate coexistence. Finally, the commission sought comment on whether the formation of one or more stakeholder groups, as defined under Docket 13-101), should be encouraged to study receiver standards.

The Commission received extensive comments on both the NPRM and the Public Notice, and based on an analysis of these comments and the outputs from the workshops held, issued a Further Notice of Proposed Rule Making in April 2014[99]. Through this new NPRM, the Commission proposed to increase the band for consideration to include the 3650 to 3700 MHz band, and confirmed the 3 tier licensing model across, but established open eligibility for Priority Access as per the public notice. Details on the proposed access models are as follows:

- Incumbent Access: The Commission confirmed the Incumbent protections outlined in the NPRM. They also encouraged additional comments on reducing the size of the exclusion zones stated in the NTIA fast track report, which were based on a macro cell deployment model, and indicated they would be revisiting this with NTIA given the technologies envisioned in this proceeding
- Priority Access: Applicants for Priority Access Licenses (PALs) must demonstrate qualifications and how a grant of authorization for priority access would serve the public interest. PALs will be assigned geographically based on the census track as 10 MHz Channels for 1 year without renewal. License holders will be allowed to aggregate up to 5

97 http://apps.fcc.gov/ecfs/document/view?id=7520947360
98 http://apps.fcc.gov/ecfs/document/view?id=7520955346
99 http://hraunfoss.fcc.gov/edocs_public/attachmatch/FCC-14-49A1.pdf

consecutive years of licenses through competitive bidding, and the Commission proposed to use competitive bids to resolve mutually exclusive applications.

- General Authorized Access: As per the NPRM with 50% of the band reserved for GAA use.

Since priority access will no longer be limited to critical users under the defined model, the Commission proposed accommodating these users by setting aside 20 MHz of GAA spectrum with protection similar to priority access users inside the confines of their facility, such as a hospital. This effectively created a fourth tier referred to as Contained Access Users.

The Notice proposed to allow users at the PA or GAA tiers to select whether to provide access under common carrier or non-common carrier basis, and sought comment on whether a SAS could effectively coordinate to allow GAA users to provide common carrier services. The Notice also proposed that there would be no fixed channel assignments. Instead, the SAS will manage assignments within each geographic area and can reassign channels from time to time as required. SAS providers are free to agree upon a convention for reassignment, but such convention will not be in the rules. The NPRM also proposed that GAA devices can use PAL spectrum that is not used at a given location and time, again with the SAS to coordinate.

A number of technical rules for Citizens Broadband Radio Service Devices (CBSDs) were proposed in the Notice, a summary of which is as follows:

- All CBSDs must register with a SAS, providing location (+/- 50 meters horizontal and +/- 3 meters vertical), antenna height above ground, requested authorization status (PA or GAA), FCC id number, user contact info, and unique serial number.
- CBSDs are only allowed to operate as authorized by the SAS, and must follow frequency and power assignments established by the SAS. A response time of 60 seconds was proposed for CBSD's to execute on instructions by an SAS.
- Communications between CBSDs and SAS must be secure.
- CBSDs must measure and report their local signal environment to the SAS.
- CBSDs must use a digital modulation technique.
- Power levels for a CBSD were set as follows:
    - ◊ 24 dBm per 10 MHz peak transmit power and 6 dBi max antenna gain for non-fixed point to point devices not operating in rural areas
    - ◊ 30 dBm per 10 MHz peak xmit power and 17 dBi max antenna gain for non-fixed point to point devices not operating in rural areas
    - ◊ 30dBm per 10 MHz peak xmit power and 23 dBi max antenna gain for fixed point to point devices
    - ◊ Max EIRP for end user devices of 23 dBm in 10 MHz bw
- CBSD's must maintain a -80 dBm received signal strength threshold measured by a 0 dBi antenna in 10 MHz bandwidth along the PAL service boundary at ground level and all heights above ground level.
- Out of band emissions limit for CBSD's will be -50 dBm/MHz, with the emissions limit in a transition gap of 30 MHz above and below set to -40 dBm/MHz.
- CBSDs operating under a PAL must tolerate interference of -30 dBm/10 MHz.

The Notice proposed that there would be multiple SAS administrators and thus there would be multiple SAS databases. Each SAS would be required to accept registration requests and manage assignment requests from all authenticated CBSDs.

Assignments will be made on a determination of available frequencies in a given location, with these determinations ensuring that Incumbent users are protected from CBSD operations, that PA users are protected from GAA emissions, that at least 50% of the band is reserved for GAA operations, and that channels are reserved for Contained Access Users. Assignments will also require determining the maximum radiated power allowed for each frequency and location. Each SAS will provide nationwide service, and information from each SAS will be shared with the other SASs to allow accurate determination of available frequencies. The proposed model would also require each SAS to retain records on all operations.

Several of the commenters from the original NPRM suggested a separate database for federal information, and so this Notice sought comment on additional security information for such a database to hold sensitive federal information.

The Notice proposed that Administrators would be required to establish the protocols and procedures necessary to ensure operation within the established rules, including cooperating with other Administrators to standardize the process for exchanging required information between SAS systems. Administrators are required to make their services available on a non-discriminatory basis, but are allowed to collect reasonable fees for the services provided.

In addition to these items, the Notice propose to add new primary fixed and land mobile allocations to the master frequency allocation table based on this proceeding, made proposals on competitive bidding for PALs, and sought comment on applying secondary market rules in the proposed band.

As of the date of this writing, the proceeding is still open and an order had not been issued.

Other related events

Department of Defense/National Association of Broadcasters Deal

In June of 2013, The President issued a second executive memorandum directing federal agencies and encouraging the FCC to adopt many of the recommendations outlined in the PCAST spectrum report[100]. This memorandum gave greater flexibility to Federal Agencies in negotiating sharing deals. One important deal resulting from this occurred in November of 2013, when the US DoD and the Broadcasting Industry agreed to relocate DoD operations in the 1755 to 1780 MHz spectrum to the 2025 to 2110 MHz band, currently used by broadcasters for remote news gathering operations[101]. Doing so allows the 1755 to 1780 MHz band to be paired with the 2155 to 2180 Mhz band as a part of the AWS-3 auction. DoD use of the 2025 to 2110 spectrum would be on a co-primary shared basis with non-Federal users. Non-federal operation will have priority over DoD operations in this band, with the fixed and mobile military stations operating in the band incorporating frequency agile technology to ensure they shall not cause harmful interference to non-Federal users.

Federal Spectrum Incentive Act of 2013

In an effort to speed clearing of Federal spectrum in support of the 500 MHz Broadband Initiative, Congress introduced a bill that amends the NTIA Organization Act to allow federal entities to participate in an incentive auction program, similar to the incentive auction plan being undertaken for the TV broadcast spectrum[102]. At the time of this writing, the bill was referred to a congressional committee for consideration.

DoD Spectrum Strategy

In February of 2014, the US DoD released a revised Electromagnetic Spectrum Strategy[103]. Citing the 500 Mhz Initiative as a specific driver, the revised strategy called for the expedited development of technologies that will increase the DoD's

100 http://www.whitehouse.gov/the-press-office/2013/06/14/presidential-memorandum-expanding-americas-leadership-wireless-innovatio

101 http://www.ntia.doc.gov/files/ntia/publications/ntia_aws-3_ltr_11252013_.pdf

102 https://www.govtrack.us/congress/bills/113/hr3674

103 http://www.ntia.doc.gov/files/ntia/publications/dod_strategic_spectrum_plan_nov2007.pdf

ability to share spectrum and improve the DoD's ability to access spectrum opportunistically. At the time of this writing, no policy or regulation had been set based on this new strategy; however an indication was made by the DoD that an action plan was in development[104].

Wireless Innovation Act of 2014

In June of 2014, a bill was introduced to "reallocate Federal Government-held spectrum for commercial use, to promote wireless innovation and enhance wireless communications, and for other purposes."

5.2.6 Conclusion

Since 2000, the FCC and NTIA have been making increasing use of spectrum sharing to meet growing demands of both federal and non-federal users. A timeline for the development of regulations support spectrum sharing presented in this chapter is provided below. The PCAST report, open proceedings and other initiatives ongoing in this area, indicate that this trend will continue for quite some time.

Table 1: Timeline for Spectrum Sharing Regulations in the United States

	2000	2001	2002	2003	2004	2005
Early Regulations	Notice of Inquiry on SDR Report and Order on SDR			NPRM on Employing Gognitive Radio Technologies		Report and Order on Cognitive Radio Technologies
	NPRM on Eliminating Barriers to the Developent of Secondary Markets			Report and Order and Further NPRM on Eliminating Barriers to the Development of Secondary Markets	Second Report and Order and Further NPRM on Eliminating Barriers to the Development of Secondary Markets	
			Spectrum Policy Task Force Formed			

104 http://www.defense.gov/releases/release.aspx?releaseid=16547

Table 1: Timeline for Spectrum Sharing Regulations in the United States (continued)

	2002	2003	2004	2005	2006	2007	…	2013	2014
Federal and Non-Federal Spectrum Sharing		NPRM on 5 GHz U-NII Report and Order on 5 GHz U-NII			Memorandum Opinion and Order on 5 GHz U-NII			NPRM Extending 5 GHz U-NII Band	Report and Order Extending 5 GHz U-NII Band
	Unlicensed Spectrum Notice of Inquiry		NPRM on Unlicensed Spectrum in the 3650 band	Report and Order on 3650 Band		Memorandum Opinion and Order on 3650 Band			

	2004	2005	2006	2007	2008	2009	2010	2011	2012
TV White Space	NPRM on Unlicensed Operation in TV Bands		First Report and Order and Futher NPRM on Unlicensed Operation in TV Bands Initial Protype Devices Invited for testing	Phase I Test Results Released	Phase II Testing Phase II Test Results Released Second Report and Order and First Memoraundum Opinion and Order on Unlicensed Operation in TV Bands		Second Memorandum Opinion and Order on Unlicensed Operation in TV Bands		Third Memorandum Opinion and Order on Unlicensed Operation in TV Bands Incentive Auctions ordered by Congress

	2010	2011	2012	2013	2014
500 MHz Initiative	First Presidential Memorandum NTIA Fast Track Review Notice of Inquiry on DSA Technologies		PCAST Spectrum Report Published 3.5 GHz Citizens Broadband Service NPRM	TAC White Paper NOI on Harm Claim Thresholds Public Notice on Licensing Models and Technical Matters related to 3.5 GHz Citizens Broadband Service NPRM	3.5 GHz Citizens Broadband Service Further NPRM

5.3 ITU Region 3

5.3.1 India

5.3.1.1 Spectrum trading (Spectrum Sharing Level 2A)

In 2013, the Telecom Regulatory Authority of India (TRAI), in its recommendations on spectrum valuation and pricing, suggested companies be allowed to share and trade excess spectrum with the ones facing a spectrum crunch. The move, if accepted by the government, is also expected to boost mergers and acquisitions in the sector. TRAI has proposed that spectrum in all bands and technologies such as 2G, 3G and Broadband Wireless Access should be allowed to be traded. However, only an outright transfer of spectrum should be allowed without any leasing, initially.

The Telecom Regulatory Authority of India has cleared the spectrum trading guidelines allowing mobile operators to buy and sell airwaves. Operators can trade spectrum which they have bought through auction or have paid market price. Administratively allocated spectrum cannot be traded. According to the guidelines recommended by the telecom regulator, the Government may collect a transaction fee on spectrum being traded between telecom companies.

The proposed transaction fee would be one per cent of the transaction amount. Operators selling spectrum through the trading mechanism will have to notify the Telecom Department about the quantity of spectrum being sold and the price. There is also a lock-in period for the spectrum traded. If an operator buys spectrum through the trading route, then it will not be permitted to sell any airwaves in the same frequency band for two years.

Under spectrum trading, only outright transfer of spectrum is permitted, that is, the ownership of the usage right is transferred to the buyer. Spectrum leasing is not permitted at this point of time.

Spectrum trading will not alter the original validity period of spectrum assignment.

For the present, spectrum trading shall be permitted only on a pan-LSA (Licensed Service Area) basis, that is, spectrum cannot be traded for a part of the LSA. In case the spectrum assigned to the seller is restricted to part of the LSA by the licensor, then, after trading, the rights and obligations of the seller for the remaining part of the LSA with regard to assignment of that spectrum shall also stand transferred to the buyer. All spectrum bands earmarked for Access Services by the licensor will be treated as tradable spectrum bands. Currently, spectrum in 800MHz, 900MHz, 1800MHz, 2100MHz, 2300MHz and 2500MHz spectrum bands have been allocated for Access Services.

5.3.1.2 Roaming agreements (Spectrum Sharing Level 2A)

Telecom Disputes Settlement and Appellate Tribunal (TDSAT) has cleared 3G intra-circle roaming pacts. Rival companies can sell services in areas where they don't have airwaves though such intra-circle arrangements, it will allow them to avoid having to buy spectrum and support infrastructure at a time when demand for data services is growing exponentially.

5.3.1.3 Spectrum sharing (Spectrum Sharing Level 2A)

According to the draft Department of Telecom (DoT) guidelines, operators can share 2G telecom spectrum after they pay a one-time usage charge for spectrum holding exceeding 4.4 MHz of GSM spectrum, or 2.5 MHz of CDMA spectrum.

The sharing regulations would come with a number of restrictions:

- Sharing would only be permitted between two operators sharing spectrum in the same geographic location, and the two operators cannot together own more than 50% of the spectrum in that area.
- The regulations would not permit any kind of leasing of the spectrum but only free sharing.

- Each sharing agreement must receive explicit authorization from the DoT and authorizations can only be granted if the auction guidelines for the relevant spectrum allow for sharing.

Finally, both operators must pay for the total spectrum utilization, not just that which they have been licensed.

While the Government had earlier opposed such agreements, the Telecom Disputes Settlement Appellate Tribunal (TDSAT) has given an order allowing intra-circle roaming. The permission to share spectrum will be granted after the payment for the spectrum holding is done based on its reserve or auction price.

The sharing of spectrum would involve both the service providers utilising the spectrum. Even as the spectrum is shared, the government says that both the service providers should individually fulfill the rollout obligations. The licence conditions for spectrum mandates the operator to complete a certain percentage of a circle to be brought under the network.

There are no indications that India plans to allow spectrum sharing for either 3G or 4G technologies[105]. While the Government would not allow sharing of 3G spectrum, the top three operators (Bharti Airtel, Vodafone India and Idea Cellular) have intra-circle roaming arrangements between themselves for the circles where they do not have required spectrum.

UPDATE: On 21 July 2014, TRAI released their "Guidelines for Spectrum Sharing"[106]. A summary and analysis of this document will be provided in the next release of the Spectrum Sharing Annual Report.

5.3.2 Japan

The Ministry of Internal Affairs and Communications (MIC) in Japan has been working to secure bandwidth for White Space Communications since 2009[107]. Broadcasting services based on ISDB-T and standardized as ARIB STD-B55 have been permitted to provide TV White Space services. MIC manages the spectrum licenses and a White Space database is not used, however coexistence mechanisms are in place for sharing with wireless microphones, etc.

5.3.3 Malaysia (Spectrum Sharing Level 2A)

The 2006 Spectrum Plan for Malaysia permits spectrum licensees to allow third parties to operate within a licensee's spectrum assignment. Although licensees do not need to seek explicit approval of the Malaysian Communications and Multimedia Commission (MCMC) for agreements, they must notify the MCMC at least 60 days beforehand and the MCMC is free to impose conditions on the agreement. The licensee is responsible for ensuring that the third party follows all regulations applicable to the licensee's use of the spectrum. Because there are no further restrictions, Malaysian regulations encourage adoption of long-term spectrum sharing among operators to improve spectrum utilization and coverage. Unfortunately, the long notification period required for sharing agreements discourages spectrum sharing on shorter time scales. On the other hand, once a third party is approved to use another licensee's spectrum, then so long as there are no corresponding restrictions imposed by the MCMC, there is no reason that operators cannot implement advanced spectrum sharing techniques such as dynamic spectrum access[108].

105 A. Mankotia, "Government may allow telecom companies to share 2G spectrum with riders," *The Economic Times*, 19 Dec 2013. http://articles.economictimes.indiatimes.com/2013-12-19/news/45377850_1_spectrum-usage-charge-spectrum-trading-and-sharing-one-time-spectrum-charge

106 http://www.trai.gov.in/Content/ReDis/527_0.aspx

107 Hiroshi Harada, "White Space Communications Systems: An Overview of Regulation, Standardization and Trial," IEICE Transactions on Communications, Vol E97-B, No. 2, February 2014

108 "Spectrum Plan." Malaysian Communications and Multimedia Commission, 2006. http://www.itu.int/ITU-D/CDS/gq/Resolution9/pdf/Part-I/MALAYSIA.pdf

5.3.4 Singapore (Spectrum Sharing Level 3A)

In June of 2014, Singapore published a regulatory framework for TV White Space operations[109]. A summary and analysis of this framework will be published in the next edition of this annual report.

5.4 Analysis and Conclusions on Regulatory Filings

Models for spectrum sharing have been around for quite some time, but only in the last decade has there been real progress at moving beyond the simple static spectrum sharing to a more dynamic spectrum approach. The 5 GHz UNII band is an early example of this and has been largely harmonized world wide. The US took the initial lead in supporting spectrum sharing in unused TV spectrum, but has been somewhat hands off in recent years as the legislated mandate for incentive auctions has made it unclear how much TV band spectrum will remain available after 2015. Other counties have followed the US in establishing TV White Space rules, but there are numerous variations in approach. For example, in comparing the US versus UK regulations for TV White Space, the UK model ties the database operators more closely to the regulator, and uses more sophisticated propagation models than the US, which provides greater access to spectrum but also requires significantly more computational power.

Regional and nationalistic differences extend beyond TV White Space as well. For example, the European Union seems to be driving toward a unified model supporting licensed shared access (Spectrum Sharing Level 2A). The US is taking a more progressive approach with the rules they are exploring for the 3.55 GHz Citizens Band Radio Service (Spectrum Sharing Level 3B), allowing three tiers with devices operating at the General Authorized Access level having broad access to unused spectrum, which in turn should lower barriers to entry for innovative services in that band.

The variations in spectrum sharing regulations makes it clear that there is no unified vision for spectrum sharing internationally. Analysis shows that areas of difference largely center on the following:

- level of involvement by regulators,
- ensuring protection of incumbents,
- role of databases,
- role of sensing technologies,
- coexistence management, and
- support for heterogeneous versus homogeneous services.

These differences are compounded by the fact that different bands have different requirements, and thus often require different approaches. For example, spectrum sensing has been found to work well in the 5 GHz U-NII band, but was determined to be less effective for the TV bands. The proliferation of standards in this area does not help in establishing harmonized regulation. Regulators can be more proactive where there is a harmonized architectural view, however the non-coordinated proliferation of "standards" gives the impression that technologies not mature, harms industry and slows regulation.

A review of regulations shows that successes occur when 1) There is a mandate or incentive for incumbents to share, 2) there is regulatory certainty allowing investors to make informed business decisions and 3) the regulatory touch is light, allowing industry to decide how to best use the spectrum and ensuring a qualification period that is far less than a technology refresh cycle. When these conditions are not met, then the regulations are less successful. For example, a

109 https://www.ida.gov.sg/~/media/Files/PCDG/Consultations/20130617_whitespace/ExplanatoryMemo.pdf

search of the FCC's license database shows that there are currently only 92 active leases[110]. Although the exact reason for this low number is unknown, if one believes the published studies showing that commercial spectrum is largely under-utilized (see Section 3), it must be assumed that the business case for spectrum leasing does not surpass the business case for not leasing. One can speculate that this is because holding unused spectrum versus leasing creates a barrier to entry for potentially competing services. Similarly, the TVWS market has been slow to take off in the US, but seems to be having success in other areas of the world, with one of the main differences being the incentive auctions in the US. When the conditions are met, the proceedings can generally be considered a success from a business perspective. For example, the 5 GHz U-NII band is broadly used to support the millions of wireless local area network and broadband access devices. In addition, there are currently 78 protected sites in the US 3650 MHz rulemaking, and a search of the FCC license database shows that there are 2608 active licenses operating in that band[111]. The success of these proceedings can be attributed to the amount of available spectrum and the ease in meeting the license requirements. A non-profit industry Forum, focused on spectrum sharing and allowing active collaboration between government and industry stakeholders from multiple market domains, would go a long way toward ensuring future proceedings can enable these successes and help the regulatory bodies achieve their objective to maximize the effective use of radio spectrum in the public interest.

Further Reading

1) MIT Communications Futures Program, "Toward More Efficient Spectrum Management", http://cfp.mit.edu/publications/CFP_Papers/CFP%20Spectrum%20Sharing%20Paper%202014.pdf

110 http://wireless.fcc.gov/uls/index.htm?job=home

111 http://wireless.fcc.gov/services/index.htm?job=service_home&id=3650_3700

6

The Economics of Spectrum and Related Business Models

6.1 Introduction

Spectrum, unlike other commodities such as gold, has no intrinsic value. Rather, the economics of spectrum are based on the value of the services that can be provided to users of that spectrum. A carrier that is considering the purchase of an exclusive use spectrum license needs to determine how much profit they believe they can obtain by providing services on that spectrum over a given period of time. They can then also determine the cost of alternative means of providing those same services, such as fixed infrastructure, unlicensed spectrum, higher frequency re-use, etc. This exercise will allow them to assign the upper and lower bounds to the value of the spectrum and make an informed purchasing decision.

Unlike the previous case of exclusive use, shared spectrum involves assessing the value of the spectrum to multiple users. With shared spectrum, the value to any particular user will be lower than what would be achievable under an exclusive license due to the increased interference that comes with sharing a band with multiple users. However, while the value to the individual user has fallen, the sum of the values over all of the users will be greater than the value achievable to the single user under an exclusive use model. This is the idea behind spectrum sharing – to increase the total value of the spectrum by sharing spectrum resources between a group of users.

6.2 Current Spectrum Business Models

Many frequency bands are currently allocated using an allocation regime known as exclusive use or "command and control." Under a command and control regime, "a regulator rigidly allocates non-overlapping frequency bands to specific uses and assigns rights to licensees."[112] In this scenario, it is reasonably straightforward for an operator to assess the value of that spectrum by determining the present value of all the future proceeds from the services that one can offer on that spectrum.

While such an allocation scheme is very effective at avoiding interference between different spectrum users, it results in inefficient usage of spectrum as the spectrum that is unused by the exclusive license holder is unavailable for use by other users.

Furthermore, it has been argued that this license system has evolved into a regime that protects the license holder not only from interference – as was its intent – but also from competition[113].

The goal behind shared spectrum is to increase the total value of the spectrum. While each individual user may suffer to some degree compared to the exclusive use scenario, spectrum sharing makes economic sense if the cumulative value of the spectrum across all users in the same band is greater than the value that any single exclusive user can achieve.

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112 B. Freyans, "The Economics of Spectrum Management: A Review," Australian National University, 2007.

113 I. Goggin, "Spectrum management and the achievement of policy goals – an independent regulator's perspective," *Utilising the Airwaives*, OFCOM, 2007.

There are also some frequency bands that are currently unlicensed, such as that used for WiFi or for ISM (industrial, scientific, medical). The benefit of unlicensed spectrum is that an operator does not have to incur the cost of licensing spectrum in order to provide services to potential users. However, a downside is that an operator doesn't necessarily benefit from any CAPEX investment made to use the spectrum more efficiently, and in fact another operator with less efficient technology stands to benefit more, because more spectrum is now available for its services. Hence, it can be difficult to get operators to adopt technology that uses spectrum more efficiently without some other mechanism such as spectrum fees or pay-per-use policies.

6.3 Potential New Spectrum Business Models

As different regulators around the world have examined moving away from the current exclusive use model of spectrum allocation, the impact of different spectrum management techniques on possible business models has been explored. This section of the report will outline some of the business models that could be used to take advantage of either new spectrum allocation models or of available spectrum in unlicensed or underutilized bands.

6.3.1 Pluralistic licensing

Pluralistic licenses are a type of license proposed by Holland *et al.*[114] following work by Cave and Webb[115]. Cave and Webb proposed that space for technologies such as Ultra-wideband (UWB) radio could be found by releasing licenses with an interference allocation for such use at a reduced price. Holland *et al.* extended this work by proposing a complete pluralistic licensing scheme, under which licenses are awarded on a sliding cost scale, with the cost of a license being tied to the amount of interference that a license holder is willing to accept from other users in the band. A user who wishes to not take part in dynamic spectrum sharing might decide that the level of interference that they will accept from outside sources is extremely low, and thus they will pay a premium price for their licenses. However, those license holders who are willing to tolerate a greater degree of interference from others will be charged significantly less for their licenses, with the cost of the license decreasing proportionate to the amount of interference they are willing to tolerate.

The idea behind pluralistic licensing is to provide an economic motivation for license holders to accept the risk of interference that comes with allowing other users to share the spectrum in a licensed band while still guaranteeing that license holder a certain quality of spectrum. When purchasing spectrum, a company will have to decide whether it makes more financial sense to spend their dollars on more restrictive licensing or on equipment that can better share spectrum with others.

Pluralistic licensing is of interest, as it seems that such a scheme will encourage more efficient use of spectrum and will provide economic incentives for spectrum sharing. Also, such licenses will provide new opportunities for players to enter the cellular market as well as provide spectrum for other possible new applications that may be developed. However, there would have to be some investigation into how to ensure that the primary licensees of spectrum would fairly share with secondary users.

6.3.2 Licensing Based on Dynamic Spectrum Sharing (DSS)

There are opportunities for much greater use of and economic value of shared spectrum via licensing on a dynamic

114 O. Holland *et al.*, "Pluralistic Licensing," *Proc IEEE DySPAN 2012*, Bellevue, Washington, October 2012.

115 M. Cave, P.W. Webb, "The Unfinished History of Usage Rights for Spectrum," *Proc. IEEE DySPAN 2011*, Aachen, Germany, May 2011.

basis, either through use of a database or through some other dynamic spectrum sharing mechanism. Three examples that will be examined here are private-public partnerships, rural broadband and spectrum trading.

6.3.2.1 Public-Private Partnerships

Various levels of government may hold the rights to spectrum bands for use on behalf of the general public. For instance, bands may be reserved for the use of public safety or for the use of radar. While it is important that these bands are available for use when they are needed, their use can be limited in time and / or space, and thus the spectrum reserved for their use is sometimes underutilized.

DSS (level 3) can be used to allocate these bands to secondary users when and where they are currently unused[116]. Secondary users can lease spectrum in these public bands dynamically and have these rights managed by a database or other means. By implementing priority and preemption rules, such a system can ensure that the incumbent user is always able to access the spectrum it needs at the time it is needed. Priority can be assigned based on multiple models. One potential model is based solely on cost, i.e., one can pay more for a higher level of priority. Such a system is attractive to private companies as they can expect to be able to achieve the QoS required in order to service their clients, while still flexible enough to allow users with less capital resources access to the spectrum. Another model could be based upon public good or other social factors. In such a model, the government is likely to be an active participant in setting the priority order based on its current policies.

In one example of such a system, Rivada Networks in the US has developed a patented spectrum commodity exchange system that implements dynamic spectrum sharing in public safety bands allowing Mobile Network Operators (MNOs) to access unused spectrum on a pay-per-use basis[117]. By leasing unused spectrum to secondary users, Rivada claims that publically owned networks will be able to recoup some of the costs associated with maintaining these networks, reducing the financial burden to the taxpayer. Meanwhile, MNOs who need extra capacity in congested areas – such as urban cores – will be able to access extra spectrum on an as-needed basis when their networks are overcrowded.

6.3.2.2 Rural Broadband

It is clear that improving access to broadband Internet for users in rural communities continues to be an issue worldwide. Due to the large distances involved, bringing high-speed access to these communities through laying cables can be cost-prohibitive. A wireless Internet solution, particularly one that leverages unlicensed or shared spectrum, is therefore worth investigating for these areas.

Traditional Wi-Fi signals are sent on spectrum that is not useful for providing Internet access within a community, as the frequencies used will not transmit for sufficient distances. However, by using whitespaces within spectrum with better transmission characteristics, it is possible to provide wireless Internet access within a reasonably large area. Such technologies are already being tested in areas of the US in order to provide rural users with access to broadband Internet with rates from 2 to 4 Mbps[118 119].

Currently, such systems use a static database lookup to determine which pieces of spectrum are being unused and thus can be allocated for other uses. However, such a system is – by nature – a conservative one. A truly DSS system would be able to use spectrum more efficiently by finding more empty spectrum than a static database lookup. By pooling the available whitespace and making it available to rural Internet users, an ISP would be able to provide rural broadband without incurring the capital expenses involved in laying cables. Extension of broadband into rural areas would benefit the users

116 W. Lehr, "Toward More Efficient Spectrum Management," Spectrum Working Group, MIT, 2014.
117 Rivada Networks, 2014. *Our Technology*. www.rivada.com.
118 K. Garnett. Feb 20, 2014, *Deployment of TV White Space Technology In El Dorado County, California*. www.whitespacealliance.org.
119 D. Murph, April 18, 2013. *Broadband internet arrives in California's Gold Country through white spaces deployment.* www.engadget.com.

living in those areas, would increase their economic and social participation, and would create market opportunities for new broadband providers to provide this whitespace service.

6.3.2.3 Spectrum trading

Spectrum trading has become a popular proposal for efficiently allocating spectrum resources by imbuing spectrum with property rights. This approach was first proposed in 1959 by economist R. H. Coase as an alternative to the command and control model of spectrum allocation and has gained traction in recent years as one possible solution to the spectrum crunch. Proponents of spectrum trading systems argue that markets are the best method to achieve efficient use of resources. By allocating spectrum via a market, spectrum would become an elastic resource – with supply increasing to meet demand, since as the market cost of spectrum increases, the justification for spending more on equipment to use spectrum more efficiently also increases. This creates a feedback loop wherein as the price of spectrum increases more spectrum is made available for purchase[120].

However, spectrum markets require certain conditions in order to be successful. Caicedo[121] underlines the characteristics of spectrum that differentiate it from traditionally traded commodities. Spectrum is non-perishable (you are unable to do anything to spectrum at any time that will ruin it for future use) and geographically re-usable. Berry *et al.* [115] also note that spectrum assets have "complementarities" – in geography, time and space - wherein some spectrum assets are worth more to a buyer due to the fact that the buyer owns neighbouring assets. Spectrum markets must be able to deal with these particular characteristics of spectrum in order to be successful.

Furthermore, Caicedo states that his simulations of spectrum trading markets indicate that there must be sufficient buyers in the market for those markets to be viable, as well as no significant under or oversupply of spectrum to trade. Caicedo also argues that an important aspect of a successful trading market is the ability for spectrum users to continually choose between purchasing and leasing spectrum[122]. Such a system implies the use of leases that are much shorter-term than those used today. These leases require that the transaction cost be minimized in order for market trading to be successful[123].

A DSS system could be used in conjunction with a spectrum market in order to dynamically allocate spectrum between market participants. Such an automated system for accessing and sharing spectrum could allow spectrum to be shared in the smaller slices of time required for a well-functioning spectrum market as well as hold down trading transaction costs.

6.4 Potential Future Considerations for Spectrum Property Rights

New approaches to managing radio spectrum will be required as wireless systems and networks move toward cognitive operation and as the demand for spectrum rises exponentially. The driving force behind this evolution will be based on two co-dependent factors: new policies and regulations governing autonomous spectrum access by wireless devices (cognitive radios) and the development of powerful adaptive software designed to undertake radio resource management. This evolution will take place in both the licensed and unlicensed bands, most likely below 6 GHz where attenuation and propagation conditions are favorable for mobile applications. For licensed service providers the evolution will provide a new means to extract value from fallow spectrum; for unlicensed users it will mean an improvement in spectrum efficiency,

120 R. Berry *et al.*, "Spectrum markets: motivation, challenges, and implications," *IEEE Communications Magazine*, vol. 48, no. 11, pp. 146-155, 2010.

121 C. Caicedo, "Spectrum Trading: Market Based Architectures for Dynamic Radio Frequency Spectrum Access," *Journal of Information Policy*, vol 3, pp. 485-500, 2013.

122 C. Caicedo, M. Weiss, "The Viability of Spectrum Trading Markets," *IEEE Commun. Mag.*, vol. 49, no. 3, pp. 46–52, Mar. 2011.

123 A. Taparia, T. R. Casey, "Toward a Market Mechanism for Heterogeneous Secondary Spectrum Usage: An Evolutionary Approach," *Proc IEEE DySPAN 2012*, Bellevue, Washington, October 2012.

reliability, and security.

As processors become more powerful and as artificial intelligence becomes embedded within radio base stations and handsets, it will be possible to undertake computationally complex wireless bandwidth and radio-resource management tasks such as spectrum auctioning, trading, and renting. However, under such regimes, it would be expedient to have spectrum defined not only by its electromagnetic wavelength or frequency, but also by its location, polarization, transmission time, and radiation extent. This would provide a granularity of control that would allow spectrum to be more effectively and intelligently used and reused, with a commensurate improvement in spectrum efficiency. Electromagnetic spectrum defined in terms of its temporal and spatial characteristics is called "electrospace" and its attractiveness lies in the fact that with this concept spectrum can be assigned spatial and temporal usage rights[124 125]. Futuristic spectrum management concepts, such as spectrum trading, renting, and re-farming, can be provided with tractable parameters that make it possible to monitor and quantify its use, localize and identify interference, and maintain quality of service and security requirements. Electrospace, as a spatial and temporal entity, can be partitioned into sub-spaces, and there are many current examples of where this is done[126 127].

One advantage of the electrospace concept is that it can provide spectrum policy with a greater enforcement capability over a larger population of users. Spectrum use rights become associated with a location, coverage area, and means for wireless signal transmission and reception. Electrospace range and extent is defined by propagation; where it is lost because of attenuation, it can be recreated and spectrum reused, thus providing nuances to policy and regulatory control not possible with conventional spectrum regulatory practice. This allows spectrum to be visualized as a commodity whose limits and characteristics can be quantified and stored in a database, allowing potential users to immediately become aware of the extent of usage rights and to both respect incumbent users and take advantage of fallow spectrum. The FCC has taken this approach with its TVWS regulations and as a consequence has not only protected incumbent primary users (such as TV broadcasts stations and news-gathering microphone systems), but also has made spectrum available to unlicensed wireless rural access networks (WRANs) and environment monitoring systems[128]. Having knowledge of electrospaces' locations and use profiles allows cognitive radios to undertake sophisticated trading, reuse, and renting of spectrum, and allows the support of concepts such as light licensing, ASA, and pluralistic licensing; which allow fallow spectrum to be productive[129].

Concepts such as electrospace point the way to futuristic wireless networks where spectrum becomes efficiently used in the support of high bandwidth demand. It also raises questions about the laws and rights regarding access to spectrum and the control of electrospace. Such questions will need to be addressed if we come to rely on wireless networks to support medical devices attached to the human body or to control the operation of driverless vehicles. The evolution of wireless radio resource management will redefine our policies and regulatory definitions for spectrum, and the rights to its use in our homes, offices, and factories.

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124 RJ Matheson, "The Electrospace Model as a tool for Spectrum Management" Addendum to the Proceedings of the International Symposia on Advanced Radio Technologies, March 2003, NTIA special publication SP-O3-401.

125 M.C Erturk and H. Arslan, "Signal Separation for Cognitive Wireless Communications" *Cognitive Radio and its Application in Next Generation Cellular and Wireless Networks*, pages 222-228.

126 Huang, Jane Wei, and Vikram Krishnamurthy. "Cognitive base stations in LTE/3GPP femtocells: a correlated equilibrium game-theoretic approach." *Communications, IEEE Transactions on* 59.12 (2011): 3485-3493.

127 Angeletti, P., and N. Alagha. "Space/ground beamforming techniques for emerging hybrid satellite terrestrial networks." 2009: 141-141.

128 "Unlicensed Operation in the TV Broadcast Bands," Second Opinion Memorandum and Order, FCC 10-174 released Sept 23, 2010.

129 O. Holland *et al.*, "Pluralistic Licensing," *Proc IEEE DySPAN 2012*, Bellevue, Washington, October 2012.

6.5 Conclusions

The economics of spectrum and related business models are already in the process of undergoing a sea change in response to the enabling capabilities of cognitive radios. This is driving spectrum management from exclusive use toward shared spectrum, with the goal of maximizing the value of spectrum across all potential users.

New business models such as pluralistic licensing and dynamic spectrum sharing (DSS) licensing are being evaluated and trialed, and will continue to be refined over time. In the future, electrospace may be a concept that can be applied in order to monetize spectrum across both temporal and spatial boundaries.

Public policy that provides straightforward and simple rules for the monetization of shared spectrum will enhance business models and promote innovation. When governments are evaluating new spectrum licensing policies, consideration should be made of the effects on business models.

Further Reading

1) WiFiForward, "The Value of Unlicensed Spectrum", http://www.wififorward.org/wp-content/uploads/2014/01/Value-of-Unlicensed-Spectrum-to-the-US-Economy-Full-Report.pdf

2) GSMA, "The Impact of Licensed Shared Use Spectrum", http://www.gsma.com/spectrum/the-impact-of-licensed-shared-use-of-spectrum/

7

DSA, White Space and Spectrum Sharing Test Beds and Field Trials Worldwide

7.1 Introduction

7.1.1 Motivation

Spectrum sharing requires the deployment of communication systems that, unlike conventional communication systems, use the radio resources opportunistically without interfering with other users of higher or equal priority. The resource scheduling is not done by the radio operator or spectral owner; rather, other techniques are applied to access spectral resource. TVWS-based spectrum sharing technology suggests maintaining a data base, where reservations can be made based on availability[130]. DSA usually assumes continuous sensing of the spectrum to determine available time-frequency slots for transmission on a dynamic basis. That is, no reservations are necessarily made. This, however, depends on the national and international regulations and other policies as well as the capabilities of the radios. An opportunistic radio, cognitive radio, DSA radio or white space device may need to be able to adapt its transmission parameters as a function of changes in the radio environment that create different spectral opportunities over time, space and frequency.

To successfully develop, test and, eventually, deploy TVWS and DSA technology several DSA/TVWS trials have been done or are ongoing and testbeds have been built[131]. Database-managed white space systems are being developed in the US. Equivalent pilot projects are ongoing in North and South America, Europe, Africa, Asia and Australia. With involvement of governments, regulators, industry and academia there is a number of ongoing activities to move wireless communications to a new era of more efficient *and* more flexible spectrum use.

This section provides an overview of some of the TVWS/DSA testbeds and trials around the world. By no means at all does this report pretend to provide a complete survey of ongoing DSA/TVWS activities. Figure 9 shows a world map of testbeds and trials that we present in this section (Table 2).

7.1.2 Definitions

DSA/TVWS Testbed: Laboratory or outdoor test system that enables investigating spectrum sharing technology and techniques and their potential impacts and risks.

DSA/TVWS Trial: Spectrum sharing experiment performed on a testbed or another temporal or permanent setup (commercial pilot).

130 Broadband Center of Excellence, "TV white space: ready for prime time? – Assessing practical realities of a share-spectrum approach for broadband Internet access," *Broadband Intelligence Series*, University of New Hampshire, Jan. 2014.

131 The Dynamic Spectrum Alliance – Worldwide Trials and Pilots Web Site http://www.dynamicspectrumalliance.org/pilots.html

Figure 9: World map of testbed and trials considered in this report (See also Table 2).

Table 2: Testbed and trials presented in this report.

No.	Trial/Testbed	Section	No.	Trial/Testbed	Section
1	Next Generation (XG) Trials	7.2.1.1	11	CorteXlab	7.2.2.4
2	Wallops Island 3.5 GHz Trial	7.2.1.2	12	NICT	7.2.3.1
3	Wilmington, NC Trial	7.2.1.3	13	Singapore Trials	7.2.3.2
4	INL Testing Facilities	7.2.1.4	14	TVWS Trial in the Philippines	7.2.3.3
5	NTIA Spectrum Sharing Testbed	7.2.1.5	15	TVWS Trial in Taiwan	7.2.3.4
6	University of New Hampshire TVWS Trial	7.2.1.6	16	Malawi White Space Commercial Pilot	7.2.4.1
7	CORNET	7.2.1.7	17	Microsoft's Super Wi-Fi Commercial Pilots	7.2.4.2
8	Cambridge Trial	7.2.2.1	18	Cape Town TVWS Trial	7.2.4.3
9	Ofcom TV White Spaces Pilot	7.2.2.2	19	New Zealand Managed Spectrum Park	7.2.5
10	CREW Federated Test Platform	7.2.2.3			

7.1.3 Spectral Bands, Regulation and Licensing

Testbeds need to operate in a safe environment, that is, isolated from normal wireless system operation. Although many cases it would be more beneficial to operate in life spectrum, any harmful interference spectrum incumbent must to be prevented. Obtaining a short or long-term license for testing operation is therefore necessary in most cases. Carlson Wireless, for instance, holds 12 experimental FCC licenses for their TWVS trials in the US. Low-power indoor testing or isolated geographical areas can help to ensure safe testing. The spectral bands used and licenses are indicated for each testbed/trial, if known.

7.2 Spectrum Sharing Trials and Testbeds

This section sketches some of the many ongoing and past DSA/TVWS trials and testbeds around the world.

7.2.1 US

7.2.1.1 DARPA's neXt Generation (XG) Trials

Synopsis[132 133]

Type	Program for the development and testing of DSA radios
Objective	Developing the technology and system concepts for DoD to dynamically access all available spectrums. Developing a long-lived framework for managing the key aspects of radio behavior through flexible application of policies.
Location	US
Time	Phase 1: 2002 to 2003 Phase II: 2003 to 2004 Phase III: 2005 to 2006
Sponsor	DARPA
Equipment	DARPA radios
Band/License	Various
Spectrum sharing level	3b
Conclusions	August 2006, Fort A.P. Hill: six-node network of Next Generation (XG) radios (A.P. Hill XG Radios) capable of using spectrum over a wide range of frequencies on a secondary basis

Status

The XG program and it successor—wireless network after next (WNaN)—have concluded. Some results are publicly available through academic papers and presentations, among others.

Summary

Mission

The mission of DARPA's neXt Generation (XG) Communications technology was to effectively make up to 10 times more spectrum available by taking advantage of assigned, but unused spectrum at a particular place and time. The goal of

132 BBN Technologies, "*The XG Vision*," XG Working Group, http://www.ir.bbn.com/~ramanath/pdf/rfc_vision.pdf.
133 P. Marshall, "*XG Communications Program Information Briefing*" Semantic Web Applications for National Security (SWANS) Conference, April 7, 2005. http://www.daml.org/meetings/2005/04/pi/DARPA_XG.pdf.

the XG program is to solve the problem of opportunistic spectrum access in its totality. At the highest level, there are two sets of goals: [134] [135] [136]

- Develop the enabling technologies for opportunistic spectrum access. This includes providing certain key behaviors such as sensing and characterizing the environment, identifying and distributing spectrum opportunity information, and allocating and using these opportunities commensurate with the demand. Such solutions would typically be implemented as part of an XG radio device
- Develop a long-lived framework for managing the key aspects of radio behavior through flexible application of policies. In order that the radio be policy-agile, we require a framework in which policies are written in a way that can be interpreted by the radio, and the radio is able to exploit such expression of policies.

Also, the XG program was focused on the development of an effective DSA demonstration and capability by evaluating three fundamental principles:

1. That DSA radios could be designed so that they did not interfere with viable links for other non-cooperative users of the spectrum, presumably primary users. This principle was broadly known as "Do No Harm."
2. That DSA radios had a positive benefit after all of the overhead costs and processing resources were included in the determination. This was the "Add Value" principle.
3. That DSA devices could be developed that would provide equivalent reliability and service despite the additional complexity of the interference avoidance requirements. This was the "DSA Works" principle demonstration.

Results

Several trials were done under the XG program and later under the wireless network after next (WNaN) program. Many companies and academics were involved. Listing them is beyond the scope of this report. We, rather, indicate a few results and issues reported.

McHenry et al. define different metrics for measuring the performance of XG radios. The trials at Ft. A.P. Hill on August 16-17, 2006 achieve 70 % *White Space Fill Factor*. It was reported that the cause for this (low) figure was the large gap in the detection window due to hardware limitations related to timing.

7.2.1.2 3.5 GHz Spectrum Sharing Trial at Wallops Island

Synopsis[137] [138]

Type	Spectrum Coexistence Trial
Objective	Provide an assessment of feasibility of small cell communication in 3.5 GHz - 3.65 GHz, which is used by U.S. Navy Radar
Location	Wallops Island, Virginia, U.S. (one antenna is toward Chincoteague and the south end of Assateague island)
Time	August 5-8, 2013
Sponsor	Wireless@Virginia Tech, Naval Surface Warfare Center Dahlgren Division (NSWCDD)
Equipment	CMW500 LTE base station from Rohde & Schwarz

134 Marshall, Preston, *Quantitative analysis of cognitive radio and network performance*, Artech House, 2010.

135 P. Marshall, "XG Communications Program Information Briefing" Semantic Web Applications for National Security (SWANS) Conference, April 7, 2005. http://www.daml.org/meetings/2005/04/pi/DARPA_XG.pdf

136 Marshall, Preston, *Quantitative analysis of cognitive radio and network performance*, Artech House, 2010.

137 J. Reed, C. Clancy, C. Dietrich, R. Nealy, M. Fowler, M. Mearns, M. Shea, and J. Vick, "Measurement Results for Radar and Wireless System Coexistence at 3.5 GHz," http://wireless.fcc.gov/workshops/sas_01-14-2014/end/Reed-VA_TECH.pdf

138 J. Nealy, C. Dietrich, J. Reed, "Preliminary 3500 MHz Radar-Communications Compatibility Tests," unofficial report, provided by Dr. Dietrich.

Band/License	3.5 GHz
Spectrum sharing level	1
Conclusions	LTE communication is possible in the presence of operating Naval radars in adjacent band. The LTE system power can overcome the naval radar's high power signal leaking into adjacent channels. Accounting for some amount of guard band allows using the otherwise unused spectrum.

Status

The trial has been completed in 2013 and the final report is available.

Summary

Radar-communications compatibility tests were performed in the 3500 MHz band. The purpose of the tests is evaluating the feasibility of using small cells in the 3500 MHz band with Navy Radar operations in adjacent bands. The tests do not demonstrate ordinary communication deployment, but rather were performed as an initial proof of concept. The tests were performed on August 7 and 8, 2013, on Assateague Island, near Wallops Island, VA, by Virginia Tech and NSWCDD. The test equipment included the CMW500 form Rhode & Schwarz as the eNodeB, broad beam horn antennas with adjustable linear polarization, and a commercial off-the-shelf (COTS) LTE User Equipment (UE). The tests showed that it is possible to establish an LTE link in the 3.55-3.6 GHz band in the presence of strong radar signal in the adjacent band. More measurements are needed to assess the level of coexistence between LTE and radar and to devise the best LTE system parameters (power level, directionality, cell size, etc.) for maximizing throughput and minimizing interference.

7.2.1.3 Wilmington, NC Trials

Synopsis

Type	TVWS Trials
Objectives	To test emerging TVWS radios and related technologies (antennas, solar power, etc.) to determine optimum design, throughput/distance ratios and operating characteristics. To deploy TVWS networks in actual working environments to create financially self-sustaining applications and real-world value propositions.
Location	Wilmington, New Hanover County, NC
Time	Since March 2011
Sponsor	TV Band Service, Spectrum Bridge, New Hanover County, NC
Band/License	Various open TV channels as determined by geolocation database administrator provided by Spectrum Bridge
Spectrum sharing level	3a
Equipment	Various
Conclusions	The trials determined that high-value applications for TVWS include video surveillance and citizen WiFi "hotspots.

Status

These trials are active; the channel bonding use case is being tested at the time of edition.

Summary

The trials tested TVWS radios in actual working environments and identified video surveillance and citizen WiFi hotspots are high-value applications for TVWS. The consortium anticipates use cases for

- SCADA applications as radio prices decrease and solar power capabilities increase,
- individual consumer broadband with initial low capacity connectivity in rural areas as radio costs decrease, and
- channel bonding to increase capacity and be applicable for mobile "cluster" applications such as school buses and other mass transit methods.

7.2.1.4 Idaho National Laboratory Testing Facilities

The Idaho National Laboratory (INL) delivers a nationally unique combination of wireless research, development, testing, integration, demonstration, and deployment capabilities and government laboratory resources. INL wireless research and experimentation, RF and systems modeling, cyber security assessment, software development, scenario simulation, hardware prototyping services, and extensive support services bring together a compelling set of capabilities and resources for spectrum sharing research and experimentation.

Secure, Spectrum Agile Wireless Communications for Video Surveillance

Synopsis

Objective	Provide a prototype platform for secured, spectrum agile wireless communications for video surveillance with a low probability of detection and interception.
Location	Idaho National Laboratory indoor R&D lab
Time	June 2012 – current
Sponsor	Idaho National Laboratory, Drug Enforcement Administration
Equipment	National Instruments Flex RIO
Band/License	2.4 GHz and 5.725 GHz
Spectrum sharing level	Multiple
Conclusions	INL demonstrated transmission and reception of audio and compressed video communications that implemented Filter Bank Multicarrier Spread Spectrum (FBMCSS)– WSComm technology at or near the Radio Frequency (RF) noise floor. [135] [136]

Status

INL is developing a new cognitive/spectrum-sharing RF access technology and waveform called Wireless Spectrum Communications (WSComm)[139] [140].

Summary

INL is building next generation cognitive technologies to support the development of next generation technologies that can efficiently use RF spectrum in new and innovative ways. WSComm is based on "Filter Bank Multicarrier Spread Spectrum (FB-MC-SS)" construct. This spectrum-agile technology enables low to medium data-rate underlay control and/or traffic channels. This is also foundational to building an adaptive/cognitive radio network that maximizes the use of available white space in the spectrum, where high data-rate overlay channels can be dynamically assigned.

139 D. L. Wasden, J. Loera, H. Moradi, and B. Farhang-Boroujeny, "Design and implementation of a multicarrier spread spectrum communication system," in *Proceedings of Military Communications Conference 2012* (MILCOM 2012), pp. 1–7, October-November 2012.

140 D. L. Wasden, J. Loera, H. Moradi, and B. Farhang-Boroujeny, "Comparison of direct sequence spread spectrum rake receiver with a maximum ratio combining multicarrier spread spectrum receiver," to appear in *IEEE International Conference on Communications 2014*, June 2014.

In the underlay mode, the WSComm technology enables operation in any spectral band(s) under the noise floor. It spreads the signal over a set of spectrally isolated subcarriers. This underlay feature enables instantaneous deployment of: point-to-point communications, Mobile Adhoc Networks (MANETs), large-scale networks that might need low-speed or secure communication channels and/or mission-critical alternate emergency communication channels in a natural emergency, friendly or hostile environment. The built-in security feature of the underlay mode enables low probability of detection, interception, and operation under harsh RF environments and jamming conditions. This transmission scheme poses little or no taxation to the spectrum under use and is resistant to high-energy narrow and/or wideband interference while allowing robust performance in high mobility environments. The security of the communication systems adopting this technology can be enhanced at the RF layer with a dynamic key generation scheme.

In the overlay mode, WSComm allows deployment of opportunistic high throughput white space spectrum utilization in licensed and unlicensed bands, and in mission-critical situations. This spectrum-sharing feature enables throughput comparable to 4G wireless technologies. Alternately, this technology can be exploited to increase the wireless range in point-to-point video surveillance situations or for deploying wider area MANETs.

INL Wireless Test Bed - Spectrum Experimentation Research Program

Synopsis

Objective	Deliver compelling large-scale spectrum research experimentation infrastructure, services, facilities and expertise, enabling secure, national wireless innovation, collaborating with all key stakeholders, in alignment with INL National & Homeland Security (N&HS) mission supporting the national security, energy security and the national economy.
Location	40 miles west of Idaho Falls, Idaho
Time	May 2003 – current
Sponsor	Idaho National Laboratory (INL), DOE, DOD
Equipment	
Band/License	NTIA Experimental Test Authority for Government, FCC STA for Industry & Academia
Spectrum sharing level	
Conclusions	INL has conducted over 400 wireless communications tests including more than 4000 test days for government, industry and academic customers. As part of DOE, INL manages an 890 square mile test range with a RF noise floor typically less than -120 dBm/10 kHz. INL supports the development, deployment, demonstration and field test of spectrum sharing technologies.

Status

The INL Wireless Test Bed (WTB) was established in 2003. Its capabilities currently include real-world Tier 1 GSM, UMTS, WiMAX cellular networks; fixed and mobile towers and trailers; several Network Operating Control Centers and high-bays; as well as microwave and optical fiber backhauls. INL is in process of standing up a full-scale Tier I and a Tier III LTE network and is developing concepts for Controlled Radio Frequency Interference (RFI) and Spectrum Monitoring Network for Spectrum Sharing Testing. Follow-on phases will include implementation of the RFI system, Spectrum Sharing Monitoring Network, as well as an array of Software Defined Radios (SDRs) that researchers can load and evaluate their technologies at full-power in a real world environment.

Summary

INL WTB is situated in a remote area in South East Idaho and was established to conduct comprehensive wireless communications tests supporting government, industry and academic customers across 890 square miles of federally owned land. As an NTIA experimental radio station, INL has local spectrum authority and management of frequency for government customers. Industry and Academia can quickly obtain a FCC STA for INL's Test Range. Situated in a low-noise environment, RF emissions are allowed at full power from DC to light on a noninterference basis with local spectrum owners.

INL offers its large outdoor test bed and independent services to closely collaborate with the NTIA, the FCC, the regulatory and standards bodies and other national agencies on spectrum sharing technology development, validation and demonstration. INL is an independent government laboratory for R&D management, systems integration, and a technology proving ground for spectrum sharing innovation.

7.2.1.5 NTIA Spectrum Sharing Innovation Testbed Pilot Program

Synopsis

Type	DSA Testbed
Objective	To develop and prove a testing methodology for systems employing DSA techniques
Location	US
Time	2009 -
Consortium	NTIA, FCC
Band/License	Various
Spectrum sharing level	3a
Equipment	Various, submitted by the participating parties (Adapt4 LLC, Adaptrum Inc., BAE Systems, Motorola Inc., Shared Spectrum Company, Virginia Tech)
Results/ Conclusions	Phase I: Institute for Telecommunication Sciences (ITS) in Boulder, Colorado performs characterization measurements of DSA capabilities of devices supplied by participants. Phase II: DSA spectrum sensing and/or geo-location capabilities will be examined. Phase III: Evaluating the DSA equipment that will be permitted to transmit in an actual radio frequency signal environment.

Status

Phase 1 is completed, Phase 2 is in progress, and Phase 3 has not started at the time of edition[141]. Early 2012, NTIA requested comments for the test plans for phases II/III. The test plans were finalized mid-2012[142]. The latest progress report is from FY12. NTIA is in the process of completing the measurements and documenting the results.

Summary

The National Telecommunications and Information Administration (NTIA), in coordination with the FCC and the federal agencies, established a *Spectrum Sharing Innovation Test-Bed Pilot Program* in 2009 to test the feasibility of sharing spectrum between federal and non-federal users. The program's purpose is examining the ability of DSA devices employing spectrum sensing and/or geo-location techniques to share spectrum with Land Mobile Radio (LMR) systems operating in federal band and in non-federal band. The program is in progress, and it has three different phases: (1) equipment characterization, (2) evaluation of capabilities, and (3) field operation evaluation.

The program was announced in 2006 and comments were received[143]. Six testbed participants—Adapt4 LLC, Adaptrum

141 L. E. Strickling, "*The Spectrum Sharing Innovation Test-Bed Pilot Program Fiscal Year 2012 Progress Report*," April 1, 2013, http://www.ntia.doc.gov/files/ntia/publications/fy12_test_bed_progress_report_march2013.pdf.

142 NTIA, Phase II/III Test Plan Spectrum Sharing Innovation Test-Bed Pilot Program (final), www.ntia.doc.gov.other-publication/2012/phase-iiiii-test-plan-spectrum-sharing-innovation-test-bed-pilot-program-fina.

143 NTIA, Spectrum Sharing Innovation Test-Bed Pilot Program Web Site, www.ntia.doc.gov/legacy/frnotices/2006/spectrumshare/

Inc., BAE Systems, Motorola Inc., Shared Spectrum Company, Virginia Tech—confirmed their participation by 2008 and submitted devices for testing. The test planning phase took long and the actual testing was delayed. Two participants withdrew, according to the latest, publicly available progress report.

7.2.1.6 University of New Hampshire TVWS Trial

Synopsis

Type	TVWS Trial
Objective	To provide broadband internet services to unserved and underserved communities through public library facilities using TVWS technology.
Location	University of New Hampshire (UNH) campus and surrounding
Time	Dec. 2013
Consortium	Broadband Center of Excellence, University of New Hampshire
Band/License	TV Channel 41 (635 MHz)
Spectrum sharing level	3a
Equipment	Carlson Wireless TVWS radios and other commercial-off-the shelf equipment
Conclusions	• TVWS is capable of providing high-quality Internet access within a radius of 8 km. • Consistent link performance (throughput) depends on terrain, antenna type and placement, channel availability, base station deployment and configuration, among others. • Conduct real-time spectral analysis to dynamically assign TVWS channel for carrier-class performance • Use of flexible modulation schemes to be able to trade throughput against robustness as a function of SNR. • Today´s TVWS technology can serve a small community, but is less well-suited for providing connectivity between communities or internet access to far outlying areas.

Status

This trial has been completed in December 2013. Reference [144] provides information about the trial setup and results.

Summary

In fall 2013, the University of New Hampshire's Broadband Center of Excellence initiated the TVWS pilot deployment as part of the Gigabit Libraries Network (GLN) project, awarded to 6 cities[145 146]. The project analyzes the use of TWVS technology for (1) providing gigabit internet access in the area of public libraries and (2) to residences and business that are not served by traditional IP networks.

The set include a single TVWS base station and three remote locations. Throughout measurements were done at two libraries and one lab facility located at 0.5, 1, and 5 km distance from the base station. TV channel 41 was used, as it was found to be available based on Google´s TVWS database.

The throughput measured at the 1 km distant Durham library was up to 1.92 Mbps on the downlink and 430 kbps – 1.3

comments.htm.

144 Broadband Center of Excellence, "TV white space: ready for prime time? – Assessing practical realities of a share-spectrum approach for broadband Internet access," *Broadband Intelligence Series*, University of New Hampshire, Jan. 2014.

145 A. Fitzpatrick, "University Transforming Unused TV Channels Into Campus Wi-Fi Networks," http://mashable.com/2013/07/10/university-white-space-wifi/.

146 BBC Wires, "Gigabit Libraries Network Announces Results of super Wi-Fi Pilot," http://bbpmag.com/wordpress2/2013/08/gigabit-libraries-network-announces-results-of-super-wi%E2%80%90fi-pilot/.

Mbps on the uplink, using BPSK modulation. Antenna placement was identified as the cause of the initially slow downlink data rates. The cheap and easily installable window-mounted antenna at the Durham library is considered the bottleneck of the link. It is expected that a rooftop antenna would provide higher and more consistent throughput. Similar results were obtained at the 0.5 km distant Diamond Library, whereas more consistent throughputs were measurements at the 5 km distant UNH Interoperability lab featuring a roof-mount antenna.

It was found that antenna deployment is critical for performance. The optimization process needs to account for building permits and other restrictions. Similarly, the base station deployment and configuration needs careful attention and trials. The trials demonstrated the viability of providing internet access to a small and nearby community. It was concluded that the current TVWS technology is less well-suited for providing connectivity between communities or internet access to far outlying areas. A hierarchical mesh-type network, such as ROSALNet may be suitable for such scenarios[147].

Similar Super-WiFi projects (WiFi over TVWS) are ongoing in other US states through GLN, which received wide industry support. Interested libraries or groups can register at the GLN portal[148].

7.2.1.7 CORNET

Synopsis

Type	DSA Testbed
Objective	Campus-wider testbed facility for leveraging cognitive radio/DSA research and education
Location	Virginia Tech campus, Blacksburg, Virginia
Time	Since 2009
Sponsor	NSF, DoD
Band/License	Experimental FCC license agreement for several bands ranging from 138 MHz to 3.6 GHz: http://cornet.wireless.vt.edu/fcclicense.html
Spectrum sharing level	Various
Equipment	USRPs, general-purpose processors, open-source software
Conclusions	CORNET provide access to 48 indoor SDR nodes and 14 outdoor nodes (O-CORNET) for students and researchers to do develop and launch a variety of wireless communications experiments, including spectrum sharing. Since its deployment in 2009, CORNET has been an indispensable tool at Virginia Tech for enriching class and research projects by providing free access to a number of radio nodes that can be programmed as desired.

Status

The CORNET testbed is operational for more than 5 years. It is currently extended with outdoor SDR nodes and LTE waveforms.

Summary

Using and developing open-source software SDR and cognitive radio research and education is gaining popularity since mid-2000. The cognitive radio network (CORNET) testbed was built in 2009 with support from the DoD, NSF and the Institute for Critical Technology and Applied Science (ICTAS) at Virginia Tech. It comprises a network of 48 SDR nodes located in a 4-story building on Virginia Tech campus in Blacksburg. CORNET is fundamentally built of commercial off-the

147 N. Rakheja, P. Bhatia, V. Sevani, V. J. Ribeiro, "ROSALNet: A Spectrum Aware TDMA Mesh Network for Rural Internet Connectivity," 2014 IEEE.

148 Gigabit Libraries Network Web Site, http://giglibraries.net/.

shelf hardware and open-source software[149]. CORNET provides a platform for quick prototyping and testing of waveforms and wireless communication techniques/systems, in general.

Several students and researcher have used CORNET for research and education in wireless communication at Virginia Tech and elsewhere. This includes SDR waveform design and testing, position location experiments, wireless distributed computing, LTE waveform development, cognitive radio metrics and DSA experiments. The CORNET web site contains information about past and present projects[150].

CORENT is currently extended with outdoor, mobile, and portable nodes as part of the O-CORNET project. Outdoor CORNET or O-CORNET provides access to a campus-wide network of SDR nodes mounted on rooftops of lecture halls (Figure 10). Most nodes have GPS receivers that enable implementing multipoint wireless transmission and reception techniques, among others. O-CORNET adds 22 outdoor nodes to CORNET: 12-14 fixed, 2-4 mobile, 6 portable, and 2 sensing nodes.

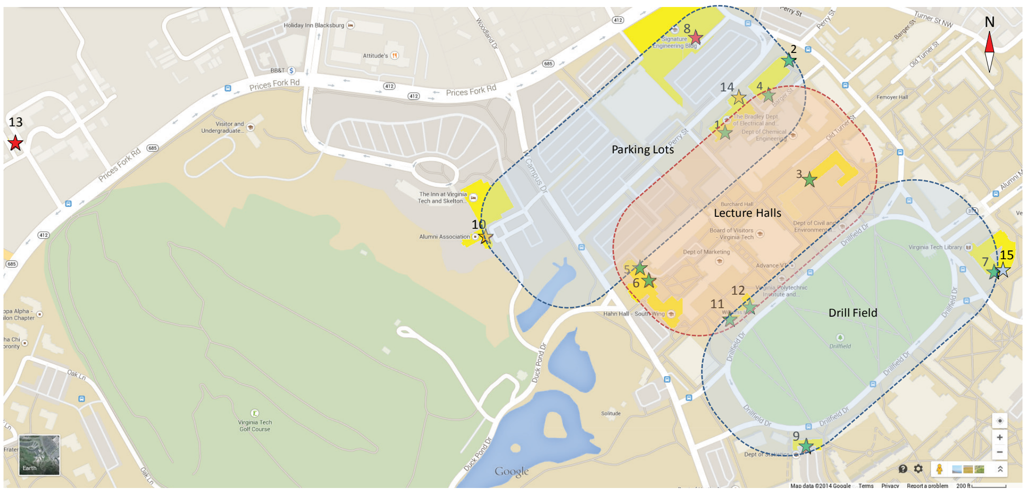


Figure 10: O-CORNET fixed node locations at Virginia Tech campus in Blacksburg, Virginia (10, 14: under construction; 8, 13: planned; 15: sensing node).

Figure 11: Typical fixed O-CORNET node: mount with antenna and enclosure (left) holding a laptop, N210 USRP with SBX daughterboard, filters and GPS receiver (right).

149 T.R. Newman, S.M.S. Hasan, D. Depoy, T. Bose, J.H. Reed, "Designing and deploying a building-wide cognitive radio network testbed," *IEEE Communications Magazine*, Vol. 48, No.9, pp. 106-112, Sept. 2010.

150 Cognitive Radio Network Testbed Web Site, http://cornet.wireless.vt.edu/

Access to CORNET is free and only requires registration. Once registered, the user can access the testbed for developing and launching experiments. Virginia Tech's experimental license agreement allows transmissions on non-interfering basis in several bands between 400 and 3600 MHz. Data can be collected and stored at the user's personal disk space, accessible from any node.

Some of the advantages of CORNET are:

- Availability of 60+ remotely accessible SDRs based on common research and educational tools
- Node locations allows designing different types of experiments
- Operation in real spectrum
- Regular software and hardware upgrades and extensions

Some of the lessons that we have learned are

- Schedule regular hardware and software upgrades to ensure system stability and usability.
- Having radio front ends close to the computing nodes (O-CORNET) is advantageous for maintenance and for limiting latency, which may otherwise lead to standard incompatibility issues. LTE, in particular, has stringent latency requirements for control signaling.
- The fixed O-CORNET nodes cover most of the campus and allow creating different radio environments for experimentation.
- Many experiments need physical node access for modifying hardware, among others. The portable and mobile O-CORNET nodes can be checked out for such experiments.
- Deploying common SDR research tools—both hardware and software—ensures quick adoption as a research tool and steep learning curves as an educational tool.
- Despite the group of experts involved to set up and maintain such testbed, undergraduate and graduate students can significantly contribute to its realization, maintenance and improvement.

7.2.2 Europe

7.2.2.1 Cambridge Trial

Synopsis

Type	TVWS Trial
Objective	Assist Ofcom's development of the framework for sharing the TV bands on a license-exempt basis and to help industry understand the application potential of the technology
Location	UK, 5 urban + 6 semi-rural/rural locations
Time	June 2011 – April 2012
Consortium	Adaptrum, Alcatel-Lucent, Arqiva, BBC, BSkyB, BT, Cambridge Consultants, CRFS, CSR, Digital TV Group (DTG), Microsoft, Neul, Nokia, Samsung, Spectrum Bridge, TTP, and Virgin Media

Band/License	The Cambridge Trial operated within the framework of a test and development license from Ofcom in the 470-790 MHz range.
Spectrum sharing level	3a
Equipment	Various
Conclusions	TVWS applications (including rural broadband access and machine to machine communications) can coexist with the licensed services in the UHF bands (TV and PMSE) Databases can enable dynamic sharing of the spectrum (e.g. shifting channels to accommodate licensed PMSE activities when required) Industry and regulator cooperation is essential to ensuring the most efficient and secure sharing of spectrum Characteristics of TVWS signals and spectrum UHF band permitted long distance connections to rural locations (~6 km) and showed excellent building penetration (e.g. in a solid stone-built college environment) White space channels varied in cleanliness – with distant TV transmissions being the prominent source of interference in the noisier channels Data produced by networks of fixed & mobile monitoring nodes can provide useful information for regulators and spectrum users

Status

The trial has been completed in June 2012 with two reports produced, the main report and a summary of technical findings[151] [152].

Summary

The Cambridge White Spaces Trial was established in 2011 to assist Ofcom in developing regulations that would enable safe and efficient sharing of the TV white spaces spectrum. It also allowed the TVWS technology's application potential to be explored. The Trial started in June 2011 and terminated in April 2012 – although much of the network remained in operation. Led by Microsoft, a total of 11 companies and organizations joined initially, increasing to 17 by the end of the project (see Synopsis). A total of 12 white space radios were set up in and around Cambridge UK, for evaluating of coverage and performance in different environments. The main applications demonstrated were – broadband access (in urban and rural locations); machine to machine applications (applied to refuse bins) and location-based services (Duxford Air Museum). Other white space radios were introduced on a temporary basis, from time to time. Two field measurement sets were planned: Fixed Customer Premises Equipment (CPE) and Mobile UE Measurements. The results of trial were mainly focused on performance and coexistence characteristics of TVWS signals, with the licensed services in the UHF bands. Technical details of the trial measurements and results can be found in [147] [148].

151 Cambridge White Spaces Consortium, "Recommendations for Implementing the Use of White Spaces: Conclusions from the Cambridge TV White Spaces Trial," http://research.microsoft.com/en-us/projects/spectrum/cambridge-tv-white-spaces-trial-recomms.pdf

152 Cambridge White Spaces Consortium, *Cambridge TV White Spaces Trail Summary of the Technical Findings,*http://www.cambridgewireless.co.uk/docs/Cambridge%20White%20Spaces%20Trial%20-%20technical%20findings-with%20higher%20res%20pics..pdf

7.2.2.2 Ofcom TV White Spaces Pilot / ICT-ACROPOLIS Led Trials

Synopsis[153]

Objective	The Ofcom TV White Spaces (TVWS) Pilot**.** in general aims to: Provide a proof of concept of the UK's TV White Space framework, developed by Ofcom and reflected in the ETSI 301 598 Harmonized European Standard specifying the requirements of white space devices (WSDs). Provide a step of verification before full-scale TVWS operations start. Involve the regulator, industry, end users, and others in the process, such that the interactions between the relevant stakeholders can be verified and all necessary fields of expertise can be included.
Location	There are a number of trials within the Ofcom TV White Spaces Pilot at various locations in the UK. This report focuses particularly on the trials led by the ICT-ACROPOLIS Network of Excellence. The ICT-ACROPOLIS trials are taking place at numerous King's College London campuses in London, including the Strand (Aldwych), Waterloo, Guys (London Bridge), St. Thomas (opposite Westminster), Denmark Hill, and Hampstead Campuses, possibly in addition to others available to King's College London. Further numerous other sites in London and across the UK are being used, at Queen Mary University of London (East London), University of York, University of Surrey (Guildford), Strathclyde University (Glasgow), Cambridge University, and the University of Bath.
Time	Throughout 2014
Consortium	ICT-ACROPOLIS Network of Excellence (www.ict-acropolis.eu), led by King's College London, the Joint Research Centre of the European Commission, and Eurecom. Also teaming up with the ICT-SOLDER project (www.ict-solder.eu), and others.
Band/License	470 MHz to 790 MHz
Spectrum sharing level	3a
Equipment	NICT white space devices (WSDs—802.11af high-power variant, 802.11af low-power variant, LTE base stations and terminals in TV white space), Eurecom software radios operating as WSDs, Carlson Wireless WSDs, KTS/SineCom WSDs.
Conclusions	At this stage too early to conclude on the results of the trials.

Status

After a lengthy process of qualification of the geolocation databases (GDBs) that will participate in the Ofcom TV White Spaces Pilot, the deployment work of the Trial lists in the Pilot (including the ICT-ACROPOLIS led trial) is now beginning. This deployment work is of course dependent on the qualification of the GBDs for operation by Ofcom. At the time of writing, Spectrum Bridge, Nominet, BT, Fairspectrum, NICT, iconectiv and Microsoft have signed contracts for GBD provision with Ofcom, with Spectrum Bridge having been the first to qualify their GDB, and others (currently NICT, Fairspectrum and Nominet) also being very close to completing the qualification process. Noting that a given model of WSD usually operates with a given GDB (e.g., KTS/SineCom WSDs use Spectrum Bridge, Carlson WSDs use Fairspectrum, NICT WSDs use the NICT database, etc.), this means that the use of particular models of WSDs can be constrained to begin operation at different times dependent on the qualification of their associated GDB.

A number device manufacturers and developers/providers are currently providing WSDs for operation in the Ofcom TVWS Pilot. These include KTS/SineCom, Carlson Wireless, NICT, Adaptrum, 6Harmonics, Eurecom, and others.

153 Ofcom TV White Spaces Pilot, http://stakeholders.ofcom.org.uk/spectrum/tv-white-spaces/white-spaces-pilot, accessed June 2014.

Summary

The Ofcom TVWS Pilot assess and verify aspects of the developed TVWS framework in the UK. Examples of aspects that the Pilot aims to verify include:

- WSD operations.
- GDB contract qualification.
- GDB operation and calculations.
- Ofcom's provision of the qualifying GDB listing.
- Ofcom's DTT calculation results and provision of Programme Making and Special Events (PMSE) data.
- Interference management, and
- Coexistence.

The ACROPOLIS participation in the Ofcom TVWS Pilot has several objectives. The first key objective is to test a number of WSDs for operation in TVWS, as well as associated applications and deployment scenarios. These include:

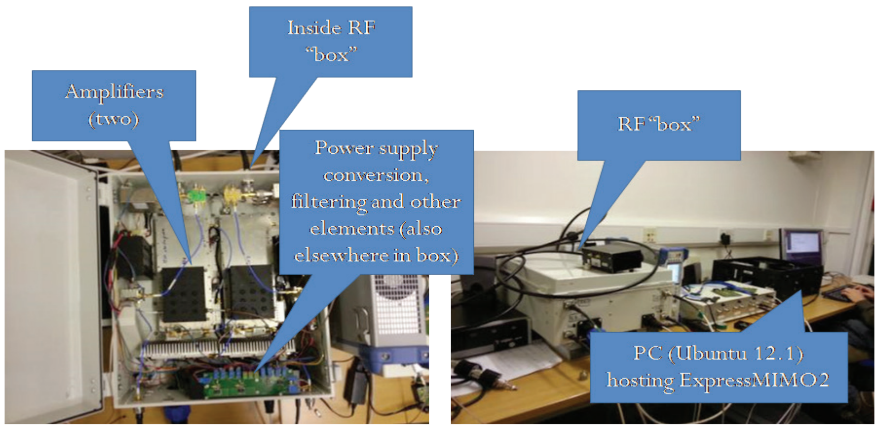
- LTE Multicast/broadcast (eMBMS), using Eurecom ExpressMIMO2/OpenAirInterface SDR equipment/software, and extensions to that. A range of transmission coverage scenarios will be investigated, from wide-area rooftop to relatively limited area (indoors or ground level), dependent on the deployment locations and associated characteristics.
- TD-LTE in TVWS, using NICT LTE WSDs. Moderate coverage ranges are anticipated to be investigated.
- Broadband for Public Protection and Disaster Relief (PPDR), LTE+TVWS, using Carlson Wireless WSDs.
  - ◊ This case also involves the investigation of point-to-point links in TVWS, as might provide emergency backhaul in PPDR scenarios.
  - ◊ A further case, video surveillance using Carlson WSDs, is also being investigated.
- WiFi in TVWS (802.11af draft), using NICT devices. It is an aspiration of the Eurecom OpenAirInterface software to also be enhanced to support this, although uncertain whether that will be achieved.
  - ◊ Conventional wireless local-area coverage using low-power WiFi, based on NICT devices.
  - ◊ High-power WiFi for direct point-to-point links, again serving PPDR among other scenarios, based on NICT devices.
- M2M implementations, using KTS/SineCom devices. More specifically, smart city-wide networking based on those devices.
- Broadband provisioning using KTS/SineCom devices and Carlson Wireless devices.

Being driven by academics and research institutes, a very strong emphasis is put on the research elements in the ICT-ACROPOLIS led trials. The research studies that are being undertaken include:

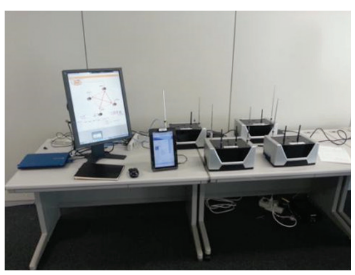
- Development and testing of solutions for aggregation of resources/links (TVWS resources/links with licensed and/or unlicensed ISM resources/links, and of separate resource/links within TVWS).
  - ◊ Qualitative and quantitative performance surveys will be undertaken.
- Secondary coexistence (e.g., LTE with 802.11af in TVWS, among others). This includes also solutions for secondary coexistence mitigation and management, and secondary-secondary interference assessment among other aspects.
- To undertake studies and surveys on the performances achieved, e.g., in terms of interference to primary TV services and PMSE services, and secondary performance through objective user opinion polling and detailed monitoring activities.

A range of devices are being used in the ICT-ACROPOLIS trials at different location and times. These include:

- Three different forms of WSDs created by collaborators at NICT, Japan, namely:
  - ◊ 2 IEEE 802.11af high-power variant WSDs[154].
  - ◊ At least 3 IEEE 802.11af low-power variant WSDs.
  - ◊ 3 TD-LTE base station and 3 TD-LTE terminal WSDs[155].
- At least 3 WSDs that are based on Eurecom ExpressMIMO2 software radios driven by OpenAirInterface LTE-MBMS waveforms (and perhaps, at a later stage, IEEE 802.11af and other waveforms) [156] [157]
- Carlson RuralConnect WSDs comprising at least 2 Base Stations and 5 Client Stations, which use a proprietary waveform[158].
- A number of KTS/Sinecom Agility White Space Radio WSDs which use a proprietary waveform[159].



(a)



(b) (c)

Figure 12: Some of the devices being used in our trials: (a) Eurecom ExpressMIMO2-based solution, incorporating a PC with an ExpressMIMO2 software radio card incorporated and a separate custom-built RF, (b) NICT low-power 802.11af devices operating in a mesh network.

154 NICT Press Release, "World's First TV White Space WiFi Prototype Based on IEEE 802.11af Draft Standard Developed," October 2012, accessible at http://www.nict.go.jp/en/press/2012/10/17-1.html, accessed May 2014.
155 NICT Press Release, "Alleviating Overcapacity, Specially Developed Smartphone Utilizing TV Whitespace with LTE Technology," March 2014, accessible at http://www.nict.go.jp/en/press/2014/03/19-1.html, accessed May 2014.
156 Eurecom ExpressMIMO2, http://www.openairinterface.org/expressmimo2, accessed May 2014.
157 OpenAirInterface Twiki, https://twiki.eurecom.fr/twiki/bin/view/OpenAirInterface/WebHome, accessed May 2014.
158 Carlson Wireless RuralConnect, http://www.carlsonwireless.com/ruralconnect, accessed May 2014.
159 KTS Agility White Space Radio, http://www.ktswireless.com/agility-white-space-radio-awr, accessed May 2014.

7.2.2.3 CREW Federated Test Platform

Synopsis

Type	DSA Testbed
Objective	Provide a common portal for accessing five heterogeneous DSA testbeds in Europe to accelerate research and trough synergistic efforts. Provide data sets to the research community for training and other uses Enable performance evaluation of external hardware under controlled test conditions
Location	Five locations in Europe: Berlin, Dresden, Dublin, Ghent, Logatec & Ljubljana
Time	1 October 2010 - 30 September 2015
Consortium	Technische Universität Dresden, Technische Universität Berlin, CTVR, Thales, EADS, IJS, iMinds, imec, sponsored by EU through FP7
Band/License	Various
Spectrum sharing level	Various
Equipment	Various: WiFi, Bluetooth, Zigbee, LTE, SDRs, CR data base, sensing equipment, etc.
Conclusions	Contributions range from advanced spectrum sensing to Virtual Wireless Networks [http://www.crew-project.eu/biblio].

Status

This project is active.

Summary

The cognitive radio experimentation world or CREW project joins five testbeds in Europe under a single portal for providing a federated testbed experience to researchers:

- Mode 1: Individual testbed usage,
- Mode 2: physically hosting of nodes from one testbed in another,
- Mode 3: replaying measurements from one testbed on another.

The open federated test platform is meant to facilitate "experimentally-driven research on advanced spectrum sensing, cognitive radio and cognitive networking strategies in view of horizontal and vertical spectrum sharing in licensed and unlicensed bands." Information on accessing each of the five testbeds and repositories can be found from the CREW portal[160]. These involved testbeds are: w-iLab.t in Ghent, TWIST in Berlin, Iris testbed in Dublin, LTE advanced testbed in Dresden, and Log-a-Tec testbed in Logatec & Ljubljana.

7.2.2.4 CorteXlab

Synopsis

Type	DSA Testbed

160 CREW Project Portal, http://www.crew-project.eu/portal

Objective	Provide a remote and freely accessible portal to a DSA testbed deployed in a shielded room of 200 m2 with 40 cognitive radio nodes. Provide a reproducible environment to the research community for training, comparison of algorithms and performance evaluation Enable performance evaluation of external hardware under controlled test conditions
Location	Located at CITI lab at INSA, University of Lyon, France
Time	Available in September 2014. Already available for beta tests.
Consortium	CorteXlab is one the facilities offered by the FIT project (http://fit-equipex.fr/)
Band/License	500Mhz – 3.5GHz
Spectrum sharing level	Various
Equipment	PicoSDR (Nutaq), USRP2 (Ettus/NI)
Conclusions	Open access to a facility including 40 cognitive radio nodes in a shielded environment providing reproducibility of experiments and no license requirements.

Status

This testbed will be available in September 2014.

Summary

FIT (Future Internet of Things, http://fit-equipex.fr) aims to develop an experimental facility and a federated and competitive infrastructure with international visibility. This facility provides a set of complementary components that enable experimentation on innovative services for academic and industrial users. FIT include three kinds of testbeds: five Embedded Object testbeds, three Wi-Fi mesh testbeds and one cognitive radio testbed (CorteXlab).

CorteXlab (www.cortexlab.fr) allows users to design, benchmark, and tune their cognitive radio protocols. It supports the development of application-driven research aimed at validating promising theoretical concepts. Compared to the other existing testbeds, CorteXlab offers several particularities in order to address complex and evolved scenarios of next generation wireless networks:

- CorteXlab is composed of a mix of radio nodes, including Wireless Sensor Network (WSN) nodes with lower flexibility (IoT-lab nodes), SISO SDR nodes (USRP), and MIMO SDR nodes (PicoSDR).
- The testbed is installed in a large (180 m^2) shielded room (isolated from any external interference) and also partly covered with EM absorbing material.
- The nodes are interconnected through a dedicated high speed Ethernet link, for cooperation and information sharing purposes.
- A unified server controls the start and coordination of experiments and collection of results in a user-friendly and remotely accessible environment.

7.2.3 Asia

7.2.3.1 National Institute of Information and Communications Technology (NICT)

Synopsis

Type	TVWS Trial

Objective	To confirm long-range broadband communications in the TV white space by using IEEE 802.22-based and IEEE 802.11af-based systems
Location	Tono City, Iwate, Japan
Time	2013/14
Sponsor	Hitachi Kokusai Electric Inc.
Band/License	TVWS (470-710 MHz) entrusted by Ministry of Internal Affairs and Communications, Japan
Spectrum sharing level	3a
Equipment	IEEE 802.22-based and IEEE 802.11af-based systems
Conclusions	IEEE 802.22-based system successfully communicated over 12.7 km between base station and customer premises equipment. Throughput was 5.2 Mbps in downstream and 4.5 Mbps in upstream. Multihop network is successfully constructed. The network is constructed using IEEE 802.22 and IEEE 802.11af wireless link. Succeeded to operate with two discontinuous TV channels at the same time. Future Prospects. Mobile communications in TV white-spaces. Contribute to the standardization activities of wireless communication systems utilizing TV white-spaces. Promote a development of portable devices based on standardized communication systems.

Status

The trials have been concluded. Press releases are available[161] [162] [163].

Summary

The National Institute of Information and Communications Technology (NICT) and Hitachi Kokusai Electric Inc. succeeded in the world's first field trial where long-range broadband communications in the TV white space was confirmed by using IEEE 802.22-based and IEEE 802.11af-based systems. In this trial, NICT and Hitachi Kokusai observed successful downstream and upstream data transmission at 12.7 km distance between IEEE 802.22-based base station and customer premises equipment, at a speed of 5.2 Mbps and 4.5 Mbps, respectively. In addition, NICT and Hitachi Kokusai constructed a multihop network by using IEEE 802.22 as a backbone link and IEEE 802.11af, which is connected to it, to expand its connection area. They demonstrated applications such as video monitoring of roads and cliffs and video telephony in mountain areas where there are no wired/wireless Internet connections available. These achievements showed feasibility of providing broadband services in rural areas and supporting radio communications during disasters relief activities.

161 Fierce Wireless Tech, "World's First TV White Space WiFi Prototype Based on IEEE 802.11af Draft Standard Developed," http://www.fiercewireless.com/tech/press-releases/worlds-first-tv-white-space-wifi-prototype-based-ieee-80211af-draft-standar

162 NICT, "World's First Breakthrough Achieved for Long-Range Broadband Communications in TV White Space," http://www.nict.go.jp/en/press/2014/01/23-1.html

163 Smart Wireless Laboratory, "World's First Breakthrough Achieved for Long-Range Broadband Communications in TV White Space," Jan 23, 2014, http://www2.nict.go.jp/wireless/smartlab/news/2014_01_23.html

7.2.3.2 Singapore Trials (Singapore White Spaces Pilot Group, SWSPG)

Synopsis

Type	TVWS Trials
Objective	Accelerating the adoption of technology relating to unused TV broadcast channels ("White Spaces") locally, regionally and, eventually, globally, by the following means: 1. Promoting Singapore as a test-bed for White Spaces commercial pilots, including facilitating White Space pilot projects in Singapore and the region, with a view to maximizing the value of White Spaces to end users; 2. Helping parties with shared interests test-bed White Spaces applications and explore business models; 3. Gathering White Spaces data, and providing input to assist regulators in adopting and implementing license-exempt White Spaces regulatory frameworks in the region; 4. Hosting educational and industry events relating to White Spaces and generally educating stakeholders, including but not limited to research institutions, product developers, system integrators, standardisation bodies, regulators and end users on White Spaces technologies and their benefits; and 5. Generally advocating and promoting the use of White Spaces.
Location	Singapore
Time	Started in April 2012 and still ongoing
Consortium	Singapore White Spaces Pilot Group (SWSPG) consisting of Institute for Infocomm Research (I2R), Microsoft, StarHub, Neul, Power Automation, NICT, Adaptrum, iConnective, Singapore Island Country Club (SICC), Spectrum Bridge, ZDW, Grid Communications, Terrabit Networks, EuroKars, Sentosa, Housing Development Board (HDB), NexWave and ST Electronics.
Equipment	I2R, Neul, Power Automation, NICT, Adaptrum
Band/License	630-742 MHz
Spectrum sharing level	3a
Conclusions	See below

Status

Trials at different locations in Singapore have started in 2012 and are still ongoing.

Summary

Since 2009, IDA, Singapore has established a roadmap to spearhead the development of a regulatory framework for White Spaces to promote the adoption and deployment of white space networks in Singapore. The four key components of this roadmap are shown in Figure 13.

Figure 13: IDA roadmap for TVWS deployment in Singapore.

Building on the results from spectrum monitoring in Singapore in March 2007—showing low duty cycles of many frequency bands between 54 MHz and 5.85 GHz—and the success of the Cognitive Radio Venue (CRAVE) trial in 2011, IDA facilitated a group of industry players, namely the Institute for Infocomm Research (I2R), Microsoft Singapore and Starhub, in forming the Singapore White Space Pilot Group (SWSPG, http://whitespace.i2r.a-star.edu.sg/) in April 2012. Under the SWSPG umbrella, various commercial pilot trials are being carried out in Singapore. Some of the trials have been completed and others are work in progress.

Smart Metering @ University Town, Singapore

Synopsis

Objective	To trial an "electric vending system" connected to selected dormitories to provide metering services using TVWS technology.
Location	University Town, National University of Singapore
Time	Completed in Oct 2013
Consortium	Power Automation and I2R under SWSPG
Equipment	
Band/License	630-742 MHz
Conclusions	All connections were successfully established between the base station located at UTown South Tower level 25 stairways (alternative reference location) and the clients with maximum speed up to 4.35Mbps at the furthest client location."

Status

This trial has been completed in October 2013.

Summary

A TVWS concentrator was placed at level 25 of a UTown South Tower. TVWS client nodes were placed at the rooftop of the Pump House (~0.40 km distance to tower), and building SR1 at ground level (~1.26 km distance to tower) and SR2 at the water tank level (~1.04 km distance to tower). Data from SR1 and SR2 were pushed to an alternative base station on UTown South Tower, which directed the data to the Pump House. This improved LOS and proved to be successful (Table 3).

Table 3: Measurement results for Smart Metering trial.

Client	Antenna	Antenna_BS	Channel	Max. Speed	Min. Speed	Link Quality	Est. Distance
SR1 Above Water Tank	12 dBi	12 dBi	48	2.67 Mbps	1.82 Mbps	19	~1.26 Km
SR1 Ground Level	12 dBi	12 dBi	48	2.95 Mbps	1.33 Mbps	8	~1.26 Km
SR2 Above Water Tank	12 dBi	12 dBi	48	4.46 Mbps	4.05 Mbps	25	~1.04 Km
SR2 Ground Level	12 dBi	12 dBi	48	1.85 Mbps	1.07 Mbps	13	~1.04 Km
Pump House Above Water Tank	12 dBi	12 dBi	48	6.53 Mbps	6.30 Mbps	58	~0.40 Km

Singapore Island Country Club

Synopsis

Objective	The aim is to extend the wireless connectivity to the golf course shelters so that members are able to use their smart devices.
Location	Singapore Island Country Club
Time	Since 2013

Consortium	Terrabit and Neul/6Harmonis under SWSPG
Equipment	
Licensing/Bands	630-742 MHz
Conclusions	TVWS technology is expected to add efficiency in getting real time coverage, which would result in enhanced security and safety for the residents.

Status

This project is ongoing.

Summary

Figure 14 shows the deployment locations. The distances between the node locations with respect to the base station ranges from 376 m (Pole) and 1.24 km (Workshop). The terrain has different elevation, with up to 16-36 m difference in elevation level between base station and the other nodes. The project is still ongoing and results were not available at the time of editing.

Figure 14: Singapore Island Country Club Course as at 12 April 2014 (Base Station to Workshop—6H—, Base Station to Hway House and Pole—Neul), Terrabit Networks.

Housing Development Board (HDB)

Synopsis

Objective	The aim of the project is to install a local communications platform to collate data such as sub-metering, sensors, other field related devices. The field data collected would be automatically consolidated within the field network and presented at the respective backend platform for further action.
Location	HDB blocks@Singapore
Time	Since 2013
Consortium	Power Automation under SWSPG.
Equipment	
Licensing/Bands	630-742 MHz
Conclusions	TVWS technology is expected to add efficiency in getting real time coverage, which would result in enhanced security and safety for the residents.

Status

This project is ongoing.

Summary

This TVWS project targets residential areas in Singapore. The communications platform will enable collecting different information to enhance security and safety in residential areas and provide various users a cost effective method for local connectivity to field devices installed in various corners of the estate. Below figure shows the coverage of HDB blocks.

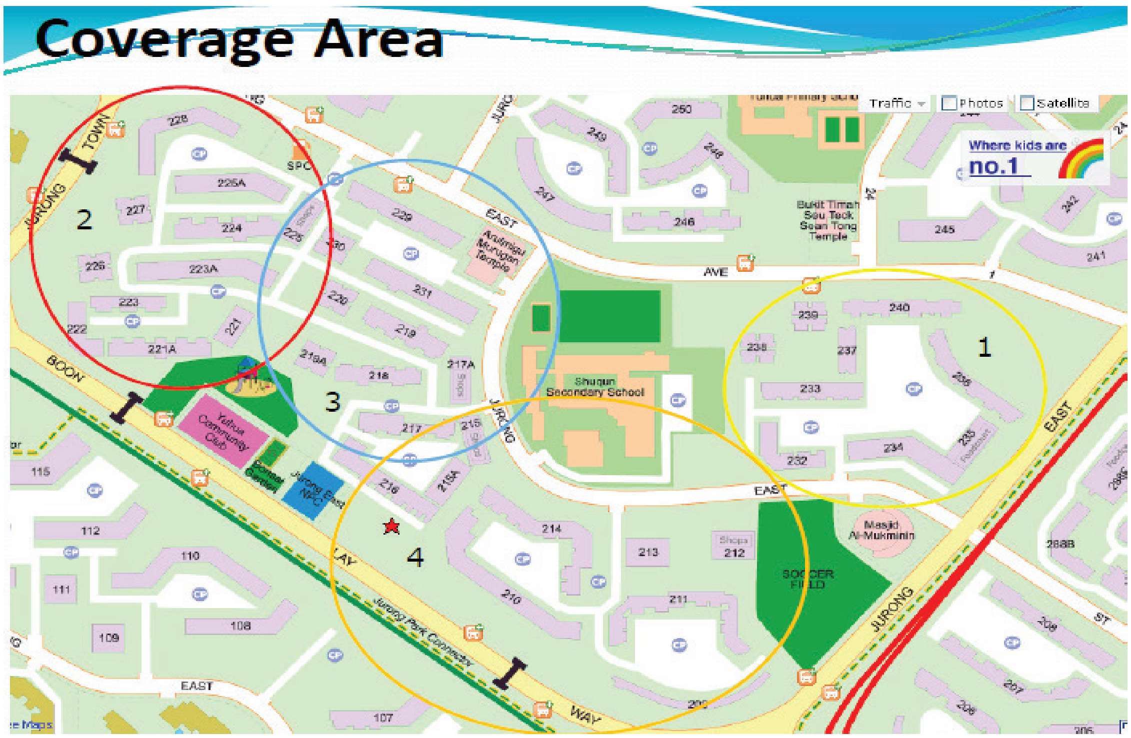


Figure 15: Coverage area of HDB blocks in Singapore.

Sentosa Island

Synopsis

Objective	To set up a TVWS communications network, providing public access to the Internet and for additional applications, such as road surveillance. To provide connectivity between Merlion and Sentosa Offices.
Location	Silos Beach, Sentosa Island, Singapore
Time	Since 2013
Consortium	Power Automation, Terrabit and NexWave under SWSPG.
Equipment	Spectrum Analyzer
Band/License	630-742 MHz
Conclusion	Though connection could be established at Siloso beach, due to high interference at Merlion area, connectivity between Merlion and Sentosa office was not stable. Stable connectivity could not be established as there was no clear frequency available at Merlion location during the period of the trial.

Status

No information available.

Summary

The aim was to set up a TVWS communications network at Sentosa Island to connect Siloso beach with Merlion are and Sentosa. The trial revealed that no clear frequency was available in the 630-742 MHz band for stable operation.

Gardens by the Bay

Synopsis

Objective	To provide free wireless internet connectivity for public users and video surveillance at location where regular events are been organized, cost-effectively.
Location	Gardens by the Bay, Singapore
Time	2013 - 2014
Consortium	Power Automation and I2R under SWSPG
Equipment	
Band/License	630-742 MHz
Conclusion	Using TVWS technology provides a scalable and cost effective solution for offering free public Wifi at the Gardens.

Summary

This project has been completed in 2014[164].

Summary

The Park management initiated this project to provide a cost-effective solution to deploy free wireless internet connectivity for public users around the main attractions at the Gardens by the Bay in Singapore as well as for video surveillance at location where regular events are been organized. TVWS technology has been integrated into various corners of the attractions, providing a scalable and cost effective solution for best user experience. The free public Wifi implemented via Wireless@ SG provides a platform for local and overseas visitors to enjoy Internet connectivity at the Gardens. The deployment at Gardens by the Bay is shown in Figure 16.

Figure 16: Deployment of WiFi access points and surveillance cameras using TVWS technology at the Gardens by the Bay, Singapore.

164 BBC News, "Singapore park becomes part of 'super-wifi' trial," 6 November 2013, http://www.bbc.com/news/technology-24822458

7.2.3.3 TVWS Trial in the Philippines

Synopsis[165]

Type	TVWS Trial
Objective	Use TVWs to provide internet access to remote fisherman villages to spur economy, health and education in the Philippines: - Improve digital literacy and competencies - Reduce geographical digital divides & promote inclusive Internet development; - Enhance Internet accessibility for people of all abilities, gender and social standing; - Ensure affordability of the Internet; - Improve Internet speed (broadband)
Location	Remote areas in the municipalities of Talibon, Trinidad, Bien Unido, Ubay and Carlos P Garcia
Time	Since July 2013
Sponsor/ Consortium	Microsoft, Department of Science and Technology's Information and Communication Technology Office (DOST-ICT Office), Department of Agriculture's Bureau of Fisheries and Aquatic Resources (DA-BFAR) and the U.S. Embassy Manila's United States Agency for International Development (USAID)
Band/License	TV Frequency Channel Allowed by Philippines' Regulator: TV Channel 42 (638-644 MHz)
Spectrum sharing level	3a
Equipment	TV White Space Technology Equipment c/o Power Automation (Base Station and CPEs)
Conclusions	Expected impact: • Social and economic integration of communities in disaster stricken areas, • Economic integration and digital opportunities for marginalized communities, • Enhanced e-learning experiences, digital competencies and e-government services.

Status

This project is active.

Summary

Wireless communications technology combined with the propagation characteristics of TV white spaces is well-suited for a country like the Philippines consisting of islands that lack communications infrastructure. Super-WiFi can transform public institutions such as clinics and public schools to e-knowledge hubs and mobile registration centers especially for fishermen located in remote areas. Local government units will be able to access the BFAR's Fisherfolk Registration System (FRS) in the field, enabling municipalities to immediately distribute critical IDs, certificates and licenses to the fishermen that need them. Government authorities will also be able to immediately access and connect to a central database to monitor compliance.

165 Department of Science and Technology - Information and Communications Technology Office (DOST-ICTO) - Philippines, "TVWS Technologies Study Program & TVWS Trial In Bohol – Philippines," http://isif.asia/projects/projects/view/583

With support from USAID's Ecosystems Improved for Sustainable Fisheries (ECOFISH) Project, the Philippine Government's economic assistance to the fisheries sector is expected to leverage "sustainable practices that seek to restore the health of the ecosystem to produce more fish, feed more people, and generate more jobs"[166].

7.2.3.4 TVWS Trial in Taiwan

Synopsis

Type	TVWS Trial
Objective	1. To create a foundation for a rollout plan for high speed wireless system to support long range high bandwidth network coverage over a large coverage area across nearby towns using the existing fiber lines. 2. To support telemedicine and outdoor wireless connectivity to villages in mountains or other remote areas with applications to sensors, meters and wireless surveillance.
Location	Fu Hsing Township, Taiwan
Time	2013
Sponsor/Consortium	Institute for Information Industry, Smart Network System Institute, Power Automation Pte Ltd
Band/License	TVWS
Spectrum sharing level	3a
Equipment	
Conclusions	Two-tier approach to extend wireless access to remote areas using back-to-back relays and TVWS technology is a practical solution for providing coverage to villages located in mountainous terrains. Approximately 5 Mbps/channel were achieved at 10.7 km distant client TVWS node for most TV channels (41, 44, 48, 50, 52, 54) with near line-of-sight deployment. The bonding of these available channels can provide higher throughput to villagers.

Status

The trials have been completed in 2013[167].

Summary

The mountainous terrain of Fu Hsing Township, Taiwan, make deployment of broadband Internet access challenging. An area of 350 km^2 can be covered from a single base/repeater station, connecting 10-20 km distant villages using TV white spaces. Each of the four remote sites can then deploy a standard 2.4 GHz WiFi hotspot to user access. Back-to-back relays can connect the TVWS base station A with the remote villages B-D. These trials are meant to lay the foundation of deploying nationwide free WiFi access for residence and tourists, supported by the government as part of the i-taiwan initiative. Remote, mountainous location can benefit from TVWS to support mobile medical cars, promote trade and tourism.

7.2.4 Africa

Several TVWS projects are ongoing in parallel in Africa with wide interest of global and local industries and governments. These commercial pilots can have a huge impact on Africa and can become a milestone for addressing the broadband access deficit in rural Africa and other unserved regions in the world.

166 Microsoft Research, "*Pilots and Demonstrations,*" http://research.microsoft.com/en-us/projects/spectrum/pilots.aspx
167 Kerk See Gim, "TV Whitespace (TVWS) in Fu-Hsing Township – proof of concept test report, version 1.0," Power Automation Pte Ltd, Sept. 2013, available at http://www.dynamicspectrumalliance.org/assets/TVWS_Field_Report.pdf

7.2.4.1 Malawi White Space Commercial Pilot

Synopsis[168]

Type	TVWS Trial
Objective	Use WiFi technology operating in TV shite spaces for providing broadband internet access to unserved rural areas.
Location	Malawi White Space Trial: Zomba, Malawi
Time	2013
Sponsor/ Consortium	University of Malawi, International Center for Theoretical Physics (Trieste, Italy), Malawi Communications Regulatory Authority (MACRA)
Band/License	
Spectrum sharing level	3a
Equipment	Carlson Wireless radios
Conclusions	For the longest tested link of 7.5 km distance between transmitter and receiver, an average SNR of 24.7 dB, data-rate of 420 kbps and latency of 118 ms were observed on average [26]. This result indicates a 2.6x propagation performance of the TVWS over commercial fixed broadband wireless access technologies. The results are valid for the dry season; equivalent trials in the rainy season are scheduled for Dec. 2014.

Status

The trials were completed in 2013. Follow up trials are planned for December 2014 during the rainy season.

Summary

The University of Malawi and International Center for Theoretical Physics (Trieste, Italy) conducted TVWS trials with support from the Malawi Communications Regulatory Authority (MACRA) to serve the rural town of Zomba. A performance improvement over other broadband access technologies has been measured on link distances of up to 7.5 km.

7.2.4.2 Microsoft's Super Wi-Fi Commercial Pilots

Synopsis

Type	TVWS Trial
Objective	Use WiFi technology operating in TV shite spaces for providing broadband internet access to unserved rural areas.
Location	Different locations in Africa: 1. Kenya "Mawingu" Commercial Pilot: Nanyuki and Kalema, Kenya 2. 2Ghana Commercial Pilot: All Nations University College and Koforidua Polytechnic 3. South Africa Commercial Pilot (Microsoft): At rural Limpopo
Time	1. since Feb. 2013 2. 2014 3. July 2013-2020

168 C. Mikeka, M. Thodi, J. S. P. Mlatho, J. Pinifolo, D. Kondwani, L. Momba, M. Zennaro, A. Moret, "Malawi Television White Spaces (TVWS) Pilot Network Performance Analysis," J. of Wireless Networking and Communications, 2014 4(1): 26-32.

Sponsor/Consortium	Different trials and teams: 1. Microsoft, Kenyan Ministry of Information and Communications, Indigo Telecom Ltd., Adaptrum 2. Microsoft, SpectraLink Wireless, Facebook 3. Microsoft, the Council for Scientific and Industrial Research (CSIR), the University of Limpopo, and network builder Multisource
Band/License	
Spectrum sharing level	3a
Equipment	Adaptrum's TVWS equipment and Microsoft's white space data base, using solar power for operation.
Conclusions	Spectrum sharing and, in particular, TVWS technology is expected to play a major role in connecting the African population to the Internet. The goal for South Africa is connecting 80 % of the population by 2020. Microsoft emphasizes educational facilities, such as schools and universities.

Status

Microsoft initiated trials in different African countries as part of the 4africa program in 2013 with a long-year plan to provide broadband access to rural areas using TVWS technology.

Summary

Microsoft sponsors broadband TVWS Internet access in Ghana as part of the 4africa program169 170 171. TV white space-enabled radios and other wireless technologies will connect campus buildings at All Nations University College and Koforidua Polytechnic, Ghana, and off-campus residencies to provide students fast broadband access. The project is operating under a TV white space pilot license granted by the Ghana National Communications Authority (NCA). A similar pilot program is ongoing in Kenya, whereas an integrated device, service and connectivity solution is targeted for university students in urban deployments in Tanzania in collaboration with the Tanzania Commission for Science and Technology (COSTECH) and UhuruOne. A local student team at University of Dar es Salaam will be involved in building the network.

Microsoft, together with the Council for Scientific and Industrial Research (CSIR), the University of Limpopo, and network builder Multisource targets providing low-cost wireless broadband access to five secondary schools in underserved parts of the Limpopo province. The project will use the University of Limpopo as a hub for a white space network deployment to provide nearby schools with wireless connectivity. Electronic devices for teaching support devices, solar panels for charging these devices, as well as training and education-related content are sponsored as well. Eventually, this pilot project will expand to achieve the target goal of 80% of the South African population being connected by 2020. Spectrum sharing and it is considered the key for achieving this.

7.2.4.3 Cape Town TVWS Trial

Synopsis

Type	TVWS Trial

169 Microsoft Research, "*Pilots and Demonstrations,*" http://research.microsoft.com/en-us/projects/spectrum/pilots.aspx

170 James Middleton, "Designing the digital dividend: Africa earmarks 700MHz band," January 13, 2014, Telecoms.com 2014, http://www.telecoms.com/209361/designing-the-digital-dividend-africa-earmarks-700mhz-band/

171 Keener Law Group, ""Super Wi-Fi" White Spaces Spectrum Goes Global," October 23, 2013, http://www.keenerlawgroup.com/super-wi-fi-white-spaces-spectrum-goes-global/

Objective	1. Demonstrate that TVWS can be used to deliver affordable broadband and Internet services without interfering with TV reception. 2. Increase the awareness of the potential for TVWS technology in South Africa and across the continent.
Location	Cape Town, South Africa
Time	For 6 months, until September 25, 2013.
Sponsor/ Consortium	TENET (tertiary Education and Research Network), CSIR Meraka, e-Schools Network, WAPA and Google with Comsol Wireless Solutions, Carlson Wireless Technologies and Neul
Band/License	470 – 694 Mhz
Spectrum sharing level	3a
Equipment	Comsol Wireless Solutions, Carlson Wireless Technologies, Neul
Conclusions	Participating schools, which previously had slow or unreliable internet connections, experienced high-speed broadband access using TVWS without causing harm on primary users. The lessons learned are: • Providing underserved schools with TVWS connectivity, coupled with capacity building (teacher training, computer upgrading), is critical to achieving increased traffic at these schools and the real benefits are what lies behind the traffic graphs. • TVWS presents an opportunity to improve broadband penetration and uptake in South African Schools and e-Schools' Network looks forward to an early rulemaking in this technology to scale it nationally 0.

Status

The trials were completed on September 25th, 2013 and the official project report was produced[172].

Summary

The first broadband TVWS trials in South Africa started early 2013 with involvement from Google, the Tertiary Education and Research Network (TENET), e-Schools Network, Wireless Access Providers' Association and Comsol Wireless Solutions[173 174].

Multiple TVWS base stations are located at Stellenbosch University's Faculty of Medicine and Health Sciences in Tygerburg, Cape Town. This network delivers broadband Internet service to ten schools within a radius of 10 km. Each school receives dedicated 2.5 Mbps service with failover to ADSL to prevent downtime during school hours[175].

While Africa is aggressively testing super-WiFi trials, similar trials have occurred in other parts of the world, including Finland, Ireland, UK, Uruguay, China, Malaysia, Indonesia, Japan, Philippines, Singapore, and North America, showing a global consensus in exploiting TV white spaces using widely-spread communications technology.

172 Albert Lysko, Moshe Masonta, Luzango Mfupe, "Report on Field measurements done on operational TVWS trial network in Tygerberg," Document Reference Number: 232603, Oct 13, 2013.

173 James Middleton, "Designing the digital dividend: Africa earmarks 700MHz band," January 13, 2014, Telecoms.com 2014, http://www.telecoms.com/209361/designing-the-digital-dividend-africa-earmarks-700mhz-band/

174 Keener Law Group, ""Super Wi-Fi" White Spaces Spectrum Goes Global," October 23, 2013, http://www.keenerlawgroup.com/super-wi-fi-white-spaces-spectrum-goes-global/

175 The Cape Town TV White Spaces Trial Web Site, www.tenet.ac.za/tvws/

7.2.5 Oceania: New Zealand Managed Spectrum Park

Synopsis[176]

Type	Managed Spectrum Park
Objective	This innovative approach was introduced by New Zealand's regulator to enable shared access to a common band for local and regional services on a cooperative, self-managed basis. The park's objective is to encourage efficient use of spectrum, innovation and flexibility with low-cost compliance and administration
Location	New Zealand
Time	Since 2009
Sponsor/Consortium	New Zealand Ministry of Economic Development
Band/License	2575-2620 MHz. Park licenses are allocated on a first come, first served fashion and provisions are in place to encourage shared use on an equal rights basis.
Spectrum sharing level	2 - Managed Shared Access
Equipment	Various
Conclusions	This regulatory mechanism was introduced to facilitate an equitable approach for achieving low-cost, shared spectrum access for regional service providers.

Status

The managed spectrum park has been in operation for over 4 years with initial licenses being granted in 2009 and with recent membership and corresponding license locations given[177] [178]. Its primary use to date in New Zealand has been the provision of rural broadband services.

Summary

The managed spectrum park is an innovative experiment by New Zealand's regulator based on encouraging a self-managed approach to the allocation and use of radio spectrum. Entry in the park is on a first-come first-served basis in each region and is both service- and technology-agnostic. Experts advise on technical feasibility, given the applied service, technology and deployment characteristics. The principle is for park licensees to resolve allocation and interference issues among themselves, with the onus to act cooperatively and responsibly. If there is more demand than supply, then ballots are drawn to reduce the number of applicants in a region.

The regulator is closely monitoring how the spectrum park is developing. To date, allocations are reported to have been "somewhat contentious as applicants have found the length of the process and possibility of challenges to be frustrating"[179]. Time will tell the degree of success of this spectrum sharing experiment and what lessons can be learned.

176 New Zealand Ministry of Economic Development, "Managed spectrum park – park rules," Feb 2009. http://www.rsm.govt.nz/cms/licensees/types-of-licence/managed-spectrum-park/managed-spectrumpark-park-rules

177 Radio Spectrum Management Web Site, managed spectrum parks, http://www.rsm.govt.nz/cms/policy-and-planning/projects/recently-completed-work/managed-spectrum-parks

178 Radio Spectrum Management Web Site, notification of applications, http://www.rsm.govt.nz/cms/licensees/types-of-licence/managed-spectrum-park/notification-of-applications

179 New Zealand Ministry of Business, Innovation and Employment, "Radio Spectrum Five Year Outlook 2012-2016," July 2013. http://www.rsm.govt.nz/cms/policy-and-planning/consultation/radio-spectrum-five-year-outlook-2012-2016/Radio_Spectrum_Five_Year_Outlook_.pdf

7.3 Observations, Lessons Learned and Recommendations

Several observations can be made when analyzing ongoing and past TVWS and DSA trials and testbeds. These observations can lead to conclusions and recommendations. We share our observations about DSA/TVWS testbeds and trials and provide our observations and recommendations on standardization and commercialization below.

Trials and test beds are done for different purposes, each requiring unique procedures.

- Most trials are done to mature technology and quantify its efficacy.
- Test beds are usually used to help define regulatory rules.
- Both trials and test beds may be used to help define a business case.
- Trials and test beds can also be used to discredit a technology. As such, bias going into a trial must be considered.

DSA/TVWS testbeds and trials: facts

- Many universities are involved in DSA trials and testbeds, but little industry implication (with exceptions, such as TVWS and the recent and ongoing SAS trials).
- Commercial TVWS pilot programs are ongoing around the world.
- The US develops the majority of TVWS radio equipment used worldwide (see Section 10).
- Results of trials and testbeds are more significant if operating in actual radio environments and using actual radio equipment.
- Quick test setup, measurement, analysis and publication of results enables rapid learning that cab have significant impact on future trials and commercial products.
- Slow and thoroughly-planned testbeds/trials can slowdown development or miss the market opportunity.
- Freely accessible testbeds and open-source software lower the barrier for education and research.
- Sharing of test and environmental parameters enables obtaining reproducible results using the same testbed and, possibly, across testbeds.

Standardization and commercialization: observations and recommendations

- Despite the push from national Governments, such as DARPA's XG and WNaN programs in the US, DSA trials and testbeds have not yet made the transition to commercial deployment.
- Push from industry and test equipment manufacturers is needed for the deployment of spectrum sharing technology.
- The definition of spectrum sharing test metrics and efficient test procedures are necessary for establishing common standards as the basis for commercialization.
- There are numerous indoor use cases, but little has been found on indoor trials and realistic indoor test beds
- Just like the standardization of cellular communications systems is driven by big industry players, DSA standardization needs industry support (See Section 8)

7.4 Conclusions and Outlook

TVWS technology is widely adopted in all five continents, underlined by the many past and ongoing trials and success stories. TVWS-capable transceivers are available from several vendors today and databases support their successful deployment. The application of TVWS radios ranges from providing broadband access to remote locations, where other infrastructure types—e.g., cellular or wired—are economically infeasible, to providing value added services, such as video surveillance, by exploiting unused VHF and UHF spectrum. The good propagation characteristics of these bands make TVWS an excellent candidate for providing Internet access to underserved, unserved, or remote locations.

However, current TVWS technology has limitations in terms of range, bandwidth (e.g., channel bonding), dynamic resource reservations/allocations, coordination and adaptation of transceivers in real-time. This is a drawback worthwhile addressing as indicated by the Broadband Center of Excellence (BCoE) of the University of New Hampshire[180]. Whereas similar or synergistic TVWS trials have been carried out around the world, a common measurement procedure, business model, or deployment strategy is missing. Many these trials focus on underserved communities in rural areas and deal with different propagation challenges, such as rugged terrain, heavy foliage, and low teledensity. It appears that the deployment of TVWS technology follows a methodology that is tailored for the particular use case and location, rather than assuming a common set of deployment metrics, procedures and performance targets. We have not found indications for clear standardization incentives as a result of the individual or series of trials.

BCoE suggests to "provide an open test environment, test equipment, test process and procedures involving industry vendors, university resources […] and/or other participants that can help speed time to market." Mass-market deployment of TVWS needs strong leadership and governance as well as protection of TVWS channels from being licensed.

In similar regard, it is of utmost importance to align governmental and standardization efforts for the definition of test metrics and procedures with the commercial development cycle. Testing needs to be timely. Long test development cycles can hinder the success of promising products. The commercial development cycle is typically much faster than the government development (and approval) cycle and devices can become obsolete if the gap between the launch of a new device and testing is too wide.

At the DSA testbed side, integration with networking and distributed computing in a virtualized environment seems to be the current trend. The University of Utah's Emulab, for instance, offers what they call a *public facility* that allows doing research on the radio access and networking sides[181]. It provides access to 802.11 nodes, spread among a multi-floor office building as well as USRP/GNU Radio SDR nodes scattered around the Merrill Engineering Building on the University of Utah campus. Emulab is primarily used by computer scientist researchers in the field of networking and distributed systems, but access to radio nodes can merge this with spectrum sharing research. Geni similarly, supports *"at scale" research in networking, distributed systems, security and novel applications in real-world conditions*[182]. Geni wireless resources are deployed at several US campuses, enabling education and research on computer networks, wireless communications and mobile computing, and, why not, spectrum sharing?

Further Reading

T. Irnich, J. Kronander, Y. Selen, and G. Li, "*Spectrum Sharing Scenarios and Resulting Technical Requirements for 5G Systems*," 2013 IEEE 24th International Symposium on Personal, Indoor and Mobile Radio Communications (PIMRC Workshops).

180 Broadband Center of Excellence, "TV white space: ready for prime time? – Assessing practical realities of a share-spectrum approach for broadband Internet access," *Broadband Intelligence Series*, University of New Hampshire, Jan 2014.

181 Emulab - Network Emulation Testbed Home Page, http://www.emulab.net/

182 Geni - Exploring Networks of the Future Web Site, http://www.geni.net/

D. Cabric, I. O'Donnell, M. Chen, and R.W. Brodersen, "*Spectrum Sharing Radios*," IEEE Circuits and Systems Magazine, 2006.

J. Boksiner, K. Chang, P. Costello, R. Huck, T. Leising, M. Zankel, Y. Posherstnik, M. Totaro, T. Mai, and J. Molnar, "*Testing of Policy-Based Dynamic Spectrum Access Radios*," The 2010 Military Communications Conference - Unclassified Program - Waveforms and Signal Processing Track.

T. Leising, D. Barton, K. Chang, M. Blair, F. Hasan, A. Pavlotskiy, D. Davis, and M. Totaro, "*64 Radio Node Testbed for Dynamic Spectrum Access Investigations Using GNU Radio*," 2010 IEEE International Conference on Wireless Information Technology and Systems (ICWITS), Sept 2010.

Rahman, Mohammad Azizur, Chunyi Song, and Hiroshi Harada. "Design Aspects of a Television White Space Device Prototype." *Vehicular Technology Conference (VTC Spring), 2012 IEEE 75th*. IEEE, 2012.

A. B. Flores, R. E. Guerra, E. W. Knightly, P. Ecclesine, S. Pandey, "IEEE 802.11af: A Standard for TV White Space Spectrum Sharing," IEEE Communications Magazine, pp. 92-100, Oct. 2013.

T.G. Leng, "Spectrum-Sharing Research and Policy Formulation in Asia-Pacific," Presentation, July 21 2010, iDA Singapore, http://www.its.bldrdoc.gov/media/33655/TanISART-Spectrum%20Sharing%20in%20Asia%20Pacific%20210710.pdf

iDA–Infocomm Development Authority of Singapore, "White Space Technology Trials." https://www.ida.gov.sg/~/media/Files/PCDG/Licensees/SpectrumMgmt/SpectrumNumMgmt/CognitiveRadioVenues.pdf

8

Relevant Standards Development

8.1 Implementation Standards

8.1.1. The ETSI TV White Space Harmonised Standard

8.1.1.1 Introduction

In order for TVWS devices to operate in Europe, they need to obtain a CE marking that shows that they operate in an appropriate manner. To do so they need to conform to any appropriate regulations. However, at present there are no specific regulations in Europe for the operation of TVWS devices, although the CEPT Reports 185 and 186 provide guidance on how such devices would be expected to operate, and these are expected to provide the basis for national Regulations.

For the benefit of equipment vendors, the framework for operation given in the CEPT Reports 159, 185 and 186 has been used by ETSI (the European Telecommunication Standards Institute) to develop a (draft) European "Harmonised Standard" for such devices. The 8.1 Harmonised Standard is actually intended to ensure that the TVWS devices comply with Article 3.2 of the European Radio and Telecommunications Terminal Equipment (R&TTE) Directive, which stipulates that all equipment " … shall be so constructed that it effectively uses the spectrum allocated … so as to avoid harmful interference." Compliance with Article 3.2 of the R&TTE Directive is a key requirement for enabling the equipment to be labelled with a "CE Mark," and hence being permitted to be placed on the market in Europe.

The document will be published as EN 301 598, under the title of "White Space Devices (WSD); Wireless Access Systems operating in the 470 MHz to 790 MHz frequency band; Harmonized EN covering the essential requirements of article 3.2 of the R&TTE Directive."

The Harmonised Standard contains "essential requirements" with which all TVWS devices must comply; these are identified in Section 4 of the Harmonised Standard. The test methods to be undertaken in order to determine whether the equipment complies with those requirements are then detailed in Section 5 of the Harmonised Standard.

8.1.1.2 Scope of the Harmonised Standard

The Harmonised Standard is intended to apply to all TVWS devices used for communications purposes, fixed and movable, operating under the control of a "TVWS database." It has been written to follow the general architecture described in the ECC Reports 185 & 186, consisting of a master device operating as a base station, and slave devices operating as user terminals under the control of the master device. The master device will interrogate a TVWS database to determine the permitted operational parameters for both itself and its associated slave devices.

183 Based on text prepared by Johnny Dixon of BT.

Two types of TVWS devices are identified, namely:

- Type A which is intended for fixed use only[184].
- Type B which is not intended for fixed use.

Not all devices are expected to have a geo-location capability (typically, but not exclusively an in-built GPS receiver), although there may be advantages in the equipment having the capability.

For Type A devices, there is no requirement for the equipment to have a geo-location capability, given that it may be permitted (according to national regulations) for the location of the equipment to have been recorded when it was installed. That location would then be made available to the database through an alternative route, such as a management layer. This is expected to be only permitted for "professionally installed" equipment, according to an agreement between the TVWS network operator and the national regulatory authority. However it is envisaged that the location of all Type A master devices must be known. Since Type A master devices will not be permitted by the TVWS database to operate if there is no location information for the device, then clearly a Type A master device that is not installed and operated subject to an agreement with the national regulatory authority for the location to be recorded manually, will be useless without a geo-location capability.

All Type B master devices must contain a horizontal geo-location capability, in order for the device to automatically determine its position in latitude and longitude.

Slave devices (both Type A and Type B) do not require a geo-location capability, since their approximate location can be deduced from their reception of a signal from a master device. If they do not have any geo-location capability then they will only be able to operate in accordance with the Generic Operational Parameters. If a slave device has a geo-location capability then it can request "Specific Operational Parameters."

In all cases a vertical geo-location capability (either altitude above sea level, or height about the local terrain) is optional. If the vertical geo-location is not known, then any calculations relating to interference (and hence permitted TVWS transmitter power) will take conservative assumptions about the altitude / height of the device, and therefore it will be advantageous to convey to the TVWS database the height/altitude of the device if it is known.

Like most other radio equipment Harmonised Standards (under Article 3.2 of the R&TTE Directive), EN 301 598 specifies the performance of the key radio specific parameters. In addition it includes the operation of the "Control and Monitoring" functions, which will be an essential part of the cognitive operation of the TVWS Devices.

8.1.1.3 Key Radio Specific Parameters

The Harmonised Standard specifies the performance of the key radio-specific parameters, such as RF power, RF power spectral density, and unwanted emissions to ensure that the device is operating appropriately. Normally a Harmonised Standard would specify fixed limits for these parameters, and the equipment will be tested to ensure that its emissions do not exceed these limits. However this Harmonised Standard is an unusual case given that there are no specific regulatory limits for the RF power and RF power spectral density. The maximum RF power and RF power spectral density for any device (in operation) will be specified by the controlling TVWS database, based on the operational and device specific characteristics of the device. It has been suggested that TVWS devices are unlikely to be allowed to emit more than 4 W (36 dBm) EIRP in an 8 MHz wide channel, and a corresponding power spectral density of 50 mW/(100 kHz) (i.e. 17 dBm/(100 kHz)) EIRP, however this has not been specified in a regulation, and therefore it would not have been appropriate to

184 Type A equipment can use an external antenna (defined as "a removable antenna which is designed for use with a broad range of radio equipment and has not be designed for use with a specific product") whereas Type B is not permitted to use such an external antenna.

include this limitation in the Harmonised Standard. Instead, it was concluded that the transmit power from the equipment should be measured, for a given configuration, to ensure that the actual emitted power does not exceed the intended value.

The unwanted emissions (both out-of-band and spurious) within the 470 – 790 MHz band will be defined by the device emission class. Transmitters with good filtering and hence low unwanted emissions will be able to declare as having a better device emission class. Given that such devices will have better compatibility with incumbent users, they would normally gain in terms of higher permitted transmitter powers (or permission to use channels that poorer filtered devices cannot use). The device emission classes are defined by a relative mask (according to the "Adjacent Frequency Leakage Ratio"), subject to an absolute limit at -84dBm/(100kHz) which will apply for very low power devices. The equipment will be tested to ensure that it complies with the appropriate emission mask for its declared emission class.

The unwanted emissions outside the 470 – 790 MHz band are defined as absolute levels, in accordance with the usual CEPT limits.

8.1.1.4 Control and Monitoring Functions

As previously mentioned, the Harmonised Standard has been written for TVWS networks operating (as described in ECC Report 186) on the basis that TVWS devices will be either master devices, providing a base station like function, or slave devices which will act as user terminals. There will also be a TVWS database, which acts as a controller and provides information to the master device regarding the permitted operation for both the master device and its associated slave devices. The Harmonised Standard specifies and tests the necessary interactions between the master device and the TVWS database, and also between the master and slave device(s). However it is important to recognise that this is only for the purpose of testing the performance of the master and slave devices, and not for testing the performance of the TVWS database. It is anticipated that the TVWS databases will operate on a national basis, and hence it will be the responsibility of the appropriate national regulatory agency (rather than the Harmonised Standard) to ensure that any such national databases are operating appropriately.

The Harmonised Standard contains a set of requirements and tests, the purpose of which are to ensure that:

- A master device does not transmit without obtaining Operating Parameters from an authorised database;
- A slave device does not transmit without associating with a master device;
- Both the master and slave device transmit in accordance with the Operating Parameters supplied by the database.

The intended operation of these different components (master device, slave device and database) is described in the following sections.

8.1.1.5 Conclusion

The Harmonised Standard has not yet been finally published, as it has progressed from a consultation stage and is currently at the approval stage; this is expected to be completed in early 2014, with final publication anticipated a few months later. However when a draft standard reaches the consultation stage, it is normally considered to be a stable draft, and a suitable basis for equipment vendors to use for their system designs. The text of the Harmonised Standard has been developed with the co-operation of both equipment vendors and national regulatory authorities, and represents a balanced solution to meet their various requirements.

Harmonised Standards can and do evolve, as the technology develops, and given that TVWS is a nascent technology it would be surprising if there were not to be future revisions of this Harmonised Standard. However, these would normally be evolutions of the first version, and the basic principles described here would not be expected to change significantly; forthcoming revisions of the Harmonised Standard would incorporate lessons learnt from "first generation" equipment, as well as the inclusion of new requirements which are identified. Recognising that there are currently no European regulations for the operation of TVWS devices, the work in ETSI has anticipated the requirements which will be required by any national regulations, as well as any forthcoming European regulations which might subsequently appear. Clearly these regulations might include requirements which have not been anticipated, and which would require the Harmonised Standard to be updated accordingly.

In the event that the Harmonised Standard were to be revised in the future, this would not necessarily present a problem for equipment which has been tested and shown to be compliant to a previous version. Radio equipment should comply with a Harmonised Standard which applies at the time that the equipment is first sold, and any subsequent revision of the Harmonised Standard does not necessarily impact on radio equipment which is already in use.

In closing, this section has summarised the requirements in the draft Harmonised Standard (EN 301 893), and which are expected to be used for the testing of the first generation of TVWS equipment operated in Europe.

8.1.2 ETSI TC RRS[185]

8.1.2.1 Roles & Activities

The work of standardizing Reconfiguration through Radio Applications and Cognitive Radio is done in TC RRS (Reconfigurable Radio System). TC RRS's main responsibility is to carry out standardization activities related to Reconfigurable Radio Systems encompassing both Reconfiguration through Radio Applications and Cognitive Radio (CR). In doing so, TC RRS will take into account all the related requirements from relevant stakeholders, as well as the work done in other fora on the same subject so as to avoid overlapping activities which could delay, if not hamper, the overall standardisation process in reconfigurable radio systems. TC RRS work includes but is not limited to the following:

- Cognitive Radio Systems
- (TV) White Spaces
- Licensed Shared Access
- Reconfigurable Mobile Devices
- Certification aspects for Dynamic Equipment Reconfiguration
- Reconfigurable Radio Systems for Civil Security
- Security aspects for Reconfigurable Radio Systems

In addition to TC RRS, JTFER (Joint Task Force ERM RRS) is responsible for developing European Norms (ENs) intended to become Harmonised Standards for Reconfigurable Radio Systems.

8.1.1.2 Standards

Standard No.	Standard title.
TR 102 967	Reconfigurable Radio Systems (RRS) ; Use Cases for dynamic equipment reconfiguration
TS 103 146-1	Reconfigurable Radio Systems (RRS); Mobile Device Information Models and Protocols; Part 1:Multiradio Interface (MURI)
TR 102 947	Reconfigurable Radio Systems (RRS); Use Cases for building and exploitation of Radio Environment Maps (REMs) for intra-operator scenarios
TR 102 945	Reconfigurable Radio Systems (RRS); Definitions and abbreviations

185 http://www.etsi.org/technologies-clusters/technologies/radio/reconfigurable-radio

TR 103 067	Reconfigurable Radio Systems (RRS); Feasibility study on Radio Frequency (RF) performance for Cognitive Radio Systems operating in UHF TV band White Spaces
TS 103 095	Reconfigurable Radio Systems (RRS); Radio Reconfiguration related Architecture for Mobile Devices
TR 102 970	Reconfigurable Radio Systems (RRS); Use Cases for spectrum and network usage among Public Safety, Commercial and Military domains
TR 102 907	Reconfigurable Radio Systems (RRS); Use Cases for Operation in White Space Frequency Bands
TR 102 684	Reconfigurable Radio Systems (RRS); Feasibility Study on Control Channels for Cognitive Radio Systems
TS 102 969	Reconfigurable Radio Systems (RRS); Radio Reconfiguration related Requirements for Mobile Devices
TR 102 944	Reconfigurable Radio Systems (RRS); Use Cases for Baseband Interfaces for Unified Radio Applications of Mobile Device
TR 103 063	Reconfigurable Radio Systems (RRS); Use Cases for Reconfigurable Radio Systems operating in IMT bands and GSM bands for intra-operator scenarios
TR 103 062	Reconfigurable Radio Systems (RRS) Use Cases and Scenarios for Software Defined Radio (SDR) Reference Architecture for Mobile Device
TR 102 839	Reconfigurable Radio Systems (RRS); Multiradio Interface for Software Defined Radio (SDR) Mobile Device Architecture and Services
TR 103 064	Reconfigurable Radio Systems (RRS); Business and Cost considerations of Software Defined Radio (SDR) and Cognitive Radio (CR) in the Public Safety domain
TR 102 803	Reconfigurable Radio Systems (RRS); Potential regulatory aspects of Cognitive Radio and Software Defined Radio systems
TR 102 733	Reconfigurable Radio Systems (RRS); System Aspects for Public Safety
TR 102 802	Reconfigurable Radio Systems (RRS); Cognitive Radio System Concept
TR 102 745	Reconfigurable Radio Systems (RRS); User Requirements for Public Safety
TR 102 838	Reconfigurable Radio Systems (RRS); summary of feasibility studies and potential standardization topics

8.1.3 IEEE DySPAN-SC

The IEEE Dynamic Spectrum Access Networks Standards Committee (DySPAN-SC) has roots in the establishment of the IEEE 1900 committee in the first quarter of 2005, as the Committee responsible for IEEE 1900 standards[186]. This was under the joint sponsorship of the IEEE Communications Society (ComSoc) and the IEEE Electromagnetic Compatibility (EMC) Society. In March 2007, the IEEE Standards Board approved the reorganization of the IEEE 1900 Committee as Standards Coordinating Committee 41 (SCC41), on the topic of "Dynamic Spectrum Access Networks" (DySPAN). IEEE ComSoc and the IEEE EMC Society remained the supporting societies. IEEE SCC41 was approached in late 2010 by ComSoc, who expressed a wise for SCC41 to be brought back directly under its sponsorship. In December 2010, SCC41 approved the decision to be brought back under ComSoc, whereby this changed structure required that SCC41 undergo a name/title change. The new name/title of IEEE DySPAN-SC was quickly settled on.

IEEE DySPAN-SC is responsible for the IEEE 1900 series standards, which are broadly on the topic of DySPAN and related technologies such as Dynamic Spectrum Access (DSA), Cognitive Radio (CR) and TV White Spaces (TVWS), among

186 IEEE DySPAN Standards Committee (DySPAN-SC), http://www.dyspan-sc.org, accessed May 2014

others. Many of the standards that are worked on and developed by IEEE 1900 working groups take an overarching viewpoint, intending to be either broadly applicable to generic concepts among a range of systems (e.g., the terms and definitions harmonization work of IEEE 1900.1 or the heterogeneous networks management scope of IEEE 1900.4, among other examples), or applicable to a wide range of use cases (e.g., the white spaces radio interface standard of IEEE 1900.7, among other examples)[187 188 189]. Such directions perhaps result more from historical developments and observations of DySPAN-SC members; it is not explicitly stated as being the objective for IEEE 1900 standards to follow broad/overarching scopes, and accordingly IEEE 1900 standards addressing very constrained topics are also welcome.

The current IEEE 1900 working groups are as follows:

- IEEE 1900.1: "Definitions and Concepts for Dynamic Spectrum Access: Terminology Relating to Emerging Wireless Networks, System Functionality, and Spectrum Management,"
- IEEE 1900.2: "Recommended Practice for the Analysis of In-Band and Adjacent Band Interference and Coexistence Between Radio Systems"[190],
- IEEE 1900.3: "Recommended Practice for Conformance Evaluation of Software Defined Radio (SDR) Software Modules" (disbanded)[191],
- IEEE 1900.4: "Architectural Building Blocks Enabling Network-Device Distributed Decision Making for Optimized Radio Resource Usage in Heterogeneous Wireless Access Networks,"
- IEEE 1900.5: "Policy Language and Policy Architectures for Managing Cognitive Radio for Dynamic Spectrum Access Applications"[192],
- IEEE 1900.6: "Spectrum Sensing Interfaces and Data Structures for Dynamic Spectrum Access and other Advanced Radio Communication Systems"[193],
- IEEE 1900.7: "Radio Interface for White Space Dynamic Spectrum Access Radio Systems Supporting Fixed and Mobile Operation."

8.1.3.1 P1900.1

IEEE 1900.1 was instantiated in March 2005 under the realisation that many of the terms used in the fields of spectrum management, policy-defined radio, adaptive radio, software-defined radio, reconfigurable radio and networks, and related technologies, do not have precise definitions or have multiple/unclear definitions. IEEE 1900.1 was created to facilitate development of such technologies by clarifying the terminology and aspects of how these technologies relate to each other. The base 1900.1 standard was published in 2008 (denoted as IEEE Std 1900.1™-2008), and an amendment covering new terms and definitions that have emerged since the publication of the base standard particularly in the scope of other IEEE 1900 working groups was published in January 2013 (denoted as IEEE Std 1900.1a™-2012, given that it was approved in 2012). Since then, IEEE 1900.1 has been working on a revision of its published 2008 standard, which will also incorporate the text of the IEEE 1900.1a-2012 amendment as is standard procedure for such periodic IEEE standard revisions. The IEEE "Project Authorization Request (PAR)" for this revision was approved by the IEEE Standards Board on the 6 March 2013, and the expected latest time by which the work of IEEE 1900.1 will be completed as specified by this PAR is the end of

187 IEEE 1900.1 working group, http://grouper.ieee.org/groups/dyspan/1/index.htm, accessed May 2014
188 IEEE 1900.4 working group, http://grouper.ieee.org/groups/dyspan/4/index.htm, accessed May 2014
189 IEEE 1900.7 working group, http://grouper.ieee.org/groups/dyspan/7/index.htm, accessed May 2014
190 IEEE 1900.2 working group, http://grouper.ieee.org/groups/dyspan/2/index.htm, accessed May 2014
191 IEEE 1900.3 working group, http://grouper.ieee.org/groups/dyspan/3/index.htm, accessed May 2014
192 IEEE 1900.5 working group, http://grouper.ieee.org/groups/dyspan/5/index.htm, accessed May 2014
193 IEEE 1900.6 working group, http://grouper.ieee.org/groups/dyspan/6/index.htm, accessed May 2014

2017. However, IEEE 1900.1 is striving to complete its work within a shorter timescale than that.

The published IEEE 1900.1-2008 standard includes terms and definitions in the following categories: "Definitions of advanced radio system concepts," "Definitions of radio system functional capabilities," "Definitions of network technologies that support advanced radio system technologies," "Spectrum management definitions," and a "Glossary of ancillary terminology." Further, the IEEE 1900.1a-2012 amendment has added the category of "Definitions of decision making and control concepts that support advanced radio system technologies." Further, the Annexes of the published 2008 standard cover a number of informative aspects, such as the consideration of the implications of DySPAN and related technologies (e.g., for regulation), some detailed consideration of the natures of the technologies, such as the relationships between then, commentary on their purposes and aspects of architecture (e.g., a detailed study on the different forms of flexible radio, among other content), and roadmapping for such technologies, among other aspects.

8.1.3.2 P1900.2

The IEEE 1900.2 standards work was initiated in March 2005, and the standard (IEEE Std 1900.2™-2008) was published July 2008. IEEE 1900.2 provides technical guidelines for analyzing the potential for coexistence or interference between radio systems operating in the same frequency band or between different frequency bands. In that sense, IEEE 1900.2 facilitates a range of spectrum coexistence technologies, assisting assessment of their potential for realisation in a viable way.

The published IEEE 1900.2-2008 includes a range of normative content, such as the specification a key concepts such as "harmful interference" and "measurement events," among others, the definition of scenarios for interference assessment, interference assessment criteria and important variables, and comment on the analysis and modelling of interference.

Since the publication of IEEE 1900.2-2008, the IEEE 1900.2 working group has been dormant.

8.1.3.3 P1900.3

The IEEE 1900.3 standards work was initiated in May 2005, but the working group was disbanded in late 2008. The standard was to provide guidance on how to estimate the conformance with relevant specifications of software intended for deployment into a SDR terminal. Concepts and methods to be used in these analyses were to be detailed, and the standard was intended to support quality control and testing. Given a range of issues that could be caused by SDR devices being hacked and misbehaving, for example, although this group is disbanded such work is still extremely relevant to assuring the correctness of the SDR modules.

8.1.3.4 P1900.4

The IEEE 1900.4 standards work was initiated in February 2007, and the base IEEE 1900.4 standard (IEEE Std 1900.4™-2009) was published in February 2009. IEEE 1900.4 aims to improve overall composite capacity and quality of service of wireless systems in multiple radio access technology environments by defining an appropriate system architecture and protocols to facilitate the optimization of radio resource usage. It specifies a three-level resource management hierarchy: the network or inter-network level, RAN level, and terminal level. These levels are managed by two key components: the Network Reconfiguration Manager (NRM) and Terminal Reconfiguration Manager (TRM), in conjunction with other functions such as the Operator Spectrum Management (OSM) entity. IEEE 1900.4 has also published an amendment to the published 1900.4-2009 standard in the form of 1900.4a (IEEE Std 1900.4a™-2011), "Architecture and Interfaces for Dynamic Spectrum Access Networks in White Space Frequency Bands," as well as an additional standard 1900.4.1 (IEEE Std 1900.4.1™-2013), "IEEE Standard for Interfaces and Protocols Enabling Distributed Decision Making for Optimized Radio Resource Usage in Heterogeneous Wireless Networks." It is noted that IEEE 1900.4 facilitates a range of spectrum coexistence technologies of interest to ACROPOLIS, although particularly emphasises those that are network driven, as might be managed by an operator, for example, with a range of spectrum bands and radio access technologies available which can adapt to operation in different bands.

The published 1900.4-2009 base standard first covers system deployment aspects including the use cases of the standard. Three broad use cases are defined:

- Dynamic spectrum assignment,
- Dynamic spectrum sharing,
- Distributed radio resource usage optimization.

Regarding the dynamic spectrum assignment use case, frequency bands are dynamically assigned to radio access networks in order to optimize spectrum usage. In other words, the assigned frequency bands can be dynamically changed. Regarding dynamic spectrum sharing use case, the frequency bands have a fixed assignment to radio access networks, however, each a particular frequency band might be shared between two or more radio access networks. In other words, the dynamic spectrum sharing use case describes how fixed frequency bands are shared and/or used dynamically by radio access networks and terminals. Regarding the distributed radio resource usage optimization use case, frequency bands again have a fixed assignment to radio access networks. Reconfiguration of radio access networks is not considered in this use case. The distributed radio resource usage optimization use case considers terminals with or without multi-homing capability. Decisions on terminal reconfiguration can be made by the TRM embedded in the terminal, and are supported by the NRM on the network side. The NRM analyzes context information, and can dynamically generate radio resource selection policies using that information and forward the policies to the associated TRMs in terminals. These radio resource selection policies will guide the terminal-side entities in their reconfiguration decisions, although may leave some scope for the TRMs to optimise their decision autonomously, depending on the scenario. The TRMs take decisions with the objectives of improving various aspects of spectrum usage (e.g., efficiency) and quality of service.

Other content in the published 1900.4 standard considers the system, functional and information model requirements (e.g., what the system must achieve, what must be interfaced, etc.), the architectural description (e.g., elements that are introduced, functions that the standard performs), the information model (e.g., the structuring of information for communicating between the 1900.4 elements), and procedures. Annexes cover extensive normative detail such as on the detailed definitions (e.g., of classes and data types) for the information model, as well as informative detail expanding on use case options, information model extensions, deployment examples and other aspects.

The IEEE 1900.4a-2011 standard considers extensions to the management cases in 1900.4 for where mobile access also makes use of TVWS, without any implied constraints on the used radio interface (physical and media access control layers, carrier frequency, etc.), by defining additional components of the IEEE 1900.4a system. This standard aims to facilitate cost-effective and multi-vendor production of wireless systems capable of operation in white space frequency bands. A key addition in 1900.4a is the White Space Manager (WSM), which provides regulatory context information to the networks or composite systems that might be using TVWS. In the network-side the Cognitive Base Station Manager (CBSRM) is also introduced, in order to enable the control of the of the base station's white space access according to the regulatory rules and flexibility that is allow based on context information, and a mirroring entity to control the terminal side in white space is also introduced.

The IEEE 1900.4.1-2013 standard provides a description of the interfaces and service access points defined in the baseline 1900.4-2009, enabling distributed decision making in heterogeneous wireless networks and obtaining context information for this decision making. This standard delves into more detail on the information exchanges between the 1900.4 elements, and the associated state transitions of those elements based on the information exchanges. It considers precise signalling interactions for the purpose of implementing 1900.4 decision, among other elements. Noting that the information model in 1900.4-2009 was abstract in the sense of specifying only the high-level ASN.1 characteristics and requirements, 1900.4.1-2013 delves down to the level of precise bit-level header structures.

8.1.3.5 P1900.5

Introduction

The IEEE P1900.5 Working Groups are under the umbrella if the IEEE P1900 working groups which collectively make up the IEEE Dynamic Spectrum Access Networks (DySPAN) Standards Committee (DySPAN-SC). The general charter for P1900.5 is to develop standard on policy language and policy architectures for managing cognitive radio for dynamic spectrum access (DSA) applications.

The current chair of the IEEE 1900.5 Working Group (WG) is Dr. Matthew Sherman of BAE Systems. The WG Vice Chair is Darcy Swain-Walsh of MITRE Bryan May of US Army CERDEC in the WG Secretary. The WG website can be found at: http://grouper.ieee.org/groups/dyspan/5/index.htm.

The IEEE std 1900.5TM-2011 defines a vendor-independent set of policy-based control architectures and corresponding policy language requirements for managing the functionality and behavior of dynamic spectrum access networks. The scope of the IEEE 1900.5 working group is set by this standard and assigned project authorization requests (PAR) of which there are currently two (P1900.5.1 and P1900.5.2).

The IEEE std 1900.5TM-2011 was published in January 2012. Follow on work for P1900.5.1 and P1900.5.2 is in progress. An overview of the IEEE 1900.5 working group efforts can be found in Section 8.1.3.5.2.

The P1900.5 standard specifies policy language (PL) requirements and policy architectures for policy-based DSA radio systems. In this standard, a distinction is made between the policy reasoning that is accomplished within the Policy Based Radio (PBR) node and policy generation and validation that is accomplished through a policy generation system prior to provision of the policy to the PBR node. Policy reasoning may be distributed, i.e. it may take place either within a PBR node or in other elements of a policy based radio communications network.

To evaluate potential options for policy languages, the basic requirements for the language were determined in developing the IEEE 1900.5 standard. In summary they are:

- A declarative language shall be used.
- A policy language shall have clear and unambiguous syntax and semantics.
- The policy language shall have the capability for annotations.
- The policy language shall have a machine-understandable syntax.
- The policy language may have an easily human understandable syntax.
- The policy language shall support permissive policies and restrictive policies.
- The policy language shall be capable of expressing inheritance and extension of policies.
- The language shall be capable of specifying the dynamics (behaviors), including temporal aspects, of policy based dynamic spectrum access radio system components.
- The policy language shall include the ability to introduce definitions of new functions in terms of other known functions and allow inferring relationships between two functions, such as whether two functions are equivalent or not.
- The expressivity of the policy language shall include the following: Classes, Individuals, Binary relations, Composition of relations, Functions, Temporal aspects of the system, Behavioral descriptions, State of the system, and Rules)
- The policy language shall be explicit about which negation [logical negation or negation as failure (NAF)] it supports.

There are two basic categories of policy: regulatory policy and mission policy. Regulatory policy is time/frequency/ spatial dependent operational constraints established by local regulatory bodies. Regulatory policy shall replace the current command and control based regulatory policy protocols in current use. Mission policy is user generated policy which delivers to the DSA radio the current user operational requirements. Regulatory policy takes precedence over mission policy.

At some point in the development of IEEE P1900.5 in became apparent that the scope of cognitive radio was rapidly expanding beyond DSA, beyond the physical (PHY) layer and beyond radio only to radio frequency (RF) systems in general. Additionally it was realized that multiple like and diverse systems must operate cooperatively in a game theoretic sense. As a result and given the rapid evolution of constituent technologies and capabilities, it was determined that the standard could not preclude the instantiation of additional capabilities in the foreseeable future. Examples of these capabilities include but are not limited to: coexisting systems, distributed cognition, distributed sensing and cross layer optimization. This implied requirement for non restrictive standardization is also a consideration in the current works in progress.

Existing standard

The IEEE Standard 1900.5TM-2011 defines a vendor-independent set of policy-based control architectures and corresponding policy language requirements for managing the functionality and behavior of dynamic spectrum access networks. In this section the policy-based control architecture of the standard is summarized at a high level for introduction.

The policy-based DSA radio system (PBDRS) functional architecture device authorization process and accreditation of its policy conformance mechanism the policy is separable from the detailed system behavior. Regulators will be able to accredit radios based on the ability to interpret policies correctly to obtain desired behavior rather than the command and control method of verifying the conformance of a fixed set of behaviors programmed into the radio at the time of manufacture. The accredited portion of the radio enforces the regulatory policy. The system (or mission) policy, which is enforced outside the accreditation boundary, will provide opportunities for innovation, including proprietary optimization techniques or other added value, by a radio manufacturer or service provider. The system components that check policy conformance are separate from those that are radio specific and optimize performance.

The PBDRS has a component that allows for policy conformance reasoning. The policy conformance reasoner should support reasoning about state-dependent behaviors and temporal reasoning. The policy conformance reasoner should be able to specify how the radio should react for any given state and to what state it should transition. The policy conformance reasoner should also be able to reason about previous and future states, events and state transitions. The PBDRS shall define a functional capability that allows for system strategy reasoning.

The PBDRS shall define a policy management component that allows for the management and distribution of policies. It shall be possible for a policy authority to revoke or amend any type of policy or invoke new policy. It shall be possible to associate a time period and geographic area with a policy to identify the time period and/or geographic policy domain in which the policy is in force. The policy shall provide evidence of the source of a policy that cannot be repudiated.

The PBDRS shall be structured such that comparisons of policies from different sources can be compared and shall permit the resolution of differences in the case of incompatibility or inconsistency of policies that originate from different sources. it shall support mechanisms to enable the logging of policy processing. The architecture shall provide a mechanism to check that all policies have been followed correctly.

Security requirements for policy languages and architectures include the security of the policy authority, the security of the local information on the cognitive radio, and the security of the policy enforcer. The network based sharing of data supporting dynamic spectrum operations should provide authentication and non-repudiation of users, limited permissions for the modification of spectrum use data on the dynamic spectrum access database, and audit logging of actions of all DSA participants so that information integrity and other security problems may be quickly and accurately diagnosed and resolved. The tools employed to create the database(s), related network(s), network service(s), and/or web site(s), and related the DSA devices should employ anti-malware measures consistent with ISO 27000 and NIST 800-series for network and device security.

The policy architecture shall support the requirement to provide acknowledgement messages to the submitter of the policy.

For further details on the policy reasoner architecture and policy language the reader is referred to The IEEE Standard 1900.5TM-2011, January 2012

Work in progress

P1900.5.1 - Draft Standard Policy Language for Dynamic Spectrum Access Systems

This standard defines a vendor-independent policy language for managing the functionality and behavior of dynamic spectrum access networks based on the language requirements defined in the IEEE 1900.5 standard. Cognitive radio, cognitive RF in general and cognitive wireless network technologies are increasingly being adopted within industry. Multiple business models as well as other needs, such as military and public safety, are emerging and many have conflicting goals and operating procedures. Devices, networks and applications that can use cognitive RF systems for DSA applications require cooperative or interoperable means of coexisting and operating under specific policy rules to govern the functionality and behavior of Cognitive Radios in a scalable manner. Policy-based management has this general capability; hence, this standard shall this need, since it enables these entities to be re-purposed to solve different application-specific needs and to serve in different scenarios where multi-vendor and multiple mission operation and interoperability is required. The functionality targeted in this standard will lead to the optimum exploitation of the radio eco-space, for all stakeholders, to obtain required metrics (e.g., Quality of Service). This in turn will support the development of anytime and anywhere wireless access to resources and services, thus perpetuating the industry and its investments.

This standard developed under PAR will take into consideration both the Policy Language Requirements of IEEE 1900.5 and the results of the Modeling Language for Mobility Work Group (MLM-WG) within the Wireless Innovation Forum (SDRF v2) Committee on Advanced Wireless Networking and Infrastructure. MLM-WG is developing use cases, an ontology, corresponding signaling plan, requirements and technical analysis of the information exchanges that enable next generation communications features such as spectrum awareness and dynamic spectrum adaptation, waveform optimization, capabilities, feature exchanges, and advanced applications. The MLM-WG expects this effort to lead to specifications/ standards for languages and data exchange structures to support these capabilities.

P1900.5.2 - Standard Method for Modeling Spectrum Consumption

This standard defines a vendor-independent generalized method for modeling spectrum consumption of any type of use of RF spectrum and the attendant computations for arbitrating the compatibility among models. The objective of this standards effort is to provide a common standard to define spectrum use so that spectrum can be shared among government, commercial, and public users as a commodity agnostically to any proprietary or classified algorithms or techniques.

To this end, the broad applicability of modeling in the activities of dynamic spectrum access and its role as a loose coupler will make it a catalyst for innovation in regulation, technology development, spectrum commerce, and spectrum management operations. The command and control based methods of spectrum management have changed little over the past 100 years, largely relying on fixed and a priori compliance verification approaches to assure and track frequency assignments. Recent policies have advanced this approach by specifying the use of databases for dynamic access to television whitespace (TVWS) and as a result new businesses have emerged to build and operate databases and to build RF devices that can access these databases to obtain permission to use the spectrum. Recent recommendations for the continued evolution of spectrum access have promoted the extension of the database system to additional bands of spectrum for the purpose of sharing spectrum among diverse applications, missons and use cases.

Current databases are built around well-known performance static emitters. This allows the use of simplified static models that define permissible reuse based on potential interference levels. The goal of the IEEE P1900.5.2 standard is to enable the extension of the existing database approach to more dynamic users. This requires an approach that facilitates modeling all types of spectrum uses that capture temporal, spatial, spectral, and behavioral boundaries. The product of this standard will define the constructs that can be used to build these sorts of models.

Spectrum management tools that are most broadly used today are ill-suited for this purpose. These tools are at their core static and require the maintenance of substantial data about how the RF systems operate and definition of the particular methods for arbitrating compatibility between systems. This is an obstacle to multi dimensionally based dynamic spectral environment sensing, resource negotiation and sharing.

Arbitrating compatibility is difficult to implement since the methods of computing compatibility must be developed for each new system that is added and be embedded in the management systems. It is very difficult for a plurality of managers to arbitrate the coexistence of spectrum uses among themselves because they must have common data and agree to the methods to define use and to compute compatibility. The product of this standard overcomes these limitations. It provides a means for specifying spectrum consumption without requiring the revelation of system details and it provides a common tractable means for computing compatibility. Multiple cognitive entities can collaborate in managing coexistence by simply sharing models.

Spectrum consumption models are a means to commoditize spectrum.

A limitation to this approach to reusing spectrum is the difficulty of arbitrating the efficacy of policy with existing spectrum assignments. The models defined in this standard shall provide an alternative means for specifying spectrum use policy to RF systems resolving the efficacy problem as it is easy to assess the compatibility of policy defined by models with the database of models of assignments used in spectrum management.

Work on this standard was officially started in March of 2013 and is based on Model-Based Spectrum Management (Stine, Schmitz 2011) contributions from MITRE.

P1900.5.a - Future work not yet started

This will provide an amendment to IEEE Std 1900.5™-2011 defining the detailed interfaces between policy architecture components.

8.1.3.6 P1900.6

The IEEE 1900.6 standards work was initiated in September 2008, and the base standard was published in late April 2011 (IEEE Std 1900.6™-2011). IEEE 1900.6 defines the information exchange between spectrum sensors and their clients in radiocommunication systems; this might be applicable in both the cooperative/collaborative sensing scenarios and in other scenarios where the intelligence that make spectrum access and other decisions in the network and spectrum sensors are at different locations in the network. The logical interface and supporting data structures are defined abstractly without constraining the sensing technology, client design, or data link between sensor and client. Of course, the facilitation of sensing technologies through standards such as IEEE 1900.6 assists many spectral coexistence techniques that utilise locally-obtained spectrum information, such as CR.

IEEE 1900.6 has also published an amendment (IEEE Std 1900.6a™-2014), on "Procedures, Protocols, and Data Archive Enhanced Interfaces." This covers a number of aspects of the precise nature of the procedure and protocols of 1900.6, including the interaction with non-compliant systems, consideration of "professional installations" in which sensors may not have location information (e.g., GPS) but may instead have their location professionally verified, data-archive assisted sensing decisions such as related to propagation "maps" that the data archive has access, support for wide-band sparse sensing implementation, and support for use of the 1900.6 subsystem for connectivity awareness, among many other additions

At the time of writing, IEEE 1900.6 is consider interesting new work items. One of these is the application and extension of the standard to the case of spectrum sensing systems being used to augment the information in regulatory databases, e.g., the white space geolocation databases. A number of considerations apply here, such as the reliability and security of the information, the implementation of (probabilistic) decision making processes, among others. A further work item is a minor revision of the terms and definitions in 1900.6 to harmonize with IEEE 1900.1 terms and definitions and the terms and definitions in IEEE 1900/DySPAN-SC in general.

8.1.4 Protocol to Access White Space Database (PAWS)

The PAWS protocol is in development within Internet Engineering Task Force (IETF) to specify a messaging interface between a database and white space devices[194]. The PAWS workgroup (both the work group and the protocol share the paws name) is chartered to[195]:

1. Standardize a mechanism for discovering a white space database.
2. Standardize a method for communicating with a white space database.
3. Standardize the data formats to be carried over the defined database communication method.
4. Ensure that the discovery mechanism, database access method, and query/response formats have appropriate security levels in place.

The protocol was developed based on a set of use cases and requirements developed within the PAWS project and released as Request for Comment (RFC) 6953 by IETF[196]. Use cases covered in this document include master slave white space networks, moving traffic to a white space network, white space serving as backhaul, rapid deployment during emergencies, and white space used for local TV broadcast. Requirements looked at data models, protocols and operations, and consideration was given to security.

The protocol is expressly designed to meet requirements of multiple countries, so that a device conforming to more than one country's regulations could be used in any of them depending on its location. It includes extensibility mechanisms to account for new regulations that may arise. It will:

1. Determine the relevant white space database to query.
2. Connect to the database using a well-defined communication method.
3. Provide its geolocation and perhaps other data to the database using a well-defined format for querying the database.
4. Receive in return a list of available white space spectrum with their characteristics, using a well-defined format for returning information.
5. Report to the white space database anticipated spectrum usage at a suitable granularity.

The draft protocol document is available[197]. The document is considered stable, and is in the initial stages of approval within the IETF. A final document is expected before the end of this year. A number of white space database administrators

194 https://datatracker.ietf.org/wg/paws/
195 https://datatracker.ietf.org/wg/paws/charter/
196 http://tools.ietf.org/html/rfc6953
197 http://tools.ietf.org/html/draft-ietf-paws-protocol

and device manufacturers, as well as regulators, have participated in the creation of this standard, and wide deployment is expected within a few years.

8.1.5 Other Relevant Standards

8.1.5.1 Standard Spectrum Resource Format (SSRF)

SSRF is a government specification published by the Military Communications Electronics Board and is issued under the authority of DOD Directive 5100.35. SSRF is aligned with the National Telecommunications and Information Administration (NTIA) Office of Spectrum Managements Data Dictionary (OSMDD) and the North Atlantic Treaty Organization (NATO) Spectrum Management Allied Data Exchange Format – eXtensible Markup Language (SMADEF-XML). The specification defines standard data elements for the automated exchange of radio-frequency (RF) spectrum-related data that includes:

- RF equipment and antenna parameters
- Spectrum supportability requests and associated host nation replies
- Temporary and permanent frequency proposals and assignments
- Frequency allotments
- Interference reports

Keybridge Global published a reference implementation of SSRF through the Wireless Innovation Forum. This reference implementation is available here:

http://groups.winnforum.org/reference_implementations

8.1.5.2 White Space Database Administrators Interface Specifications

The White Space DataBase Administrator (WSDBA) is authorized by a Regulator to manage and provide secondary access to a spectrum band in such a way that ensures existing incumbent users are protected against harmful interference by the secondary users. The Regulator may authorize multiple WSDBA, in which case the Regulator will specify the extent to which WSDBA must be in alignment to provide consistent results. In some cases, for example the US FCC rules, this requires that WSDBA be able to synchronize information to ensure that consistent results are provided.

The Regulator makes the determination about who is designated as an incumbent user and what protection they are to be provided. There are different approaches to how the Regulator conveys this information to the WSDBA. In the case of the FCC the information about the incumbents and the protection criteria is provided to the WSDBA and the WSDBA calculates the protection and available White Space. In the case of Ofcom (UK) the regulator calculates the protection and available white space and provides this information, in the form of a pixel map, to the WSDBA.

In general the regulation defines the operating parameters for the secondary users, including maximum transmit power, the emission mask for co-channel and adjacent channel operation as well as other parameters necessary to ensure protection for incumbents.

Once the regulator is satisfied that the WSDBA meets its protection criteria by correct application of the rules the WDSBA is certified or authorized to begin operation. The process of testing the WSDBA by the regulator is extensive, typically lasting up to 6 months, and covers all aspects of the operation of the WSDBA. The regulator testing is solely focused on the protection of the incumbent. Any additional services or capabilities that the WSDBA provides to the white space users is typically beyond the scope of the rules. This area is where multiple WSDBA differentiate themselves to the users.

The regulation specifies what information the white space devices must give to the WSDBA as well as the calculations and decisions the WSDBA must make based on that information. As a minimum it includes information about the device, it's location and typically the height of the antenna above ground (AGL). The rules also specify the minimum information that the WSDBA must deliver in response. Typically an available channel list, which may have maximum power restrictions overall or per channel, as well as the length of time the permission is valid.

The regulations also require some form of logging, monitoring and tracking to be performed by the WSDBA and this information has to be made available to the regulator and often made public. The main reason for collecting this information is to assist in dealing with interference issues. The specific information collected and made available varies by regulator.

In the Ofcom (UK) Model the regulator provides each WSDBA with pixel maps of protection for DTT and periodic updates (currently every three hours) of PMSE data. Ofcom also requires a commone query system to allow it to investigate issues such as interference. As such there is no requirement for WSDBA to synchronize.

In the US Model the FCC requires that WSDBs support PMSE registration for licensed and unlicensed wireless microphones as well as other broadcast equipment. In support of this capability the FCC mandated that the WSDBA share this registration data so that a PMSE registration with one WSDB would be effective in all WSDB. This was achieved by an industry developed synchronization protocol. The active WSDBA got together and created a working group to create and validate a specification that met the FCC rules. This protocol has been published on the FCC website http://apps.fcc.gov/ecfs/document/view?id=7520963472

This protocol has been tested as part of the FCC certification of the second and subsequent WSDB and the current version of the specification is believed to be complete and meets the FCC requirements. The specification is continually reviewed by the group, which is open to all FCC designated WSDBA, and may be updated in the future based on new FCC rules and requirements or if any issues are identified. Substantial changes to this protocol are not anticipated in the near future.

As mentioned this protocol has been implemented by all currently certified WSDBAs and validated by the FCC as part of their certification process. The protocol specifies a near real time secure FTP and web services mechanism to permit initial synchronization as well as updates.

One final component of the rules relates to enforcement. The regulator does not typically abdicate responsibility to the WSDBA. Policing and enforcement remains a regulatory action. However the regulations require the WSBDA make information available to the regulator to assist in these activities and they have to provide capabilities to support enforcement. These include, the ability, under regulator instruction, to ban or blacklist individual devices or groups of devices, the ability to make temporary changes to protection rules and, ultimately, to stop offering service to devices.

8.2 Physical Layer Standards

8.2.1 802.11af

8.2.1.1 Introduction

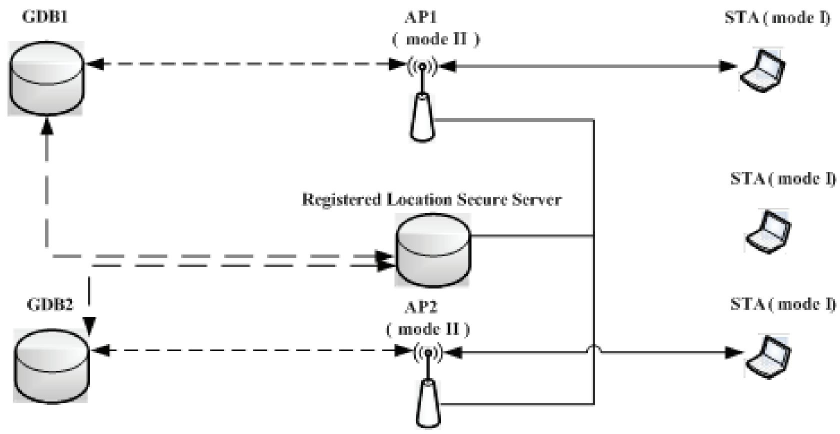
The P802.11af project, formally known as "IEEE Standard for Information Technology - Telecommunications and Information Exchange Between Systems - Local and Metropolitan Area Networks - Specific Requirements - Part 11: Wireless LAN Medium Access Control (MAC) and Physical Layer (PHY) Specifications - Amendment: TV White Spaces Operation" was authorized by the IEEE 802 Executive Committee in November of 2009. The scope of the project was "An amendment that defines modifications to both the 802.11 physical layers (PHY) and the 802.11 Medium Access Control Layer (MAC), to meet the legal requirements for channel access and coexistence in the TV White Space." The Project Authorization Request stated "The purpose of this amendment is to allow 802.11 wireless networks to be used in the TV white space." With regulators worldwide looking for ways to enable more users in the finite space of the radio frequency spectrum, geo-location and time-based sharing was an easy choice to start with, and with the transition from analog to digital broadcast television, the TV White Spaces looked like the place to start.

In a previous, similar sharing effort, the US FCC authorized lightly-licensed sharing of the 3650 to 3700 MHz band. This became IEEE 802.11y-2008. The standard development took three years, but due to the large exclusion zones, which excluded 60% of the US population, silicon vendors, who enable low-cost products, did not participate and the market never developed. Some of the contention-based protocol techniques developed for 802.11y served as a starting point for the standard for the TV White Spaces.

8.2.1.2 The System

The dynamic spectrum access system defined by 802.11af comprises a Geo-location database, database enabled components including enabling master devices, enabled slave devices, and in some configurations, a registered location server which controls masters within a specified area.

1. **Geolocation Database (GDB).** The primary element is the GDB. The GDB is a database that stores usable frequencies and operating parameters by geographic location for WSDs to meet regulatory requirements. The GDBs are authorized and administrated by regulatory authorities, and are therefore dependent upon the security and time requirements of the appropriate regulatory domain.
2. **Geolocation Database Dependent (GDD) entities.** The enabling and enabled elements in the IEEE 802.11af network are labeled Geolocation Database Dependent (GDD), which specifies that their operation is controlled by an authorized GDB which ensures that they satisfy regulation requirements.
   a. **GDD enabling station.** The GDD enabling station is equivalent to the entity common 802.11 access point (AP). In the 802.11af standard the GDD enabling STA securely accesses the GDB to obtain the operating frequencies and parameters permitted in its coverage region. With this information the GDD enabling STA can enable and control the operation of the STAs under its service, identified as GDD dependent STAs. The parameters obtained from the GDB are used to create a white space map (WSM), which the GDD enabling STA maintains and distributes. The GDD enabling STA also transmits a contact verification signal (CVS), for GDD dependent STAs to check validity of the WSM on a regular schedule.
   b. **GDD dependent station.** The GDD dependent station is equivalent to the common 802.11 STA in the basic service set (BSS) architecture. The 802.11af standard specifies that the operation of the STAs is controlled by the GDD enabling STAs. The GDD dependent STAs obtain the permitted operating frequencies and parameters in a WSM from the GDD enabling STA.
3. **Registered Location Secure Server (RLSS).** The Registered Location Secure Server (RLSS) operates as a local database that contains the geographic location and operating parameters for a small number of BSSs. The RLSS distributes the permitted operation parameters to the APs and STAs within the BSSs under the RLSS control. This element may not be approved in all regulatory domains.



Outside the scope of 802.11af > | < Within the scope of 802.11af

Figure 17: 802.11af TVWS network with all elements shown

8.2.1.3 The Physical Layer

In the IEEE 802.11af standard, the TV High Throughput (TVHT) physical layer (PHY) specification replaces the HT (20 MHz OFDM) and VHT (20, 40, 80, 80+80, 160 MHz OFDM) PHY specifications in WSD devices when operating in TVWS bands. A TVHT device has support for single-channel bandwidths or basic channel unit (BCU) W of 6, 7, and 8 MHz depending on the regulatory domain. Additional bonded or non-contiguous bandwidths of 2W, 4W, W+W, and 2W+2W are possible as illustrated in Figure 18. A single-channel bandwidth W and a single spatial stream are mandatory, although Multiple-Input, Multiple Output (MIMO) transmissions with space-time block coding (4x STBC) and multi-user (4x MU) diversity are supported

The TVHT transmission format is similar to that of a 40 MHz VHT transmission. It currently defines 144 OFDM subcarriers for 6 and 8 MHz channels and 168 for 7 MHz channels so that 6 and 7 MHz transmissions are spectrally identical. For all W, data is sent on subcarrier indices -58 to -2 and 2 to 58, with index 0 at DC and 6 pilot tones inserted at indices ±11, ±25, and ±53. In the case of multiple frequency segments (2W, W+W, etc.), this subcarrier assignment is duplicated.

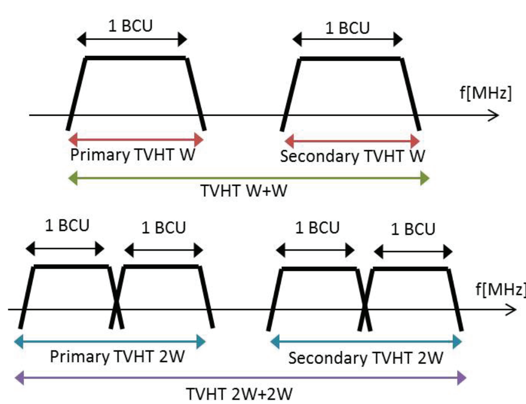


Figure 18: 802.11af TVHT PHY channel configurations

8.2.1.4 Operation

Although the components are basically regulatory domain independent, the operation of the components must comply with regulations in the appropriate domains.

Figure 17 is a system diagram showing all of the components, and their position within or outside of the bounds set by the 802.11 standard. IETF Protocol for Access to White Spaces (PAWS) may be used for the protocol outside the scope of the 802.11af standard. The following briefly describes the protocol specified by the standard.

A Registered location query protocol (RLQP) is provided to share the white space maps and current channel use among GDD enabling STAs in a neighborhood. GDD dependent STAs can query both their GDD enabling STA and the registered location secure server about white space maps and channel utilization. In some regulatory domains a Registered Location Secure Server (RLSS) can provide GDBs with the current channel use information for all the BSSs and IBSSs that communicate with it. In some regulatory domains the registered location secure server communicates with controllers of other white space systems to coordinate emissions footprints of their services. By accessing and using this information, the STAs can make intelligent decisions about the most effective way to utilize the available spectrum, power, and bandwidth for their communications.

The specific mechanisms are as follows:

- Channel availability query, used to obtain one or more white space maps of available channels for an area or a geo-location
- Channel schedule management, used to obtain start and ending times for each available white space channel
- Contact verification signal, used by a GDD dependent STA to verify it is still receiving frames from its GDD enabling STA
- GDD enablement, the procedure where a GDD enabling STA forms a network and maintains the network under the control of a geo-location database
- Network channel control, used to inform a local channel controller that has a view of nearby transmitters and their emissions footprints
- White space map, used to retrieve the available white space channels and their transmit power restrictions

The use of the mechanisms in a particular regulatory domain depends on the specific regulatory requirements. Table 1 (GDD mechanisms and timescales) gives a view of the use of specific mechanisms to meet regulatory requirements in terms of daily, hourly and minute timescales.

Table 4: GDD mechanisms and timescales

Mechanism	Daily Consultation Required	Hourly Consultation Required	Minute Responsiveness
Channel availability query	Informative	Informative	Not applicable
Channel schedule management	Informative	Informative	Not applicable
Contact verification signal	Required to be secure	May be secure	Loss of consecutive signals requires action
GDD enablement	Required to be secure	Required	Required
Network channel control	Informative	Informative	Not applicable
White space map	Required for GDD enabling STA, might be translated for GDD dependent STA	Required for GDD enabling STA, might be translated for GDD dependent STA	Required for GDD enabling STA, might be translated for GDD dependent STA

8.2.1.5 Conclusion

Developed to provide a framework for WLAN sharing of the broadcast TV bands in multiple regulatory domains, IEEE 802.11af specifies a physical layer based on the 802.11ac PHY, and a flexible architecture to meet the meet the regulatory and sharing requirements to avoid interference with the licensed TV band devices. Interference mitigation via a government controlled geo-location database enables efficient sharing of the TV White Spaces.

8.2.2 IEEE 802.22

8.2.2.1 Introduction

The IEEE 802.22 Working Group has several on-going activities. The IEEE Std. 802.22-2011 on Wireless Regional Area Networks (WRANs) was completed in 2011 and is being revised with expanded scope where the new revised standard will specify operation of the 802.22 devices in other bands that allow spectrum sharing. The WhiteSpace Alliance (www.WhiteSpaceAlliance.org) is developing inter-operability and test procedures for its Wi-FAR™ specification that is derived from the IEEE Std. 802.22-2011. The IEEE P802.22a specifies the Management Information Base (MIB), whereas, the P802.22b project is an amendment to the 802.22 Standard to support higher throughput and larger number of users.

Other activities of the IEEE 802.22 Working Group include, the IEEE Std. 802.22.1-2010 that proposes a beaconing system to protect auxiliary licensed devices in TV Broadcast Bands. This standard is currently being revised through the ***Advanced Beaconing Project*** to support spectrum sharing in the 3.5 GHz Band between the Federal systems and the Commercial systems. The IEEE 802.22.2 Standard specifies the ***recommended practice for the installation and deployment of the IEEE 802.22 Systems***. A new project IEEE 802.22.3 called the ***Spectrum Occupancy Sensing (SOS)***, proposes a standard specifying spectrum occupancy sensing measurement devices and means that enable coalescing the results from multiple such devices.

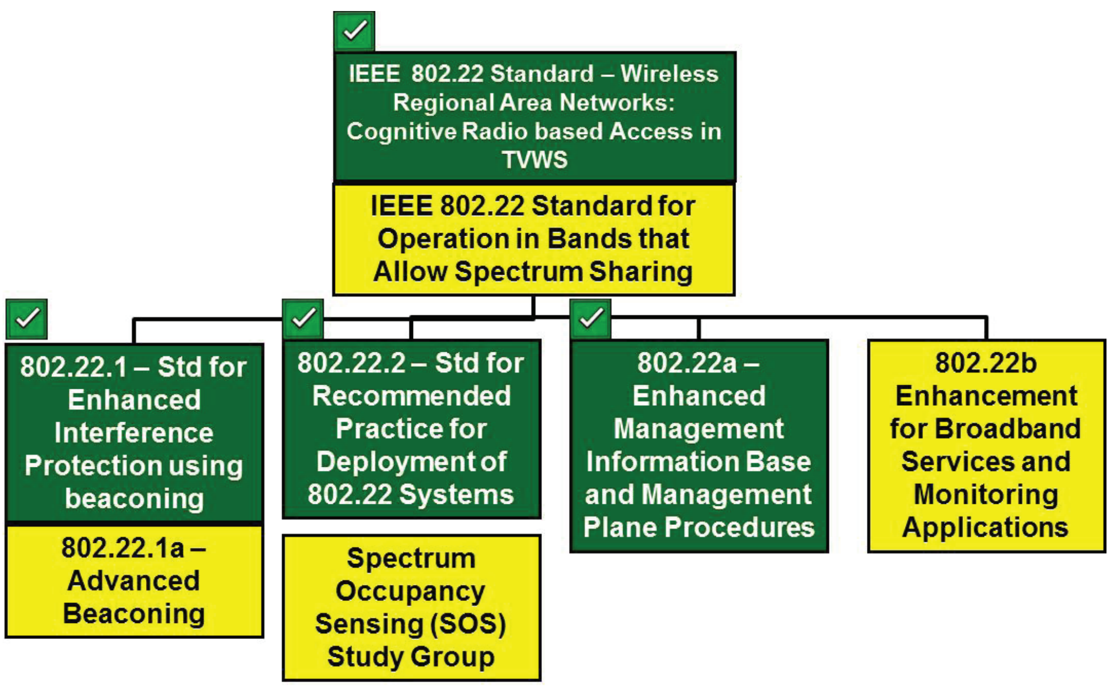


Figure 19: Various completed, on-going and proposed standards under the IEEE 802.22 Working Group

8.2.2.2 IEEE 802.22 Family of Standards on Wireless Regional Area Networks

The IEEE 802.22 Working Group was established in the year 2004 in response to the Federal Communications Commission's Notice of Inquiry (NoI) followed by the Notice of Proposed Rule Making (NPRM) allowing unlicensed cognitive radio operation in Television Broadcast Bands.

The IEEE 802.22 Working Group has several on-going activities. The IEEE Std. 802.22-2011 on Wireless Regional Area Networks (WRANs) was completed in 2011 and is being revised with expanded scope where the new revised standard will specify operation of the 802.22 devices in other bands that allow spectrum sharing. The WhiteSpace Alliance (www.WhiteSpaceAlliance.org) is developing inter-operability and test procedures for its Wi-FAR™ specification that is derived from the IEEE Std. 802.22-2011. The IEEE P802.22a specifies the Management Information Base (MIB), whereas, the P802.22b project is an amendment to the 802.22 Standard to support higher throughput and larger number of users.

some of the salient features of the IEEE 802.22 family of standards include:

1. IEEE 802.22 (Wi-FAR™) provides Broadband Wireless Access to Regional, Rural and Remote Areas Under Line of Sight (LoS) and Non Line of Sight (NLoS) Conditions using without causing harmful interference to the incumbents.
2. The IEEE 802.22 Working Group is the recipient of the 2011 IEEE SA emerging technology of the year award.
3. Cognitive Radio technology added to a simple and optimized OFDMA waveform similar to the OFDMA technology used in other broadband standards
4. Each Wi-FAR™ cell can provide 22 to 29 Mbps per TV Channel and provide support for 512 devices. Typical distances covered ranges from 10 km up to 30 km under favorable conditions
5. Enhancements to 802.22 are currently under way. It will support
    a. High-capability and Low-capability CPE modes
    b. Double the throughput (40 Mbps) per 6 MHz TV Channel – MIMO, Channel Aggregation, Channel Bonding or high rate modulation and coding
    c. Support for up to 2500 users per channel
6. IEEE 802.22 (Wi-FAR) trials are under way in many countries including Japan, US and Canada. Link: NICT/ Hitachi Kokusai IEEE 802.22 and IEEE 802.11af trials.

TV Channels in VHF / UHF bands have highly favorable propagation characteristics. In some administrations like the United States, opportunistic license-exempt usage of the spectrum used by the incumbents is allowed on a non-interfering basis using cognitive radio techniques. Operation in the TV white space requires the use of one or more among several cognitive radio technologies which have been incorporated in the IEEE Std 802.22-2011. These features include geolocation and access to an incumbent database, spectrum sensing, regulatory dependent policies, channel set management, spectrum etiquette and self co-existence mechanisms. Based on the regulatory rules, these cognitive radio features can be turned ON or OFF.

8.2.2.3 Operation

The 802.22 network consists of base stations serving fixed and portable client devices, called customer premises or portable equipment (CPE). The network is based on an orthogonal frequency division multiple access (OFDMA) physical layer with support for long range operation and harsh channel multipath in order to service large geographical regions. More recently, portable device operation that would typically take placed closer to the base station (BS) was added to the WRAN operation. In order to operate in the TV white space, the FCC regulations require that wireless networks support several cognitive radio features such as geolocation and access to an incumbent database. Other value added features such as spectrum sensing, regulatory dependent policies, channel set management, spectrum etiquette and self co-existence mechanisms are also available in IEEE 802.22. The first feature is geo-location (often referred to in the cognitive radio literature as location awareness) in which the fixed devices need to acquire their geographic location. This geo-location capability is coupled with Internet access which will allow querying a database of licensed services in order to identify which channels are available locally for unlicensed use. The other cognitive radio technology is spectrum sensing in which the wireless devices make observations of the RF spectrum and, based on those observations, determine which channels are occupied by licensed services. The IEEE 802.22 standard has been developed to support the geo-location capability, the ability to access the database of licensed services, and the spectrum sensing capability. However, due to the regulatory leanings to not make spectrum sensing mandatory, switches have been provided into the standard to turn features such as sensing on or off. The medium access control (MAC) layer supports control and messaging for all these cognitive radio features. The standard has been developed to include a Spectrum Manager which compiles all the inputs from the geo-location/database, spectrum sensing, regulatory dependent policies and makes the final decision on which channel the network is to occupy. Table 5 provides some salient features of the IEEE 802.22 Standards based devices.

Table 5: Technical and operating features of IEEE Std 802.22-2011

Item	Value
Supported frequency bands (licensed or unlicensed)	54 MHz to 862 MHz, 2.7 GHz to 3.7 GHz
Nominal operating range	Optimized for range up to 30 km in typical PMP environment, functional up to 100 km
Mobility capabilities (nomadic/mobile)	Nomadic and mobile
Peak data rate (uplink/downlink if different)	22-29 Mb/s, greater than 40 Mb/s with MIMO
Duplex method (FDD, TDD, etc.)	TDD
Nominal RF bandwidth	6, 7 or 8 MHz
Diversity techniques	Space, time, block codes, spatial multiplexing
Support for MIMO (yes/no)	Yes
Beam steering/forming	Yes
Retransmission	ARQ, HARQ
Forward error correction	Convolutional, Turbo and LDPC
Interference management	Yes
Power management	Yes, variety of low power states
Connection topology	Point to multipoint
Medium access methods	TDMA/ TDD OFDMA, reservation based MAC.
Multiple access methods	OFDMA
Discovery and association method	Yes, through device MAC ID, CID and SFID
QoS methods	QoS differentiation (5 classes supported), and connection oriented QoS support
Location awareness	Geolocation
Ranging	Yes
Encryption	AES128 - CCM, ECC and TLS
Authentication/replay protection	AES128 - CCM, ECC, EAP and TLS, replay protection through encryption, authentication as well as packet tagging.
Key exchange	Yes, PKMv2
Rogue node detection	Yes
Unique device identification	48 bit unique device identifier, X.509 certificate

8.2.2.4 IEEE 802.22.1 Standard on Advanced Beaconing

The IEEE Std. 802.22.1-2010 that proposes a beaconing system to protect auxiliary licensed devices in TV Broadcast Bands. This standard is currently being revised in through the ***Advanced Beaconing Project*** to support spectrum sharing in the 3.5 GHz Band between the Federal systems and the Commercial systems.

Beacons have been reliably used in many different forms since more than 90 years and deployed for protection of many different types of systems that exist today. IEEE Std. 802.22.1-2010 beacon was designed for the purposes of protecting Part 74 device systems (e. g. wireless microphones) in the Television Bands. Extensive studies were conducted and a beaconing approach was found to be feasible, robust and reliable by a wide variety of participating organizations including the chipset vendors, TV Broadcasters, wireless microphone manufacturers etc. The FCC later decided to create dedicated channels for the licensed wireless microphones, and put this information in the database.

The on-going revision to IEEE Std. 802.22.1 will create an ***Advanced Beaconing technology*** that will open up many new frequency bands for spectrum sharing while protecting primary users of the band including radars, commercial federal/ defense communications, space to earth satellite receivers, wireless microphones etc.

IEEE 802.22.1-2010 uses direct sequence spread spectrum (DSSS) technology that has been widely adopted in many standards based products for more than a decade. The DSSS PHY and TDMA based MAC technologies have been widely deployed. These beacon transmitters and receivers are expected to be inexpensive. Also, since each these beacons are detectable at a low Signal to Noise Ratio (SNR) (e. g. IEEE Std. 802.22.1-2010 based beacon can be detected at -114 dBm) it is likely to support operation over a large area. Hence the cost of deployment over a large area is likely to be reasonable.

8.2.2.5 IEEE 802.22.2 Standard on Recommended Practice for Installation and Deployment of IEEE 802.22 Systems

The IEEE Std. 802.22.2-2012 Standard specifies the ***recommended practice for the installation and deployment of the IEEE 802.22 Systems***. The standard was published in 2012.

8.2.2.6 IEEE 802.22.3 Proposed Standard on Spectrum Occupancy Sensing

This emphasis on greater spectrum efficiencies, spectrum sharing and spectrum utilization requires not only database driven configuration of the radios, but systems that can provide spectrum occupancy at a particular location and at a particular time. Regulators all over the world have realized the importance of better spectrum utilization.

Since 2005, the 802.22 Working Group has been developing cognitive radio technologies which include spectrum sensing, cognitive radio messaging and control as well as spectrum management. The Spectrum Occupancy Sensing (SOS) Project plans to extract and re-structure these functions, in order to create a stand-alone system.

8.2.2.7 Conclusions

1. Spectrum sharing can benefit *developed and developing countries*.
2. Cognitive Radio technology and use of White Spaces will provide ubiquitous wireless connectivity.
3. Spectrum sharing can create *tomorrow's spectrum super-highways*. It supports licensed, license-exempt and hierarchical access business models.
4. *Technologies and Standards* for Cognitive Radios, and Database enabled Spectrum Access exist.
   a. *Emerging Technology Award Winning IEEE 802.22 (Wi-FAR™) spec* is specifically designed for rural, regional areas and developing countries to provide broadband access aimed at removing the digital divide.
   b. *The IEEE 802.22.1 Standard on Advanced Beaconing* will provide an ability to share the spectrum with federal systems.

8.2.3 IEEE P1900.7

The IEEE 1900.7 standards work was initiated in September 2011, after a study period. IEEE 1900.7 work is concerned with defining a new Radio interface (PHY/MAC, among other aspects) for white space access. The aim is for this radio interface is to be generic, applicable to a range of use cases spectrum bands. However, in practice, it is currently limited to application in TV white space, as TV bands are the only bands currently allowed from a regulatory perspective for white space access.

At the time of writing, IEEE 1900.7 has progressed extensively in its work—already creating the "System Engineering Document" that will serve the development of the standard, and populating a large proportion of the content of that. It has, as expected, defined a wide range of use cases covering aspects from wireless sensor networking, to in-building provisioning (e.g., wireless local-area networking), to backhaul provisioning, and to maritime coverage enhancement through white spaces, among others. It has one physical layer currently defined, based on Filter-Band Multi-Carrier technology (FBMC), noting that such technology is particularly good at taking advantage of white spaces, even if they are very thin and distributed gaps in spectrum usage (although, it must be noted, there are regulatory implications and challenges of possible non-contiguous spectrum access particularly by a single radio chain). Other physical layer implementations are close to being incorporated based on spread-spectrum technology, for example, in order to realise use cases that require ultra-high energy efficiency. It currently has a MAC layer defined based on a variation on the 802.11 CSMA MAC, incorporating an adaptive algorithm in the collision back-off to enhance fairness and performance. Interactions of that MAC with other systems present in white space (e.g., 802.11af, 802.22) are being considered – e.g., it would not be preferable if 1900.7 would lose out to competing 802.11 systems in its efforts to be fair and improve performance.

Other accepted contributions have defined the broad elements of the system architecture and "convergence plane," whereby other elements are currently being worked on – such as the "cognitive plane," security and message encoding.

At the time of writing, it is anticipated that IEEE 1900.7 will progress to an internal ballot on its readiness at the start of 2015, and will progress to the sponsor ballot process toward the end of 2015. Publication of the standard is anticipated toward the end of 2016.

8.2.4 Weightless

8.2.4.1 Weightless design requirements

Weightless is designed to enable machine communications, initially targeting white space spectrum. This leads to two sets of requirements – those related to machine applications and those related to operating in white space. The machine requirements are summarised below:

- *Support of a large number of terminals.* A typical cell might have between 100,000 and 1 million devices within it and a national network could easily contain 1 billion devices.
- *Long battery life.* Ten year lifetimes from one battery are needed in many cases.
- *Mobility.* A subset of applications has moving terminals which need to be supported as they move, potentially across national borders.
- *Low cost equipment.* Costs of $2 per chip or less would appear to be necessary.
- *Low cost service.* Network costs must be low and the marginal cost of each terminal very low.
- *Global availability.* Some applications will require global roaming. Others, like automotive, will require that one solution can be fitted into all vehicles regardless of their country of destination.

- *Ubiquity*. Excellent cover, including within buildings, is needed.
- *Guaranteed delivery*. Some applications require certainty that messages have been delivered. This may also require strong authentication and encryption.
- *Broadcast messages*.
- *Efficient transmission of small bursts of data*. Most machines send data packets of the order of 50 bytes.
- *Accommodating sub-optimal terminals*. In many cases terminals will be small and low cost and will have a poor quality antenna and limited power supplies.
- *Event-stimulated loading peaks*. The network needs to be able to accommodate and control the resultant peak in loading.

Operating in TV white space operation leads to the following requirements:

- *Very low levels of out-of-band emissions*. This minimises interference caused to licensed users and so maximises spectrum availability.
- *Avoid interference caused by other unlicensed users*. This can be random and sporadic.
- *Reduce the impact of interference where it cannot be avoided*. Where interference cannot be avoided the system needs to be able to continue to operate.
- *Reduce power where there are few white space channels available*. It is often possible to increase availability by transmitting with lower power and hence causing less interference.

Some of these requirements have immediate design implications as discussed in the next section.

8.2.4.2 Immediate design implications

Each of the requirements has different implications and there is no obvious order to tackle them in. Perhaps the most important one is the need for ubiquitous coverage. This implies a solution with a cellular architecture. Along with this comes the need for a network, roaming, authentication, billing and many other aspects of cellular technology. It implies that at a high level the system architecture will look very similar to that of conventional cellular systems. However, as will be discussed, the scale of the various network components can be much reduced compared to cellular.

Achieving coverage even deep indoors has a further implication. Current cellular systems have relatively poor indoor coverage and white space transmitters will typically be restricted to lower power levels than cellular base stations. One solution would be smaller cells but the result of this would be a very costly network deployment. Instead, a way needs to be found to achieve better coverage than cellular with fewer base stations and less transmit power. The only way that this can be achieved is to use spreading. Direct sequence spread spectrum (DSSS) multiplies each transmitted symbol by a codeword resulting in either a high transmitted data rate or longer effective bit duration. This enables range to be extended at the cost of data rate. It is a technique employed in GPS transmissions to allow the weak satellite signal to be received with a handheld device at ground level. Spreading can achieve a 30dB gain in link budget or more – sufficient to achieve the objectives set out above. However, it has other design ramifications, discussed in the next section.

The need for devices to work for years from batteries and the regulatory restrictions that result in lower power for the portable devices causes further problems. With more powerful base stations than terminals there is a risk of an unbalanced link budget where the terminals can hear the base station but not vice versa. In Weightless it is quite normal for the base station to be transmitting at 4W EIRP (36dBm) but the terminal to only transmit at 40mW EIRP (16dBm) resulting in a 20dB difference in the link budget. This can be accommodated by using narrower bandwidth channels on the uplink resulting in a lower noise floor at the base station receiver and enabling the SNR targets to be achieved. Using uplink channels of 1/64th of the bandwidth of the downlink provides a noise floor 18dB lower which approximately balances the budget.

Another implication of the use of white space is to adopt time division duplex (TDD). This is because the availability of two appropriately spaced white space channels as needed for FDD cannot be guaranteed. TDD also provides flexibility in that at the time of design it was far from clear what the balance of downlink versus uplink traffic would be on a machine network.

Another implication of white space for the initial design was a need to be able to avoid random interference from other unlicensed white space users. The classic approach to this, used by systems such as Bluetooth, is frequency hopping. Hopping also brings many other benefits such as averaging of self-interference, good neighbourly behaviour to other white space users and mitigation against being stuck in a fade.

White space operation also strongly biases designs toward structured synchronous solutions where there are frames, frame headers and devices are provided with allocations rather than transmitting randomly. This is because base stations must communicate information to terminals such as the frequency hopping pattern that is in use and in some cases restrictions on transmit power. With such a structure in place it then makes sense to schedule traffic rather than allow devices to transmit whenever they wish since scheduling gives much high efficiency of loading by avoiding random transmissions colliding. This does require a somewhat more complex system and terminal design but still one significantly simpler than even 2G cellular systems.

8.2.4.3 Subsequent design thinking

These design decisions have subsequent impacts. One of the most far-reaching is the use of spreading. Spreading extends the duration of messages. Any frame header information transmitted in a cell must be at the highest spreading factor supported in the network to ensure that all terminals are able to receive it. Although every attempt has been made to minimise header information, it cannot be removed completely. The minimum size of the header information times the symbol rate times the maximum spreading factor dictates the time spent at the start of each frame transmitting header information. This works out at around 100ms. In order to keep the overhead of the header information to below 10% this implies that the frame duration should be of the order 1s or more. In Weightless the duration can be set as a variable within the network but a length of 1-2s is recommended. This is much longer than the frame duration in most wireless systems, hence Weightless can be considered to have a long frame duration.

The long frame duration has implications. One is that the minimum round-trip delay is about the frame length – of the order 2s – at best case and twice this at worst case. This would be disastrous for voice calls or even for Internet browsing but is typically not a problem for machines. The second is that it allows a different base station implementation where most of the processing is removed to the core network. There is ample time for the core to prepare a complete frame and send it to the base station for conversion to RF and transmission. This enables low-cost base stations, a simple upgrade path and more intelligent scheduling decisions across the network.

Another set of implications flow from the requirements for a long battery life. This implies terminals that want to save energy are able to enter into a sleep mode. However, too long a sleep mode would compromise the ability to contact them unexpectedly (eg with an alert message) or increase the probability that network changes such as updated frequency assignments would take place while asleep. For Weightless, calculations suggest that a sleep time of around 15 minutes would result in a battery drain sufficiently small that battery life is constrained more by the shelf life of the battery than the current consumption. Weightless has therefore been designed with the idea of a superframe that repeats at around 15 minute intervals. The start of a super-frame is a point where all terminals are expected to wake up and listen and hence it can be used to alert them to network changes and send other relevant control information.

Of course, low battery drain is only achieved if terminals listen for the minimum amount of time then revert to sleep mode. To achieve this all the information needed by a terminal is contained within the header of each frame. Hence, any terminal need only listen for about 100ms and if there is no information destined for it, can then return to sleep. This requires careful header design to avoid the terminal having to listen to subsequent frames to obtain a complete set of information. For example, it implies that the hopping sequence cannot be communicated by listing in the header the next frequency to be used and requiring the terminal to listen to sequential frames until the pattern repeats. Instead, the entire pattern, albeit efficiently encoded, must be transmitted in each frame.

The need to be able to handle sudden peaks in traffic due to some event such as a power failure stimulating multiple devices requires careful control of the uplink resource. Mechanisms to forestall devices sending alerts once the error condition has been noted by the network are also needed.

Mobility support requires terminals to be able to move from cell to cell. In cellular systems the network controls handover based on measurement reports provided by terminals. However, this generates substantial network traffic in terms of measurements and imposes a heavy battery load on the terminals when monitoring adjacent cells. Because machines do not need seamless handover a much simpler approach is adopted in Weightless. Handover is almost entirely driven by terminals. Once a terminal detects it has moved out of coverage of a cell it re-starts its acquisition process and attaches to a new cell providing coverage. This means there is little need for any signalling traffic either from the terminal or the network which dramatically improves network efficiency. Hence, handover is terminal-driven.

The need to achieve stringent adjacent channel emissions has an impact on the modulation approach used. Tightly filtering OFDM transmissions tends to distort the waveform more than the same degree of filtering on single carrier modulation due to the higher peak-to-average power ratio requirements of OFDM. Hence single carrier modulation is preferred for white space operation. Weightless uses single carrier modulation but benefits from the frequency domain equalisation possible in OFDM by using single carrier frequency domain equalisation (FDE) where a cyclic prefix is inserted as in OFDM and then used to determine the channel frequency response.

Finally, the need to handle a very large number of devices requires considerable intelligence in the network to schedule communications and adapt network parameters according to load. The loading problem is exacerbated by the varying nature of the frequency resource available with white space channel availability changing and interference potentially occurring randomly from other white space users.

This, then, sets the key parameters of Weightless as a TDD system with single carrier modulation, direct sequence spreading, broadband downlink and narrowband uplink, long frame duration, frequency hopping at the frame rate and 15 minute sleep cycle capability.

8.2.4.4 System overview

A high level overview of Weightless is shown in Figure 20.

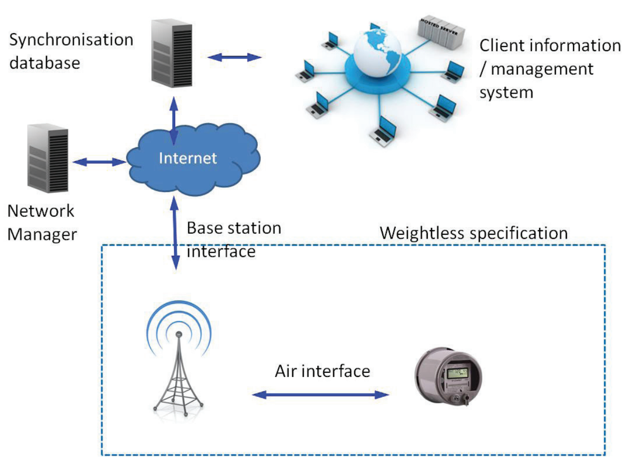


Figure 20: Overview of Weightless

Terminals signal to base stations over the air interface. Base stations send and receive frames of information into the core network via a backhaul connection which might be routed through the Internet or through private connections. The Weightless specification covers the air interface and the base station interface allowing multiple companies to develop terminals and base stations. The core network functionality resides within a network manager, which may itself be a virtual entity within the cloud. This delivers frames of information to the base stations as well as coordinating frequency hopping assignments, managing location records and more. Information sent by the terminals is then routed to a "synchronisation database" which acts as an interface between the Weightless network and any software system the client might be using such as SAP or Oracle.

Another way to view this is to look at the information flow as shown in Figure 21.

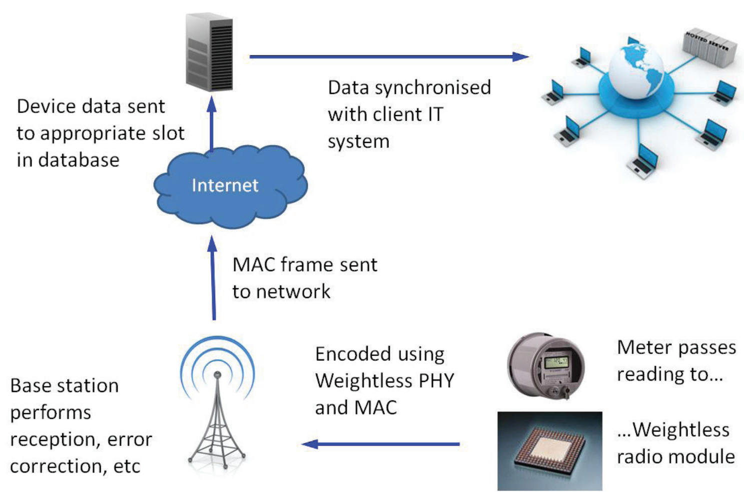


Figure 21: Overview of information flow within a Weightless network

This shows a terminal such as a smart meter passing a reading to an inbuilt Weightless module. This encodes and transmits it over the air interface to the base station which performs functions such as error correction before forwarding the frame to the core network. This routes the information within a frame to the appropriate client interface function.

A third way to look at the network is in a functional layered diagram as shown in Figure 22.

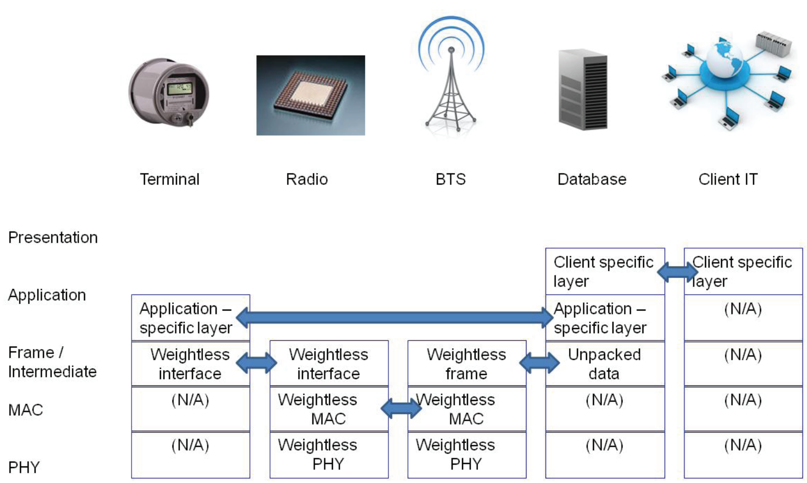


Figure 22: Layered diagram of a Weightless network

At the highest level the database communicates to the client IT system using a layer that is likely specific to that client based on their preferred IT solution. Below that the application in the terminal communicates with an application layer within the database. This allows application specific coding to be implemented. The terminal communicates with a Weightless radio through an interface to the radio unit and the radio then uses MAC and PHY layers to communicate to the base station. The base station sends frame level information onto the database. Note that the only interfaces defined within the Weightless specification are the MAC/PHY level air interface and the frame-level base station to database interface. Application level specification might be provided but are likely to be developed by application groups outside of Weightless and the client specific layer interface does not need standardisation as it is likely to be somewhat bespoke.

8.2.4.5 Overview of the PHY layer

The PHY layer consists of a number of manipulations performed on the MAC-level signal as shown in Figure 23.

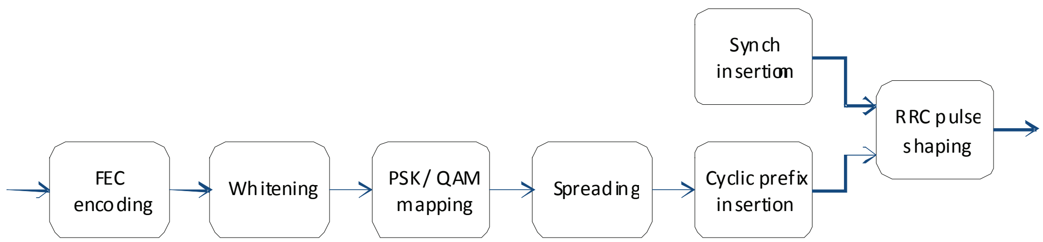


Figure 23: Overview of the PHY layer

Exactly how these manipulations are performed depends in part on whether transmission is downlink (base station to terminal) or uplink (terminal to base station) and the regulatory environment. In overview, the functions of each block are:

- *Forward error correction (FEC) encoding*. This uses convolutional coding to add extra redundant bits to the MAC level message in order that errors can be corrected. The amount of extra information is selected to correct the likely level of errors while minimising the overhead required.
- *Whitening*. This randomises the bit stream by multiplying it by a known random sequence to make it approximate to white noise. This overcomes problems that can be caused if the data contains long strings of 1's or 0's which might confuse synchronisation systems or result in unwanted spurious emissions.
- *Phase shift keying (PSK) or quadrature amplitude modulation (QAM) mapping*. This encodes the data onto "symbols" representing complex points in a transmitted constellation (corresponding to the phase and amplitude of the transmitted waveform). The encoding used depends on the signal to noise level available on the link.
- *Spreading*. This multiplies the data by a codeword resulting in a longer data sequence. It is used where there is insufficient signal level to support communications using non-spread communications. Broadly, it trades off extra range against a reduced data rate.
- *Cyclic prefix insertion*. This adds a repetition of the end of the frame to the start of the frame. This allows the received frame to be readily converted into the frequency domain uncontaminated by multipath from previous transmissions.
- *Synchronisation (sync) insertion*. This adds known patterns of bits that can be used by the receiver to synchronise its internal clocks to the transmitter.
- *Root raised cosine (RRC) pulse shaping*. This turns the square wave binary signal into a more sinusoidal pulse to reduce out-of-band emissions when transmitted.

Note that interleaving is not used as most bursts of data are too short for it to bring benefit. Generally, interleaving is used to distribute errors more evenly across received data. In a radio system errors can tend to occur in clusters when particularly bad propagation conditions are experienced. These clusters can overwhelm the error correction system so interleaving attempts to distribute them across multiple error correction blocks so that all blocks experience a similar error rate, ideally within the capabilities of the error correction system to correct. However, if a terminal only transmits a small number of blocks of data the room for such interleaving to spread clusters of errors is limited.

Next the signal is converted to radio frequency (RF). Frequency hopping is employed so the frequency that the signal is converted to will vary from frame to frame.

The receiver broadly follows the reverse process as shown in Figure 24.

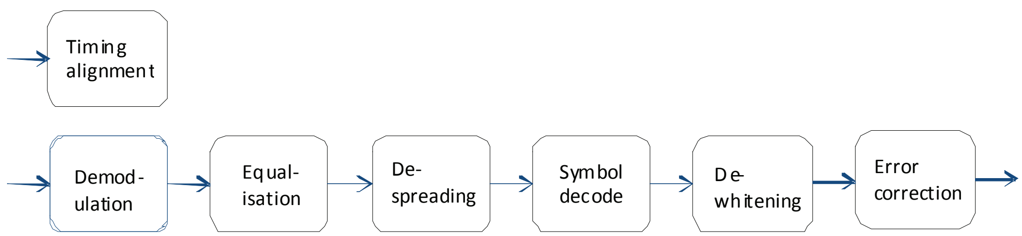


Figure 24: Receive process

The key differences are that:

- Symbol decoding is used to turn the shaped signal back into binary data.
- The inserted synchronisation sequence is used to achieve timing references.
- The cyclic prefix is used in the equaliser that compensates for frequency selective fading in the channel.

One of the key features of the PHY layer is that it accommodates a very wide range of path loss values corresponding to terminals close to the base station to some distance away – perhaps 10km. An overview of how it does this is provided in Table 6.

Table 6: Overview of variation in PHY parameters [Source: Weightless standard]

Modulation scheme	Coding rate	Spreading factor	Downlink PHY data rate (Mbps)	Required SNR before FEC & spreading (dB)	Required SNR for 10-4 BER (dB)	Required signal level at Rx input (dBm)
16-QAM	1	1	16.0	18.5	+18.5	-82.5
16-QAM	3/4	1	12.0	18.5	+14.5	-86.5
16-QAM	1/2	1	8.0	18.5	+11.0	-90.0
QPSK	3/4	1	6.0	11.5	+7.5	-93.5
QPSK	1/2	1	4.0	11.5	+4.0	-97.0
BPSK	1/2	1	2.0	8.5	+1.0	-100.0
BPSK	1/2	4	0.5	8.5	-5.0	-106.0
BPSK	1/2	16	0.125	8.5	-11.0	-112.0
BPSK	1/2	63	0.040	8.5	-17.0	-118.0
BPSK	1/2	255	0.010	8.5	-23.0	-124.0
DBPSK	1/2	1023	0.0025	10.5	-27.0	-128.0

A key point to note here is that the PHY layer uses a combination of the number of modulation levels (QAM to QPSK to BPSK to DBPSK), the error correction rate (1 to ¾ to ½ rate) and the spreading factor (1 to 1023) to accommodate received signal levels varying from -82dBm to -128dBm.

Note that the modulation scheme used is a form of single-carrier modulation rather than the code division multiple access (CDMA) used in 3G or orthogonal frequency division multiple access (OFDM) used in 4G. The reason for not using CDMA is that it requires accurate timing and power control of the messages from terminals but with many messages being short bursts there is insufficient time for power control loops to settle. This could result in a significant drop in capacity. OFDM primarily simplifies the equalisation problem for very high data rate transmissions. Since data rates in Weightless are low compared to 4G, OFDM is not needed and simpler approaches can be adopted. Further, OFDM requires a high peak-to-average power ratio which results in relatively high battery drain. With long battery life a key concern within Weightless this is a significant disadvantage. Other factors in the design choice also included a desire to keep terminal royalty costs as low as possible by avoiding technologies where there were known to be significant intellectual property right (IPR) portfolios. Many of the core techniques used in Weightless have been known for more than 20 years and hence are no longer covered by valid patents.

8.2.4.6 Standardising Weightless

Experience shows that there are no successful proprietary wireless technologies – all of the wireless systems we use routinely are open standards. This made it clear that Weightless needed to be an open standard in order to deliver on its vision.

A key decision was whether to use an existing standards body (the most likely would have been ETSI or the IEEE) or to create a new standards entity. Bluetooth had demonstrated the speed and success that a "SIG" could deliver and Weightless decide to use the same approach.

The Weightless SIG was established in February 2012 and by April of 2013 had published the first complete Weightless Specification as version 1.0. That it was able to work so quickly was partly due to starting with a partially-complete design and partly due to the focus that a dedicated standards body is able to provide. The SIG now has over 1,650 members and expects to complete the testing and certification specification before the end of 2014.

8.2.4.7 Weightless – where next?

As we set out at the beginning of this article, Weightless was initially developed to enable connectivity for machine communications within white space spectrum which suggests that it does not operate exclusively within these frequency ranges. In fact, from inception, the specification has been designed to be frequency agnostic and agile. The consistent, core values that characterise a Weightless system are exceptionally low cost, low power consumption and good signal propagation characteristics and in fact these can typically be delivered within a wider spectrum – particularly sub 1 GHz. We will progressively see more implementations of Weightless technology within licence exempt, unlicensed, and even perhaps in licenced spectrum. The criteria for the decision of which spectrum will include quality of service, bandwidth requirements and location specific licensing requirements. Details of emerging implementations will be provided on the Weightless SIG website as they are announced.

8.3 Analysis and Conclusions

There appears to have been fairly broad participation in the development of physical layer standards supporting spectrum sharing, and there continues to be evidence of business interest in advancing these standards through the industry associations promoting them:

- The White Space Alliance for 802.22[198]
- The Weightless SIG for the Weightless Standard[199]

Typically, the WiFi Alliance would promote the 802.11 based standards, but at the time of this writing their plans for this standard were not known. Business interest is Weightless is further evidenced by the development of silicon supporting this standard. While interest in these standards is high, whether they will be a business success is yet to be seen. Deployments to date of systems utilizing these standards have been limited however (See Sections 7 and 10 of this report), and so their future remains uncertain.

Business interest in the development of implementation standards, on the other hand, appears to be low. Participation in these standards development activities has not been robust, and analysis shows that these activities are fragmented, with competing standards developments that often appears to be driven more by academic enthusiasm or support by a single independent company or organization than any collaborative business objective. This analysis implies that the reasons for this fragmentation are three-fold:

- There is no central architectural model broadly accepted by the community against which standards should be developed, driven in part by the understanding that requirements are often band specific.
- The boundary between what needs to be standardized and what does not is not clearly defined.
- Regulatory uncertainty may be inhibiting investment. For example, the TV White Space market appears to be frozen in the US awaiting the results of the incentive auctions.

These three issues are obviously interlinked. It is reasonable to assume that these issues make it difficult to justify investment in either advancing or implementing these standards, and at the time of this writing little evidence could be found on adoption of these standards in commercial systems. The exception to this lies in the development of database interface standards. The database to database interface developed in US is a defacto standard, not defined in standards body, and success was achieved because of a clearly defined boundary and regulatory demand. Similarly, regulatory demand in Europe drove the development of the ETSI database standard. In both of these cases, the regulatory model drove standards development, not vice versa.

That said, it does not appear that current opportunities are limited by standards, and activities to date clearly indicate that industry can drive standards as required moving forward. It is reasonable to assume, therefore, that other successes can be achieved following a similar model to what was done for the database interface specifications in support of the 3.55 GHz Citizens Band Radio Service being defined in the US. A multi-stakeholder group will likely form from incumbent representatives, PAL and GAA operators and technology suppliers to define a common architectural model which in turn will provide a basis for follow on standards activities. This will enable an ecosystem of organizations to form supporting the standard to enable interoperability within the architectural model.

198 http://whitespacealliance.org/
199 http://www.weightless.org/

9

Relevant Research Programs

9.1 European Programs

9.1.1 EU-funded Programs

Many of the programs supporting Spectrum Sharing within Europe are funded under the Radio Access and Spectrum (RAS) portfolio of projects supporting Objective 1.1 (Future Networks) of the 7th Framework Program (FP7)[200]. A summary of some of the more relevant programs is provided in the following sections.

9.1.1.1 Advanced Coexistence Technologies for Radio Optimization in Licensed and Unlicensed Spectrum (ACROPOLIS)

ACROPOLIS was a European project that brought together 16 partners from 10 countries across Europe, led by King's College London, UK. Its purpose was to develop solutions assisting spectrum sharing and coexistence, including extensive work on concepts such as dynamic spectrum access and cognitive radio, among others[201]. The project included the technical aspects of communications and also the economical, regulatory, and standardization challenges involved with such technologies. ACROPOLIS began in October 2010 and lasted until December 2013. It's total funding was over 4 million Euros in terms of research expenditure, out of which 3 million Euros funding was provided by the EU.

Although ACROPOLIS has relatively recently completed its planned research program, it is continuing a number of high profile initiatives. One of these is the leading of an extensive participation in the UK's Ofcom TV White Spaces Pilot, a key test in Europe of the UK (reflected in the EU) approach to the management of TV White Spaces.

9.1.1.2 Sensor Network for Dynamic and Cognitive Radio Access (SENDORA)

SENDORA was a research project coordinated by Thales Communications and partners with eight other European universities and corporations. Its purpose was to develop a sensor network aided CR[202]. The sensor network monitors the surrounding spectrum and determines what spectrum is in use for the CR to utilize. The project began in January 2008 and concluded in December 2010. It had a total funding of 5.63m Euros.

9.1.1.3 Quantitative Assessment of Secondary Spectrum Access (QUASAR)

The QUASAR project was coordinated by Kungliga Teckniska Hoegskolan (KTH Royal Institute of Technology), Sweden, and partners with ten other universities, companies, and agencies. The project aimed to bridge the gap between the claims made in CR research and its practical implementation[203]. QUASAR analyzed the ability for a secondary user to detect and

200 http://www.ict-ras.eu/index.php/ras-projects
201 ICT-ACROPOLIS, http://www.ict-acropolis.eu, accessed June 2014
202 ICT-Sendora, http://www.sendora.eu, accessed June 2014
203 ICT-QUASAR, http://www.quasarspectrum.eu, accessed June 2014

use available spectrum and the electromagnetic impact of secondary users on primary users. The project also provided roadmaps and guidelines to develop new regulatory standards for spectrum sharing. The project began in January 2010 and concluded in June 2012, and had a total funding of 3M Euros.

9.1.1.4 Cognitive Radio Exploration World (CREW)

CREW is a research project coordinated by the Interdisciplinary Institute for Broadband Technology in Belgium (recently changed title to "iMinds") and includes eight other European universities and companies. The CREW research project aims to establish a federated research platform to experiment on advanced spectrum sharing and CR techniques[204]. The results from an open test platform establishes a benchmarking framework to maintain consistent testing scenarios of dynamic spectrum access and CRs. The project began in October 2010 and will conclude in September 2015. CREW has a total budget of almost 5M Euros.

9.1.1.5 Cognitive Radio Oriented Wireless Networks (CROWN)

CROWN was a research project coordinated by Queens University Belfast in Belfast, UK, and partnering with six other universities and companies. CROWN aimed to realistically implement CRs for spectrally and financially efficient wireless communications[205]. CROWN also aimed to understand the technical issues that plague CRs and dynamic spectrum access. The project began in May 2009 and ended in April 2012.

9.1.1.6 Cognitive Radio Systems for Efficient Sharing of TV White Space in European Context (COGEU)

COGEU was a research project led by Instituto de Telecomunicacoes in Portugal which included ten other academic, corporate, and governmental partners from around Europe[206]. The background intention of COGEU was to take advantage of Europe's digital TV switchover. The project aimed to develop CRs to take advantage of TV white space through secondary spectrum trading. COGEU also purposed new methodologies for equipment certification while complying with current European standards. COGEU studied three main applications over TV white spaces: cellular, Wi-Fi, and WiMAX network extension of mobile TV and public safety applications. The project began in January 2010 and concluded in December 2012.

9.1.1.7 Spectrum OverLay through aggregation of heterogeneous DispERsed Bands (SOLDER)

The goal of SOLDER is to develop a new spectrum overlay technology which will provide the efficient aggregation of non-continuous dispersed spectrum bands licensed to heterogeneous networks (HetNets) and heterogeneous Radio Access Technologies (h-RATs). Importantly, SOLDER also prominently encompasses aggregation of spectrum opportunities and links that have been created by the usage of TV White Spaces, opportunistic spectrum access and spectrum sharing solutions[207]. SOLDER started in November 2013 and will continue until October 2016.

9.1.1.8 Cognitive Radio Standardization Initiative (CRS-i)

The aim of Cognitive Radio Standardization initiative (CRS-i) is to coordinate and support existing and future FP7 projects and to facilitate the exploitation of their results by establishing a concentrated approach to Cognitive Radio Systems standardisation[208]. This also includes removing barriers and ensuring the efficient participation of EU research in the global CR standardization process. CRS-i started in November 2012 and is scheduled to continue until October 2015.

204 ICT-CREW http://www.crew-project.eu, accessed June 2014
205 ICT-CROWN, http://cordis.europa.eu/projects/rcn/90432_en.html, accessed June 2014
206 ICT-COGEU, http://www.ict-cogeu.eu, accessed June 2014
207 ICT-SOLDER, http://ict-solder.eu, accessed June 2014
208 ICT-CRS-i, http://www.ict-crsi.eu, accessed June 2014

9.1.1.9 Aerial Base Stations with Opportunistic Links For Unexpected and Temporary Events (ABSOLUTE)

ABSOLUTE aims to design and validate an innovative rapidly deployable future network architecture which is resilient and capable of providing Broadband multi-service, secure and dependable connectivity for large coverage areas affected by large scale unexpected events (or disasters) leading to the partial or complete unavailability of the terrestrial communication infrastructure or for temporary events leading to the demand for very high throughput and augmented network capacity[209]. ABSOLUTE heavily incorporates cognitive radio concepts in its solutions. ABSOLUTE started in October 2012 and finishes in September 2015.

9.1.2 European Defense Agency Funded Programs

9.1.2.1 COgnitive RAdio for dynamic Spectrum MAnagement (CORASMA)

CORASMA is an EDA funded initiative that ran from November 2010 to November 2013 to study "the application of the Cognitive Radio (CR) to military needs and to assess the benefits of such technique."[210]

9.1.3 National-funded Programs

9.1.3.1 C4/19

C4/19 is a CR-related research project by the Signal and Image Centre at the Royal Military Academy in Brussels, Belgium[211]. Its main objectives are broken down into three areas: make a survey of software defined radio and CR techniques, study spectrum management in UHF and VHF bands, and study waveform design for ad-hoc tactical CRs. The research project began in January 2009 and lasts for 54 months.

9.1.3.2 Software and Cognitive Radio for Telecommunications (SOCRATE)

The SOCRATE Research Team is led by Inria from Lyon, France and partners with the Insa-Lyon Engineering School in France. The SOCRATE Research Team purposed to maintain up-to-date knowledge of SDR technologies and propose new solutions to research challenges regarding SDR systems[212]. SOCRATE research areas are to develop a flexible radio front-end, study how distributed signal processing will enhance performance and reduce power consumption, and analyze various software radio programming models.

9.1.3.3 Virtual Centre of Excellence in Mobile and Personal Communications (Mobile VCE)

Mobile VCE is a UK consortium of industry and universities that aims to achieve progress in a number of areas of mobile communications technology through coordinated, focussed research. Mobile VCE has worked heavily on spectrum sharing and cognitive radio related technologies in some of its "Core" research programs, particularly Core 4 "Wireless Efficiency" research for example[213]. Mobile VCE is partly funded by contributions from the UK research-funding councils, and partly by financial contributions (membership fees) from industry partners.

209 ICT-ABSOLUTE, http://www.absolute-project.eu, accessed June 2014
210 http://lenst.det.unifi.it/node/590
211 Royal Military Academy. *C4/19*. http://www.sic.rma.ac.be/research/RURN/proj-6.html, accessed June 2014
212 SOCRATE Research Team, *Software and Cognitive radio for telecommunications*. http://www.inria.fr/en/teams/socrate, accessed June 2014
213 Mobile VCE Core 4 Wireless Efficiency, http://www.mobilevce.com/wireless-efficiency, accessed June 2014

9.1.4 Other Collaborative Initiatives

9.1.4.1 Authorized Shared Access (ASA) and Licensed Shared Access (LSA)

ASA is a joint initiative of 7 companies: Digital Europe, Ericsson, Huawei, Intel, Nokia, NSN, and Qualcomm. Its purpose is to promote the use of unused spectrum in Europe using dynamic spectrum access and cognitive radio technology[214]. In Europe, there are many spectrum bands that are left unused or used infrequently. ASA seeks to grant shared access licenses to users to operate on bands that have been licensed to other users. One operator can pay another operator for a certain amount of bandwidth, at a certain quality of service. This type of system uses the idea of a licensed secondary user, in which the secondary user has rights to the spectrum in locations (time, frequency, geographic) where the primary user is not present. A licensed primary and secondary user can also be thought of as two licensed primary users, where one has priority over the other. Having licenses for shared access allows operators to predict the quality of service. For ASA to succeed, the project must look beyond technical details and develop standardization requirements and discuss new spectrum policies.

LSA is a recent attempt to codify ASA by bringing licensing to the forefront in the concept, implying a guaranteed quality of service for the secondary user (spectrum borrower) as well as the primary[215]. There are different viewpoints on what LSA is, however, one key observation is that while ASA incorporates cognitive technology (or at least, initially did), LSA appears to be currently directed more toward pure "sub-licensing" of spectrum.

9.1.4.2 COST Actions

COST Actions are a form of EU collaboration that is not a "program" in the traditional sense of being funded in order to undertake research activities. COST Actions fund only research visits and events supporting for collaborative work, not the research itself. More about COST Actions can be read at reference[216].

There are two key recent COST Actions that are highly-relevant to the topic of this report. One is COST IC0902, which worked on Cognitive Radio technologies from a "layered" perspective, bringing solutions forward that consider the PHY implications, MAC implications, cross-layer implications, and other aspects, of the realisation of Cognitive Radio technologies[217]. COST IC0902 commenced in December 2009 and ended in December 2013.

Another key COST Action is COST-TERRA, which worked on regulatory implications of cognitive radio and related technologies, taking strongly into account technical, economic and societal implications[218]. The key intention was to advance the prospects of cognitive radio technologies, and associated benefits through the development of regulatory solutions, noting that regulation is one of the key challenges that must be overcome in the realization of such technologies. COST-TERRA commenced in May 2010 and lasted until May 2014.

214 Qualcomm. *ASA (Authorized Shared Access) – A Novel Spectrum Policy Vision.* http://ipsc.jrc.ec.europa.eu/fileadmin/repository/sta/corsa/docs/SDR_ASA.pdf, accessed June 2014

215 EU Radio Spectrum Policy Group (RSPG), "RSPG Opinion on Licensed Shared Access," November 2013, accessible at https://circabc.europa.eu/d/d/workspace/SpacesStore/3958ecef-c25e-4e4f-8e3b-469d1db6bc07/RSPG13-538_RSPG-Opinion-on-LSA%20.pdf, accessed June 2014

216 European Cooperation in Science and Technology (COST), http://www.cost.eu, accessed June 2014

217 COST IC902, http://newyork.ing.uniroma1.it/IC0902, accessed June 2014

218 COST-TERRA, http://www.cost-terra.org, accessed June 2014

9.2 US Programs

9.2.1 DARPA Programs[219]

9.2.1.1 neXt Generation Communications (XG)

The XG project is a DSA related project being funded by the Defense Advanced Research Projects (DARPA) who sponsors numerous defense related research projects. The project is headed by the Shared Spectrum Company (SSC) who is an industry leader in developing DSA technology for the Department of Defense. The purpose of XG is to develop the next-generation communication system for warfighters[220]. The project's significance lies in that it allows military radios to dynamically access spectrum. This ability is critical in foreign areas of operations because it allows operators to access 10 times the amount of spectrum than previously available with little to no set-up time and without interference to existing communications systems. There is no need to pre-plan frequency assignments or to deal with a country's muddled frequency spectrum assignments.

9.2.1.2 Wireless Network after Next (WNaN)

WNaN is a next-generation communications project also under development by DARPA. Instead of using traditional radio communications, WNaN uses Cognitive Radio (CR) techniques to adapt to changing battlefield conditions[221]. Nodes are set-up with each radio unit which creates an adaptable ad-hoc network. This project is significant in battlefield communications, because CR technology allows the network to adapt to changing geography and landscape. WNaN aims to use commercial, off-the-shelf systems to reduce overall cost. Raytheon BBN Technologies is the current contract holder for WNaN and has successfully tested the system in 2010[222].

9.2.1.3 Shared Spectrum Access for Radar and Communications (SSPARC)

There is significant research involving radar and communications. One such research project, proposed by DARPA, is SSPARC. SSPARC is an investigation into how communications can be used on spectrums currently reserved for radar[223]. Currently in the United States, the FCC has reserved a large portion of spectrum in the 3.5 GHz band for radar use; however, in most cases, that spectrum is hardly ever used. It would be a much more efficient use of spectrum to allow communication signals to operate in radar spectrum, especially since available spectrum is running scarce. The proposed study seeks to analyze the ability of communication systems to detect if radar spectrum is being used and if not be able to transmit information in that spectrum. A call for research proposals was put out by DARPA in February 2013[224].

9.2.1.4 Mobile Ad-Hoc Interoperable Network Gateway (MAINGATE)

The DARPA sponsored MAINGATE is a Network Centric Radio System which seeks to enhance the way warfighters

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219 Taken with permission from McGwier, Reed, Lichtman, Nguyen and Beggs, "World Wide Impact of Dynamic Spectrum Access," April 2013.

220 Shared Spectrum Company, DARPA neXt Generation Communications Program. http://www.sharedspectrum.com/resources/darpa-next-generation-communications-program/

221 Defense Industry Daily Staff, *WNAN: DARPA's Idea for Next-Generation Soldier Networks,* June 29, 2011. http://www.defenseindustrydaily.com/wnan-darpas-idea-for-next-generation-soldier-networks-05475/

222 Raytheon BBN Technologies, *Wireless Network After Next (WNAN).* http://www.bbn.com/technology/networking/wnan

223 DARPA, *Congested Frequencies: How to Improve Bandwidth Access for Military and Commercial Use.* Feb 8, 3013. http://www.darpa.mil/NewsEvents/Releases/2013/02/08a.aspx

224 Defense Advanced Research Projects Agency (DARPA), Solicitation Number: DARPA-BAA-13-24, *Shared Spectrum Access for Radar and Communications (SSPARC),* Feb 21, 2013. https://www.fbo.gov/index?s=opportunity&mode=form&id=8e85f738e53747b502b4b9c3732c2e54&tab=core&_cview=1

communicate[225] [226]. It provides enriched capacities for warfighters, whether on the move or stationary, to communicate via voice, video, or data. MAINGATE uses modern communication protocols, such as multiple-input multiple-output and dynamic spectrum access, to provide IP based communications to warfighters in areas with limited spectrum. In addition, the project seeks to reduce high latency and packet loss. MAINGATE is being developed by Raytheon and has successfully completed tests involving high bandwidth and low bandwidth users[227].

9.2.2 Enhancing Access to Radio Spectrum (EARS)

EARS is a study sponsored by the National Science Foundation to enhance the efficiency of spectrum usage[228]. EARS aims to utilize unused spectrum with dynamic spectrum access to deliver wireless-enabled goods and services to rural America which does not have access to the modern communications in urban areas, such as high-speed internet and next generation cellular technology. This study is unique in that it is an interdisciplinary study that involves researchers from mathematics, engineering, computer science, and economics. A significant portion of EARS research is in the regulatory and enforcement of dynamic spectrum. Researchers must find means of enforcing spectrum policy and analyze various enforcement protocols in order to establish solid regulatory requirements and being large-scale testing of dynamic spectrum.

In August 2010, a workshop was convened to make recommendations on achieving the goals of EARS. A subsequent call for research proposals was issued by NSF to achieve the goals set by the EARS workshop. Multiple grants were awarded, and in October 2013, the NSF held a Principal Investigators (PIs) workshop to review the ongoing research[229]. The following table summarizes the presentations made at that workshop.

Table 7: Summary of EARS projects presented at 2013 PI Workshop

Title	Award #	Principal Investigator	Summary Statement	Link
Enhancing Spectral Access via Directional Spectrum Sensing Employing 3D Cone Filterbanks: Interdisciplinary Algorithms and Prototypes	1247940, 1247853, 1247935, 1247946	Habarakada Madanayake (U. Akron), Chunsheng Xin (Norfolk State), Srinivasa Vemuru (Ohio State), Vijay Devabhaktuni (U. Toledo)	This project "proposes a new spectrum sensing architecture combined with joint link scheduling and routing to significantly enhance access to the radio spectrum."	http://www.nsf.gov/awardsearch/showAward?AWD_ID=1247940&HistoricalAwards=false
Spectral Tweets: A Community Paradigm for Spatio-temporal Cognitive Sensing and Access	1247885	Nikolaos Sidiropoulos (U. Minnesota)	"The vision and starting point of this project is that today's smart phones and tablets are ideal platforms for crowdsourcing spectrum sensing, and this is a viable way to create a spectrum sensing web that spans across much of our living and working space"	http://www.nsf.gov/awardsearch/showAward?AWD_ID=1247885&HistoricalAwards=false

225 DARPA Strategic Technology Office, *Mobile Ad hoc Interoperability Network GATEway (MAINGATE)*.http://www.darpa.mil/Our_Work/STO/Programs/Mobile_Ad_hoc_Interoperability_Network_GATEway_%28MAINGATE%29.aspx

226 Defense Advanced Research Projects Agency (DARPA), Solicitation Number: BAA08-21, *Mobile Ad hoc Interoperability Network GATEway (MAINGATE),* May 30, 2008. https://www.fbo.gov/index?tab=core&s=opportunity&mode=form&id=64abdb70de09c847db0614e83ad31de4

227 Lynford Morton, *As Lead Technology Integrator for AEWE, Raytheon Demonstrates High-Bandwidth Wireless Communications and Network Interoperability*, May 11, 2010. http://investor.raytheon.com/phoenix.zhtml?c=84193&p=irol-newsArticle&id=1425196

228 National Science Foundation (NSF), *Enhancing Access to the Radio Spectrum (EARS),* Jan 14, 2013. http://www.nsf.gov/pubs/2013/nsf13539/nsf13539.htm

229 http://www.nsf.gov/mps/ast/ears_pi_workshop.jsp

Title	Award #	Principal Investigator	Summary Statement	Link
Spectrum Efficiency Analysis using Multisite Spectrum Observatory Network	1248000	Dennis Roberson (IIT)	"the resulting research objectives are: 1) create a sufficiently low-cost and scalable approach to generating and accessing the necessary high quality RF dataset; 2) provide new methods for analyzing, modeling, and visualizing the resulting large, multi-dimensional information base; and 3) model spectrum activity to test the feasibility of spectrum sharing in candidate bands in order to facilitate decision making and innovation in spectrum repurposing and sharing."	http://www.nsf.gov/awardsearch/showAward?AWD_ID=1248000&HistoricalAwards=false
Market Structures for Efficient Spectrum Sharing	1247984	Randall Berry (Northwestern)	"The cross-disciplinary study of … market structures and the related spectrum sharing technologies is the focus on this project."	http://www.nsf.gov/awardsearch/showAward?AWD_ID=1247984&HistoricalAwards=false
Techno-Economic Models of Secondary Spectrum Use	1247546	Martin Weiss (U. Pittsburgh)	"This research explores some essential but unexplored techno-economic aspects of DSA that are crucial if these systems are to come to commercial reality."	http://www.nsf.gov/awardsearch/showAward?AWD_ID=1247546&HistoricalAwards=false
Providing Predictable Service and Spectrum Access With Realtime Decision in Cognitive Multihop Wireless Networks	1247944	Xiang-Yang Li (IIT)	The objective of this project is to design real-time temporal-spatial spectrum sharing, trading and accessing schemes to improve the network performances by fully exploiting the channel availability (e.g., spatial, temporal, and spectral) and quality (e.g., signal to interference plus noise ratio and data rate) diversities.	http://www.nsf.gov/awardsearch/showAward?AWD_ID=1247944&HistoricalAwards=false
Cog-TV: Business and Technical Analysis of Cognitive Radio TV Sets for Enhanced Spectrum Access	1247941, 1247914	Mehmet Vuran (U. Nebraska) & Eylem Ekici (Ohio State)	This project explores whether it is "economically and technically viable for broadcast companies to utilize TV white spaces for low-cost Internet provision and web-enabled TV services."	http://www.nsf.gov/awardsearch/showAward?AWD_ID=1247941&HistoricalAwards=false
Achieving Efficient Spectrum Usage in Active and Passive Sensing Through a Market-Based Approach	1247840	Joel Johnson, Chris Baker, Lixin Ye (Ohio State)	"The research will investigate the incorporation of a time dimension to spectral allocations, and will also investigate relevant market assessments of the value of spectrum made available through temporal sharing."	http://www.nsf.gov/awardsearch/showAward?AWD_ID=1247840&HistoricalAwards=false
Manifold-Based System for Passive-Active Spectrum Sharing	1248010	Albin Gasiewski (U. Colorado)	The research explores "coordinated interference mitigation techniques" to be used where terrestrial based transmitters may interfere with space-based remote sensing systems.	http://www.nsf.gov/awardsearch/showAward?AWD_ID=1248010&HistoricalAwards=false

Title	Award #	Principal Investigator	Summary Statement	Link
Technical, Economic, and Regulatory Evaluation and Demonstration of Policy based Dynamic Spectrum Access-Enabled Broadband Wireless Communications Networks	1216186	Mark McHenry (Shared Spectrum Co.) & Martin Weiss (U. Pittsburgh)	"This … project will demonstrate the technical and commercial feasibility of the near-term innovative Dynamic Spectrum Access (DSA) technology to efficiently share spectrum resources with legacy Federal systems."	http://www.nsf.gov/awardsearch/showAward?AWD_ID=1216186&HistoricalAwards=false
Reconfigurable Wireless Platforms for Spectrally Agile Coexistence	1212340	Sam MacMullan (ORB Analytics) & Alexander Wyglinski (Worcester Polytechnic U)	"This … project will involve research on and development of a reconfigurable wireless platform enabling secondary access of wireless spectrum via simultaneous data transmission across several disjoint frequency channels."	http://www.nsf.gov/awardsearch/showAward?AWD_ID=1212340&HistoricalAwards=false
Spectrum Efficient Waveform Design with Application to Wireless Networks	1247848, 1247694, 1247875	Qilian Liang (U. Texas), Hyeong-Ah Choi (George Washington U.), Jie Wang (U. Massachusetts)	"This project seeks innovative approaches on nested and co-prime samplers for spectrum efficiency, and subsequently applies it to wireless networks."	http://www.nsf.gov/awardsearch/showAward?AWD_ID=1247848&HistoricalAwards=false
Interference-Aware RF Theory and Design	1247915	Amir Avestimehr (Cornell U.)	"The objective of this … program is to develop disruptive Radio Frequency (RF) technologies that provide significant spectral efficiency gains at the physical layer, by leveraging recent advances in physical layer interference management and integrated receiver design."	http://www.nsf.gov/awardsearch/showAward?AWD_ID=1247915&HistoricalAwards=false
Spectrally Aware Interference Tolerant RF Nanosystems	1247893	Dimitrios Peroulis (Purdue)	"The overarching goal of this proposal is to investigate fundamental issues of interference mitigation based on novel filtering architectures and nanomechancial resonators."	http://www.nsf.gov/awardsearch/showAward?AWD_ID=1247893&HistoricalAwards=false
Beamspace Communication Techniques and Architectures for Enabling Gigabit Mobile Wireless at Millimeter- Wave Frequencies	1247583	Akbar Sayeed (U. Wisconsin)	"The objective of this project is to develop basic theory and design strategies for new wireless communication architectures that are expected to deliver transformative enhancements in the access to, and usage of, the electromagnetic spectrum at millimeter-wave frequencies."	http://www.nsf.gov/awardsearch/showAward?AWD_ID=1247583&HistoricalAwards=false

Title	Award #	Principal Investigator	Summary Statement	Link
Test Methodology for MIMO Over the Air Testing in a Small Anechoic Chamber	1217558	Fanny Mlinarsky (octoScope, Inc.) & Nicholas Kirsch (U. New Hampshshire)	"This … project will investigate the feasibility of using a small controlled environment for over-the-air (OTA) testing and validation of multiple antenna radio systems for next generation wireless networks."	http://www.nsf.gov/awardsearch/showAward?AWD_ID=1217558&HistoricalAwards=false
Cognitive and Efficient Spectrum Access in Autonomous Wireless Networks	1247924, 1247955, 1247929	Xin Wang (SUNY Stony Brook), Shiwen Mao (Auburn), & Harish Viswanathan (Alcatel-Lucent)	"The objective of this project is to enable more efficient and reliable operation of autonomous femtocell networks with agile spectrum access, autonomous interference control, as well as intelligent network self-organization and self-optimization."	http://www.nsf.gov/awardsearch/showAward?AWD_ID=1247924&HistoricalAwards=false
Dynamic Behavior and Coexistence of Intelligent Radio Spectrum Access Systems	1247909	Xiaohua Li (SUNY Binghamton)	"This project develops a theoretical framework for modeling and analyzing the dynamic behavior and the coexistence of heterogeneous DSA systems."	http://www.nsf.gov/awardsearch/showAward?AWD_ID=1247909&HistoricalAwards=false
Design, Analysis and Implementation of Social Interactions in Cognitive Radio Networks	1247834, 1247778	Husheng Li (U. Tennessee) & Robert Qiu (Tennessee Tech)	"This research studies the social interaction mechanism for secondary users to fully exploit the … temporal and spatial correlations of spectrum availability."	http://www.nsf.gov/awardsearch/showAward?AWD_ID=1247834&HistoricalAwards=false
SAVANT - High Performance Dynamic Spectrum Access via Inter Network Collaboration	1247764	Dipankar Raychaudhuri (Rutgers)	"This project is aimed at achieving significant spectrum efficiency gains through inter network collaboration in radio resource management."	http://www.nsf.gov/awardsearch/showAward?AWD_ID=1247764&HistoricalAwards=false
SpiderRadio: Enabling Cognitive Dynamic Spectrum Access Wireless Communications	1212357	Vijay Kumar (Dynamic Spectrum, LLC) & R. Chandramouli (Stevens)	"This … project consists of the research and development of a comprehensive, integrated multi-layer solution for cognition enabled dynamic spectrum access wireless communications. Several spectrum measurement studies indicate that valuable radio spectrum is severely underutilized."	http://www.nsf.gov/awardsearch/showAward?AWD_ID=1212357&HistoricalAwards=false
Autonomous Cognitive Radios for Smart Communications for First Responders	1217444	Kamil Agi (K&A Wireless) & Sudharman Jayaweera (U. New Mexico)	"This … project seeks to develop a cognitive radio system to provide reliable wireless communications to first responders."	http://www.nsf.gov/awardsearch/showAward?AWD_ID=1217444&HistoricalAwards=false

Title	Award #	Principal Investigator	Summary Statement	Link
Enhanced Radio Spectrum via Information Acquisition and Learning	1247995, 1248017	Tara Javidi (UC San Diego) & Bhaskar Krishnamachari (USC)	"This research focuses on the problem of information acquisition in the context of spectrum sensing and utilization where a (set of) decision maker(s) … dynamically refines his/her belief about stochastically time-varying parameters of interest such as spectrum availability and quality."	http://www.nsf.gov/awardsearch/showAward?AWD_ID=1247995&HistoricalAwards=false
Big Bandwidth: Finding Anomalous Needles in the Spectrum Haystack	1247864, 1247298	Wade Trappe (Rutgers) & Paul Prucnal (Princeton)	"The objective of the project is to explore the problem of scanning large amounts of spectrum in order to detect anomalous usage of that spectrum."	http://www.nsf.gov/awardsearch/showAward?AWD_ID=1247864&HistoricalAwards=false
Enabling local spectrum markets for enhanced access and flexible service	1247958	Koushik Kar (RPI)	This project "studies the viability of regional wholesale spectrum markets …, investigates the design and pricing of flexible provider-customer spectrum service contracts … and studies access, security and incentive mechanism design questions that can enable users to serve as micro-providers."	http://www.nsf.gov/awardsearch/showAward?AWD_ID=1247958&HistoricalAwards=false
Paving the way to dynamic spectrum sharing: Understanding regulatory and enforcement mechanisms	1247928	Jeffrey Reed (Va Tech)	"The objective of this program is to help eliminate key barriers to implementing new spectrum sharing policies though the development of regulatory and enforcement mechanisms that protect incumbents users."	http://www.nsf.gov/awardsearch/showAward?AWD_ID=1247928&HistoricalAwards=false
Efficient Management and Opportunistic Usage of Radio Spectrum based Graph Theory	1247545	Geoffrey Ye Li (Ga Tech)	"The objective of this project is to … utilize graph theory/algorithms to develop efficient resource management schemes for general coexistence scenarios."	http://www.nsf.gov/awardsearch/showAward?AWD_ID=1247545&HistoricalAwards=false
Enhanced Spectral Efficiency through Adaptive Utilization of Fragmented Spectrum	1217475	Luzhou Xu (IAA) & Tan Wong (U. Florida)	"This … project aims at addressing the challenging issue of spectrum scarcity for high throughput wireless communication systems by developing an innovative cognitive radio (CR) communication system capable of operating within a fragmented spectral band."	http://www.nsf.gov/awardsearch/showAward?AWD_ID=1217475&HistoricalAwards=false

Title	Award #	Principal Investigator	Summary Statement	Link
MEMS Reconfigurable Radios: System Development and Entry Costs in Wireless Phones	1247565	Mina Rais-Zadeh (U. Michigan)	"This research …develops a miniaturized micromachined tunable filters as well as hard-contact high-power micromachined transmit/receive switches …, implements new flexible wireless transmitter and receiver integrated circuit schemes …, produces empirical estimates and interprets them in the context of market entry costs based on the proposed reconfigurable radio technology.	http://www.nsf.gov/awardsearch/showAward?AWD_ID=1247565&HistoricalAwards=false
Novel Beam Steering Apertures and Waveforms for High Capacity Broadband Wireless Nodes	1247503	Mohammod Ali (U. South Carolina)	"This work … brings together innovations in beam steering antenna arrays and interference immune waveforms and algorithms."	http://www.nsf.gov/awardsearch/showAward?AWD_ID=1247503&HistoricalAwards=false
Adaptive Miniaturized Ultrawideband Antenna	1212319	Johnson Wang (Wang Electro-Opto Corp) & John Volakis (Ohio State)	"This … project aims at an adaptive ultrawideband miniaturized antenna with the capability of real-time adaptation to changes in mobile operating environments."	http://www.nsf.gov/awardsearch/showAward?AWD_ID=1212319&HistoricalAwards=false
Transparent Coexistence for Multi-Hop Secondary Cognitive Radio Networks: Theoretical Foundation, Algorithms, and Implementation	1247830	Thomas Hou (Va. Tech)	"The goal of this project is to make a fundamental advance in the transparent coexistence paradigm for multi-hop secondary networks."	http://www.nsf.gov/awardsearch/showAward?AWD_ID=1247830&HistoricalAwards=false
Software-Defined Multi-pulse Wideband Radios for Spectrum Reuse and Assured Communications	1212314	Richard Twogood (Dirac Solutions) & Farid Dowla (UC Santa Cruz)	"This … project seeks to develop secure/covert short-range wireless personal area communication networks by addressing the critical technical challenges of RF communications in harsh environments."	http://www.nsf.gov/awardsearch/showAward?AWD_ID=1212314&HistoricalAwards=false
Metamaterial Based Vacuum Electron Devices for Next Generation Communication Systems	1212327	Jagadishwar Sirigiri (Bridge12) & Mohammed Afsar (Tufts)	"This … project aims to develop novel technology for Vacuum Electron Devices (VED) such as Traveling Wave Tubes (TWT) for the next generation high spectral efficiency, high data rate civilian and military communication systems."	http://www.nsf.gov/awardsearch/showAward?AWD_ID=1212327&HistoricalAwards=false

9.3 ITU Region 3

9.3.1 Japan

The National Institute of Information and Communications Technology has been heavily involved in Spectrum Sharing research[230].

9.3.2 Republic of Korea

Given the global trend, after DTV channel relocation, Korea needs to modify the existing law and policy such as Radio Waves Act and its Enforced regulation, notifications and technical rules allowing new wireless communication services introduced through spectrum sharing on the broadcasting spectrum band. Government has introduced the application plan of TVWS in December 2010 and organized a steering committee prepared roadmap of TVWS policy in 2011, technical verification committee in 2012 and operational expert group in 2013.

9.3.2.1 Experimental Service Program

Experimental Service Program launched a TVWS-related service sponsored by government and coordinated by RAPA (Korea Radio Promotion Association) in 2012.The purpose of this program was to develop the feasibility of new services in TVWS. Two services were carried out through this program, one was public domain service provided by NEMA(National Emergency Management Agency) at Namyangju City and the other demonstrated the feasibility of high speed wireless internet service at Jeju island in November 2011.

9.3.2.2 Trial Service program

Trial service was driven for preliminary commercial service coordinated by RAPA in August 2013. Five consortiums were selected in this trial service program and demonstrated high speed wireless internet service, hybrid HDTV, smart grid wireless service and various trial services.

In December 2013, a workshop was convened to present achievements of the trial service program. Presentation issues at this workshop are summarized

230 Hiroshi Harada, "White Space Communications Systems: An Overview of Regulation, Standardization and Trial," IEICE Transactions on Communications, Vol E97-B, No. 2, February 2014

as following:

- TVWS trial service progress
- TVWS DB development
- TVWS applications
- Trial service demonstration

9.3.2.3 Other collaborative initiatives

The Smart Spectrum Engineering Research Center(SSE-ITRC) inaugurated in this year, part of the university IT research center specializing on the subject of spectrum and radio technologies for smart frequency utilization sponsored by government and coordinated by NIPA(National IT Industry Promotion Agency). SSE-ITRC is now carrying out research and development projects on the open spectrum engineering including frequency sharing technologies, core technology development of enhanced spectrum efficient transmission systems and enterprise-university co-development for new radio services and products.

Government is now preparing practical document suggesting how to revise the existing policy related law for TVWS commercialization after accomplishment of national TVWS policy from 2011 and for spectrum sharing application to new commercial services.

9.4 Analysis and Conclusions

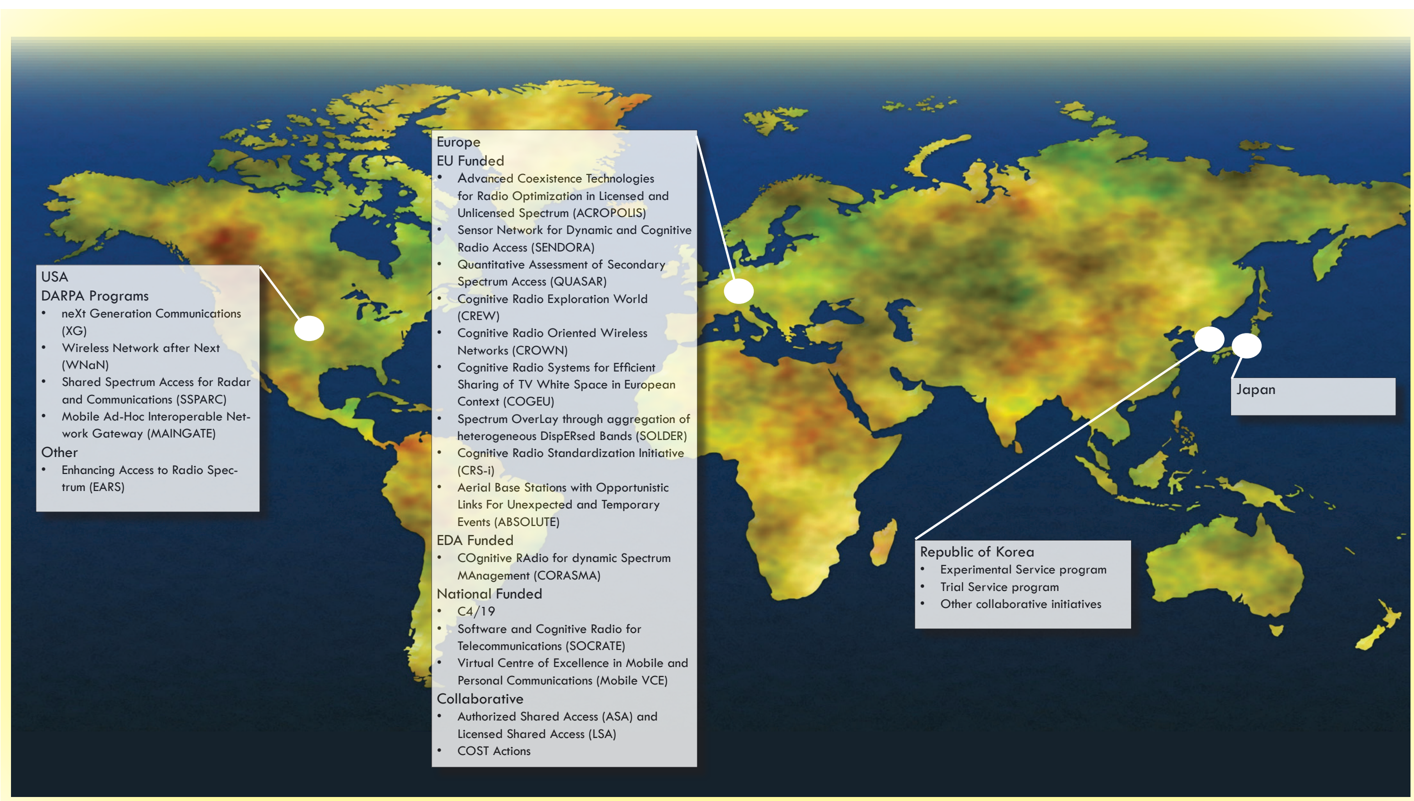


Figure 25: Spectrum Sharing Research Programs Worldwide

While many country and regions are investing in academic research in spectrum sharing, a review of the programs presented appears to indicate that the US is making the largest publically funded investment in spectrum sharing research for defense purposes, and the European Union, through its Framework 7 Programme, appears to be making the largest publically funded investment in spectrum sharing research for commercial use. Both of these investment areas have had broad industry participation. It is recognized that there is also private investment ongoing in many regions around the world, but information on these is often hard to find due to the protections placed on the intellectual property under development.

A review of the programs presented also shows a significant repetition of effort, with research occurring in areas that have already been adequately explored. An international harmonizing body or industry association may be required to help quantify the foundation of existing research and focus investment in research and development required to establish the spectrum sharing technology ecosystem.

Further Reading

1) TIA, "Spectrum Sharing Research and Development", https://www.tiaonline.org/sites/default/files/pages/SpectrumSharingR%26DPaper%3D10-20-13.pdf

10

Technology Review

10.1 Introduction to the Technology Review

This section focuses on technology advances and product development for dynamic spectrum sharing. The focus is twofold: field tested R&D systems and technology R&D roadmaps toward implementations. In addition, this section focuses on technology advances and new developments. Products addressed include white space and TV band devices and other dynamic spectrum sharing products and technologies. This section highlights those products and systems available now or in very short order. Bands are tied to what equipment is available in each band. Spectrum sharing databases are a key enabling technology, so they are discussed as well. In this context spectrum sharing has been divided into the two categories homogeneous spectrum and heterogeneous spectrum.

10.1.1 Homogeneous Spectrum Sharing Technology

In homogeneous spectrum sharing, the same radio communication technology is used within a given shared spectrum band. LTE systems, for example, include spectrum sharing both in the 3GPP standard and via manufacturer-specific products. These spectrum sharing systems are limited to commercial mobile cellular services operating in licensed spectrum as their primary allocation. *Spectrum Sharing* in this context is defined as the result of assigning spectrum blocks for usage by multiple mobile network operators in a cooperative fashion. In homogeneous sharing, the licensee manages the sharing of spectrum resources on behalf of its customers. The licensee is protected from harmful interference from non-affiliated users. This arrangement applies to spectrum licensed for exclusive use, which accounts for most of the spectrum used by wireless network service providers (i.e. cellular operators). Homogeneous sharing occurs in the licensed wireless service bands and in bands that will be re-farmed or cleared. This arrangement corresponds to sharing level 0 (exclusive use) or level 4a (pool of spectrum to be shared) of the levels of spectrum access described in section 2 of this report.

10.1.2 Heterogeneous Spectrum Sharing Technology

In heterogeneous spectrum sharing, on the other hand, different radio services (in the regulatory sense) occur in the same radio band and locale at the same time. In particular, heterogeneous shared spectrum may be allocated to a primary user such as naval radar that makes little to no use of the band except in relatively limited locations and time periods. As a special case of heterogeneous spectrum sharing, alternative communications technologies may co-exist in the same band and in the same locale at the same time. TV white space sharing of spectrum with unique signals of wireless internet service providers (WISP) exemplify this type of heterogeneous shared spectrum. Future shared spectrum bands may mix other technologies such as WiMAX, LTE, and WiFi air interfaces adapted to a shared band such as the US Citizens Broadband Service (CBS) in the 3550 MHz band.

In the CBS band, US naval radars, for example, may operate along coastlines on an infrequent basis. For large land masses, the spectrum allocated to radar is both unused and unusable across most of the country by regulation. Sharing such spectrum enables secondary usage provided such users defer to the incumbent, e.g. military radar usage in certain locales or when detected by a secondary user. For example, cellular network service providers may employ channels of a share spectrum band for small cells while private citizens and businesses employ other channels of the same shared spectrum band at the same time for short range wireless local area networking (WLAN), the familiar WiFi experience. Level 0 spectrum usage allocates different bands for exclusive use of small cells on the one hand versus WiFi where exclusive use is not provided. Level 4 enables sharing of a single band in a pooled arrangement. Radio technologies in a given heterogeneous sharing arrangement may be uniform or not. Small cells and WLAN devices both may employ LTE, for example, or not, corresponding to Level 3 sharing. While the typical use case envisions LTE in small cell channels, WLAN devices may employ proprietary interference resistant signals in space such as those of xG[231].

TV white space (TVWS) provides an example of heterogeneous spectrum sharing where certain channels of the TV UHF band contain digital television broadcast (DTV), while other channels may contain backhaul for a wireless internet service provider (WISP), and others may contain WLAN signals. TV white space devices where the secondary TVWS usage is allowed provided it does not "cause harmful interference" to the primary licensee, e.g. television broadcast.

Multiple wireless services may operate in heterogeneous shared spectrum based on regulatory policy, usage priorities (such as according to service tier), secondary market structure, and other innovative regulatory rules and technologies. Heterogeneous spectrum sharing in this context includes the managed allocation, assignment, and authorization of spectrum for the usage of a variety of wireless network use cases including small cells, backhaul, WLAN, and short range indoor radio access networks termed Closed Access Facilities (CAF). Coexistence of signals in space may be managed by personal or commercial infrastructure access points themselves; by an associated larger wireless service provider network; by an authorized third party spectrum access system (SAS); or by a combination of these methods. The Notice of Proposed Rule Making (NPRM), License Public Notice, and Further NPRM (FNPRM) for the 3550-3700 MHz band in the US envisions allocation, management, and enforcement of that band as a Citizens Broadband Service (CBS) via one or more federally authorized commercial SAS networks.

Heterogeneous spectrum sharing, thus, is the regulatory regime in which underutilized bands such as military radar bands may be put to other usage, such as WiFi-like indoor short range wireless LANs or to outdoor small cells. In the US Citizens Broadband Service (CBS) proposed for the 3550-3700 MHz band, WiFi like usage is termed General Authorized Access (GAA). Commercial small cells may be protected from GAA interference as secondary users py purchasing a Priority Access License (PAL). Such secondary and tertiary usage must not cause harmful interference to the federal incumbent. Such a three tier arrangement enables heterogeneous technology deployments in the same band, such as LTE small cells and WiFi or WiMAX like GAA devices along with the incumbent military radar. Thus, heterogeneous spectrum sharing creates new opportunities for novel usage where multiple users access spectrum in complementary ways allowing one or more tiers of shared access to coexist with incumbents on a non-interfering basis. Heterogeneously shared spectrum combines levels 1, 2, 3 and 4 of the levels of spectrum access described in section 2. Depending on the regulatory regime, heterogeneously spared spectrum may combine methods under the control of an authorized entity such as SAS in the US or by rule, such as ASA in Europe, or on an ad-hoc basis such as sharing of the 5GHz radar band by WiFi devices in a detect-and-avoid schema.

10.1.3 Heterogeneous Networks

In contrast to heterogeneous shared spectrum, heterogeneous networks combine multiple bands with multiple air interfaces into a coherent user experience. Bands may include spectrum licensed for common carrier services (e.g. 2G

231 xG Patent Awarded 27 May 2014, http://www.prnewswire.com/news-releases/xg-technology-announces-new-cognitive-radio-patent-award-260744261.html

GSM, 3G WCDMA, and 4G LTE bands), unlicensed bands (e.g., Wi-Fi), and/ or shared spectrum such as the future CBS band into a given wireless device.

10.2 Homogeneous Spectrum Sharing Technologies

This section is specifically focused on the sharing of available resources within a coverage area that is common to the sharing operators, and where sharing can lead to a more balanced and efficient use of limited resources, whether these are limited by their very nature, as for licensed spectrum, or by business case, when operators wish to reduce capital expenditure required to deploy network infrastructure.

10.2.1 Homogeneous Sharing in LTE

The 3GPP standards body responsible for the LTE-Advanced technology has published technical specification and technical reports addressing various aspects of resource sharing in LTE-Advanced, looking at various considerations from network architectures, deployment scenarios, service aspects and requirements, RAN sharing, network operations and resource management. Two sharing models have been defined for LTE-Advanced: Multi-Operator Core Network (MOCN), where operators share Radio Access Network (RAN) and can pool their spectrum, but operate independent CNs; and Gateway Core Network (GWCN), where operators share certain elements of the CN in addition to RANs and spectrum.

10.2.2 Manufacturer-Specific Homogenous Spectrum Sharing

Manufacturers openly discuss generic solutions to network sharing as is the case for Nokia Siemens Networks[232, 233, 234] and Ericsson[235] and have been doing so for over a decade[236]. NEC, Huawei, and Alcatel-Lucent also offer comprehensive manufacturer-specific implementations as well as technology R&D roadmaps toward homogeneous spectrum sharing.

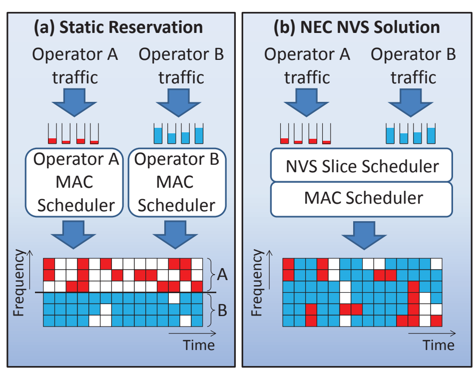


Figure 26: (a) Static Reservation vs. (b) NEC's Network Virtualization Substrate Solution

232 Nokia Siemens Networks, "Network sharing MORAN and MOCN for 3G," May 2013.

233 Nokia Siemens Networks, "Infrastructure Sharing in Practice: Sharing Mobile Networks," NTC ITU ASP COE Workshop on Infrastructure Sharing, September 2010.

234 Nokia Siemens Networks, "Infrastructure Sharing and Shared Operations for Mobile Network. Operators," Proceedings of IEEE Int'l Conf. on Communications (ICC), May 2008.

235 Ericsson, "Network Sharing - Technical Possibilities in GSM/UMTS and LTE," May 2011.

236 Nokia, "Nokia launches Multi-Operator Radio Access Network for controlled 3G network sharing," Press Release, May 2001.

NEC, for example, proposes a sharing solution[237,238] illustrated in Figure 25. This solution features an "innovative" radio resource management (RRM) approach based on a network virtualization substrate (NVS) in the enhanced Node B (eNB), which manages sharing of the spectrum and radio processing resources and "allows these resources to be virtualized and shared in an efficient way." The NEC solution supports two types of virtual radio resources: (1) reserved resources, guaranteed to be always available to the operator that "owns" them; and (2) shared resources, which may be allocated to any operator based on a policy configured by the network manager as shown in Figure 25. Spectral efficiency is achieved by means of dynamic resource scheduling.

Figure 27 presents the infrastructure architecture to implement NEC's RAN sharing solution using the Network Virtualization Solution.

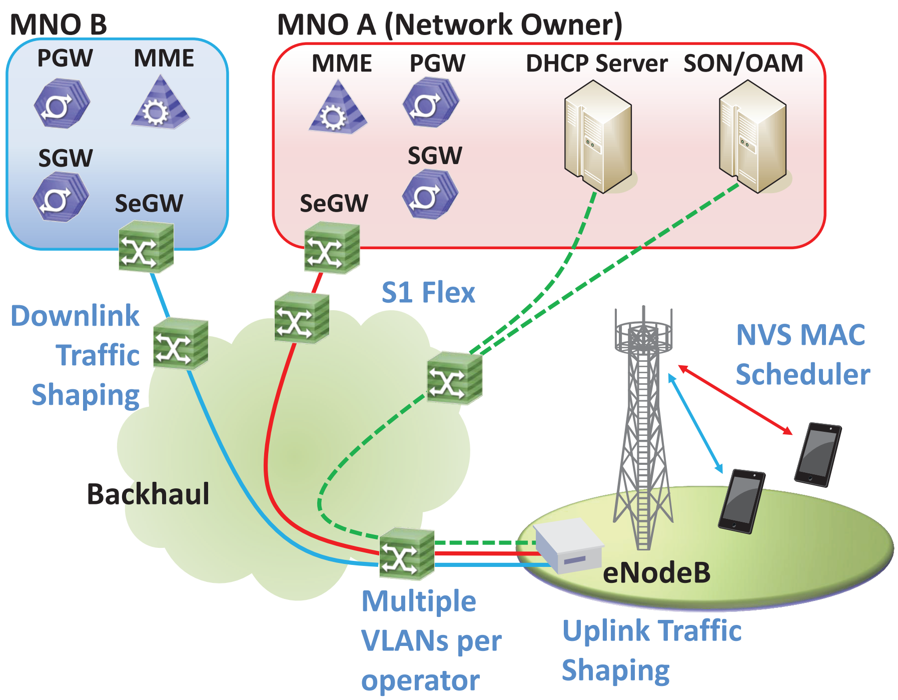


Figure 27: NEC's End-to-End RAN Sharing Solution

Huawei offers LTE infrastructure product solutions which support different spectrum and MOCN active network sharing configurations. Some of the features include resource carrier aggregation and resource usage fairness. For instance, when applying resource usage fairness, dynamic sharing and traffic throughput dynamic sharing can be controlled independently, the rate and sharing rate also can be configured independently. Unused resource within sharing rate can be dynamically shared between operators, it is the best balance between maximum resource usage and fairness between MOCN operators. The counter of traffic throughput and connected user can be reported by per operator. They can be used to measure the effect of dynamic sharing, and also can be used to settlement reference. Figure 27 presents Huawei's resource usage fairness concept.

237 NEC, "White Paper - RAN Sharing: NEC's Approach toward Active Radio Access Network Sharing," February 2013.
238 NEC, "CellSlice: Cellular Wireless Resource Slicing for Active RAN Sharing," Proceedings of Fifth Int'l Conference on Communication Systems and Networks (COMSNETS), January 2013.

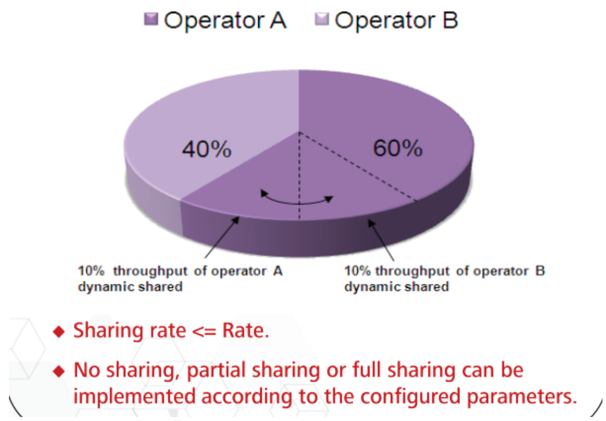


Figure 28: Resource Usage Fairness in Huawei Solution

In addition, Alcatel-Lucent reports on their LTE solution to support RAN sharing between operators[239]. This includes flexibility in spectrum management; capacity sharing; end-to-end QoS control; traffic separation between operators; and support for operator-based accounting information. Spectrum management would support dedicated and shared spectrum assignments, as depicted in Figure 28 for a scenario with two operators (A and B) having respective licensed spectrum BW#1 and BW#2. In these scenarios, subscribers with either operator would be assigned capacity in either spectrum block if shared. Their end-to-end QoS control model would support policing of resource assignment and fair access to resources, i.e. in order to guarantee fulfillment of sharing agreements between operators.

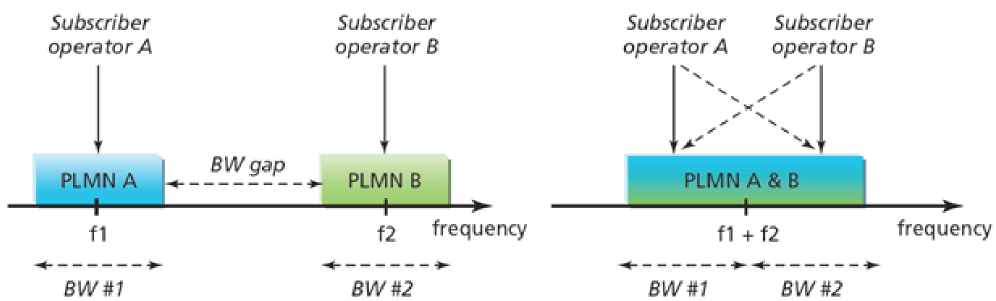


Figure 29: Spectrum Assignment in Alcatel-Lucent Solution.

Capacity sharing is achieved by Alcatel-Lucent with four different strategies depicted in Figure 29 "Fully pooled" with complete sharing of all radio resources; "Fully split" with the traditional approach of strict reservation per operator; "Partial reservation" representing the best compromise between the first two strategies; and "Unbalanced," which is a special case of partial reservation where resources are reserved for some but not all operators. The capacity sharing strategies depicted in Figure 29 are for a scenario with two operators (A and B) and available total capacity either reserved (solid colour) or shared (gradient colour), and are configured in the Network Management System using the same parameters used for configuring call admission control. To achieve fair use and fair access of resources, and to ensure that Service Level Agreements among sharing operators are respected, Alcatel-Lucent proposes that resource usage be reported individually for each sharing operator, and that traffic for each operator be separated using virtual LANs.

239 Alcatel-Lucent, "Technology White Paper: Network Sharing in LTE - Opportunity & Solutions," January 2010.

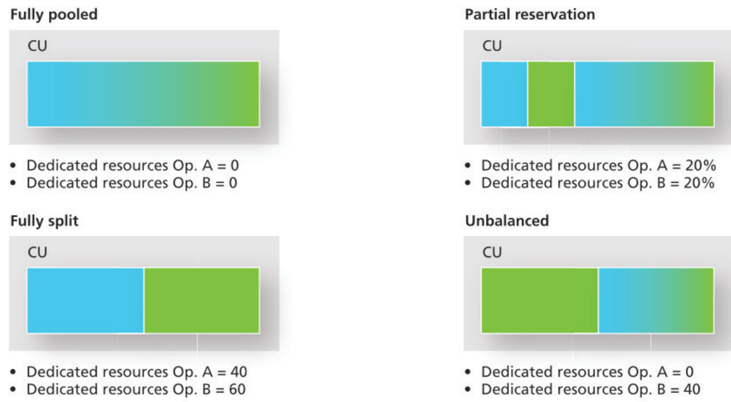


Figure 30: Capacity Sharing in Alcatel-Lucent Solution.

10.2.3 Technology Challenges of Homogeneous Spectrum Sharing

While the LTE standards provide a rich set of mandatory and optional features to support network sharing, some aspect of mobile networks are neither defined nor addressed by the standards, e.g., resource management and scheduling of resource assignment. Although the standards bodies address some of these challenges in technical reports, there is nothing mandatory that manufacturers must implement. These aspects are left up to the discretion of the manufacturers, who often propose proprietary, "closed" solutions which allow for competitive differentiation but reduce operator flexibility in configuring their network since proprietary solutions usually do not allow equipment interoperability between manufacturers.

10.3 Heterogeneous Spectrum Sharing Technologies

This section is specifically focused on the sharing of a band of spectrum resources heterogeneously within a coverage area that combines sharing of spectrum by multiple types of entity including an incumbent such as a military radar usage shared in space, time and RF with secondary users such as WLAN, commercial service providers (or network operators), and backhaul, all of which must defer to incumbent usage, not providing harmful interference. Heterogeneous spectrum sharing can lead to socially and economically more balanced and efficient use of limited radio spectrum resources.

10.3.1 Categories of Heterogeneous Spectrum Sharing

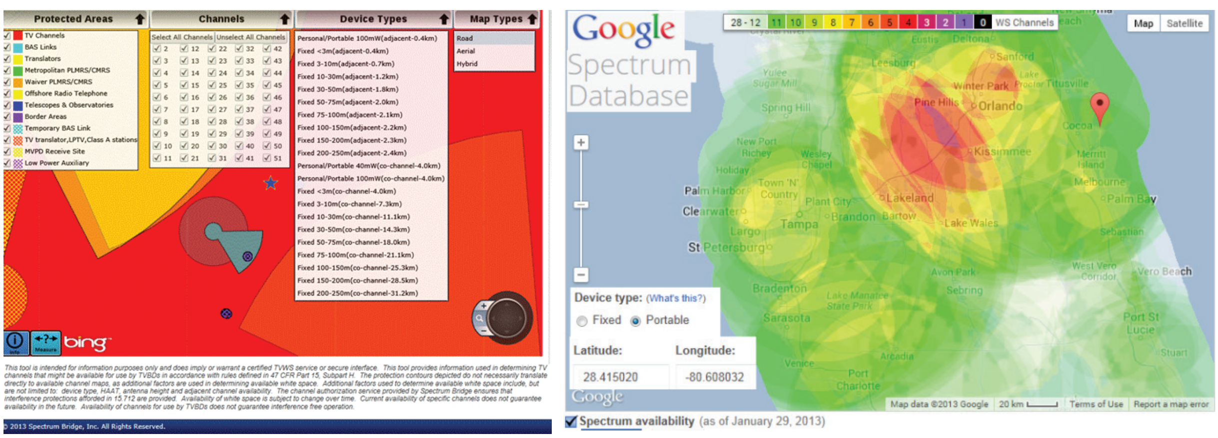
Two broad categories of heterogeneous spectrum sharing have emerged: database mediated heterogeneous shared spectrum and SAS mediated heterogeneous shared spectrum. These two categories are differentiated based on the time scales and complexity of mediation among incumbent and secondary usage.

Database mediation employs a public database with which a shared spectrum transmitter must interact on a daily basis to assure that the channel to be used in the locale to be radiated has not been reserved for incumbent usage. TV white space (TVWS) is the currently deployed example of database mediation. Often the TVWS databases do not accurately reflect reality on the ground. Channels specified as in use may be licensed but not operating, e.g. for an interim period of time between broadcast operators. Other channels not specified as in use may present harmful interference to a secondary user because of multipath propagation effects that are not accurately modeled in the database. The TVWS databases have provided a useful mechanism for enabling WISPs in the US to expand service to rural subscribers, e.g. in wooded regions where other radio bands are less effective in connecting a WISP RAP to an individual subscriber.

SAS-mediated heterogeneous shared spectrum has yet to be fully deployed. SAS as envisioned by the CBS NPRM will operate with much higher fidelity in space, time, and radio frequency. Rule-making includes alternate approaches to spectrum sensing for enforcement.

10.3.2 Database Mediated Heterogeneous Spectrum Sharing Technologies

Interference among early AM radio broadcast towers (1906 to 1927) resulted in the licensing of broadcast towers by location, which is a spatial mechanism for spectrum sharing among primary users. Regulatory practices of nearly the first 100 years (1887 to 1978) were based primarily on the allocation of usage to bands of spectrum for mobile users (e.g. ground to air radio for international flights of commercial aircraft), with location-based licensing of fixed assets such as radio and TV broadcasts. A contemporary version of location-based spectrum sharing is the US TV white space (TVWS) database, alternatives of which are illustrated in Figure 30.



(a) Spectrum Bridge (b) Google

Figure 31: Spatial Sharing of Unused Television (TV) Channels Mediated by Internet Databases

The spatial exclusion zones of these databases significantly oversimplify the patterns of available radio frequency channels and interference levels encountered in order to balance complexity of technology and fairness to licensed incumbents. Technology complexity, such as requiring measurements of incumbent radiation, could reduce separation but increases the cost of TVWS devices and hence would limit market uptake. The large number of TVWS devices listed in Figure 30 (a) shows the current proliferation of TVWS devices in US markets. Large exclusion zones of the databases reduce the probability of unintended interference by these new devices.

10.3.3 TV White Space (TVWS) Product Technologies

TVWS space products connect to a TVWS database via backhaul. Examples of TVWS radio products include RuralConnect from Carlson Wireless (www.carlsonwireless.com) that delivers extended coverage, non-line-of-sight (NLOS) broadband connectivity by transmitting over TVWS frequencies, 470 to 698 MHz, which offer superior signal propagation characteristics. According to Carlson, TVWS frequencies were opened for unlicensed public use by the FCC in 2010. Using vacant UHF TV channels, the RuralConnect TVWS signal penetrates foliage and travels around hills to bring wireless broadband to locations too rugged or remote to be served by traditional line-of-sight radio technology. Carlson argues that with spectrum scarcity a growing issue in today's world of wireless connectivity, the opening of TV white space frequencies and the development of dynamic spectrum sharing technology offers more than 200 MHz of new potential spectrum, the actual amount depending on the area and proximity to licensed TV broadcasters. TVWS products make wireless connectivity possible in areas previously difficult or prohibitively expensive to reach. Products like RuralConnect launch a new era of opportunity for rural communities demanding high-speed internet access. It also expands the capability of businesses and governments needing to extend their communications and private networks, such as data monitoring and control for utilities, oil & gas operations, resource management, public safety, video surveillance, and VoIP networks.

Adaptrum, a Silicon Valley- based company, delivers broadband wireless access solutions including TVWS broadband technology. Their TVWS System ACRS 1.0 was certified by the Federal Communications Commission (FCC) in 2011 and commercially deployed in the U.S. Adaptrum explains that their wireless technology platform allows dynamic spectrum access in a pooled spectrum base comprising, unlicensed, licensed, government, and public safety spectrums, with an initial focus on sub-GHz spectrum bands. Their platform provides real-time resource monitoring, automated resource management, and self-forming and optimizing networking capability to facilitate easy and scalable wireless network deployment.

Finally, xG Technologies, Inc., Sarasota, Florida, is a developer of a portfolio of wireless communications technologies, including spectrum sharing solutions, granted eight spectrum sharing patents in 2013. Their current spectrum sharing product, xMax leverages patent positions in dynamic spectrum access, interference mitigation, compression (protocols, payload, signaling), modulators/demodulators, antennas/shielding, wired and wireless networks and media access control protocols. Their xMax signal in space exhibits robustness to interference specifically including white space spectrum sharing.

10.3.4 Actively Managed Heterogeneous Spectrum Sharing Technologies

On January 14, 2014, the FCC conducted a Spectrum Access System (SAS) workshop with a primary goal of seeking public input on a minimum set of high level system requirements and functional parameters for the SAS. The workshop record includes twenty papers discussing technical aspects of the SAS. The workshop focused on four focus areas that relate to the high-level functionalities described in the NPRM. Respondents addressed the operation of the SAS. Focus areas were A., general responsibilities and composition of SAS, B., Key SAS functional requirements, C., SAS monitoring and management of spectrum use, and D., issues related to the initial launch and evolution of SAS and band planning.

10.3.5 LTE Technology for Heterogeneous Spectrum Sharing

In the SAS Workshop, Nokia (NSN) offered that the CBS band could and should use 3GPP TD-LTE since the CBS band corresponds to LTE Bands 42 and 43. These are preferred in Europe and Japan; the envisioned 10MHz channels would fit exactly, and carrier aggregation across channels enables high data rate in such small cells.

10.3.6 Bell Labs White Cell Architecture

Alcatel-Lucent's Bell Laboratories continues to develop technologies for sharing spectrum, particularly within small cells. Their approach includes design and prototype of a "seamless Layer-3 / Layer-4 aggregation solution" that leverages their novel Multipath TCP tunneling technology and supports low-grade end-user mobility. Their indoor white cell architecture is illustrated in Figure 31.

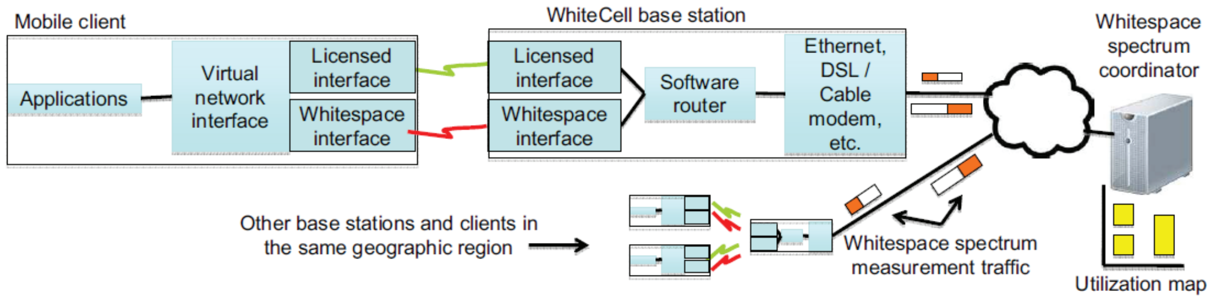


Figure 32: Alcatel-Lucent White Cell Architecture

This architecture incorporates both licensed and white space RF transceivers into a single base station that works with similarly configured mobile client user equipment (UE). For a multiband capable tablet or phone, Alcatel-Lucent aims to show with a simple client software application how 200-500 Mbps of wireless access capacity can be obtained from their new prototype SSPICE high capacity small cells. The white space coordination process uses white space measurements as well as information from other nearby base stations and clients. The measurements differentiate this approach to white cells from the current TV whitespace spectrum sharing paradigm.

10.3.7 Ericsson Architecture

The Ericsson architecture reflects work on-going globally to define a licensing approach that allows spectrum sharing where incumbent users and mobile operators would share spectrum resources with those authorized to share the licensed spectrum under well-defined conditions. This regulatory approach is called Authorized Spectrum Access (ASA) or Licensed Shared Access (LSA). It is applicable both to homogeneous spectrum sharing where those sharing spectrum employ the same communications technologies (e.g. LTE), and where those sharing spectrum employ heterogeneous radio resources (e.g. LTE, WiMAX) and may employ that spectrum for non-communications services such as radar. The Ericsson architecture for heterogeneous spectrum sharing of Figure 33 is intended to provide:

- Fast unlocking of spectrum for:
  - ◊ harmonized mobile spectrum (homogeneous and heterogeneous)
  - ◊ low or localized usage of spectrum (typically heterogeneous)
  - ◊ not obtainable in reasonable time due to incumbent use (military, radar, satellite)
  - ◊ for flexible use of the existing mobile eco-system
- Either-or usage between incumbent and licensee
- Predictable quality of service
- Protects incumbent, lends investment security

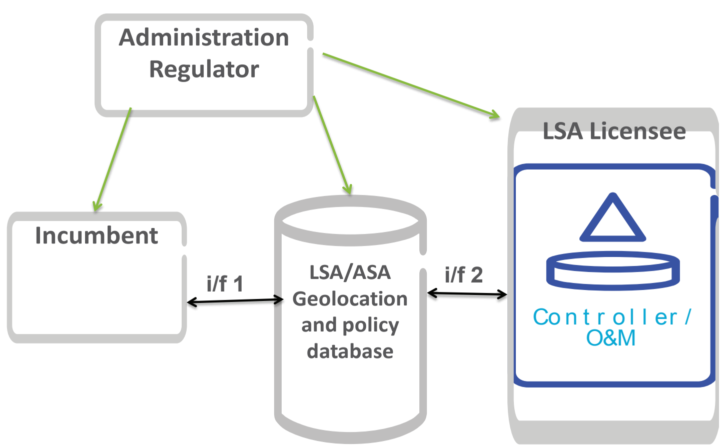


Figure 33: Ericsson LSA Architecture

10.3.8 Technology Challenges of Heterogeneous Spectrum Sharing

In the SAS Workshop, Federated Wireless pointed out key challenges. For example, that efficient sharing of radio spectrum requires sensing and use of channel state information (CSI) measured by commercial shared spectrum radio access equipment. CSI sensing could be construed by a malicious agent to reveal the structure, capabilities, limitations, and vulnerabilities of incumbent US federal wireless signals in space, including military waveforms. CSI must not be aggregated in a way that would allow a third party to infer federal patterns of spectrum usage, especially via the potentially millions of infrastructure and user equipment devices whose measurements of CSI would be needed by the SAS for maximizing spectrum utilization. Federated Wireless also has developed and deployed a private spectrum observatory in order quantify the interference relationships among incumbent military radar systems and commercial standards including LTE. Federated Wireless thereby will show that with an appropriate SAS, the FCC need not specify exclusion zones since such a SAS enables spectrum sharing devices to detect and avoid causing harmful interference to incumbents [reference to filing]

Additional challenges concern methods for differential band usage. Motorola offered the flexible band plan of Figure 34.

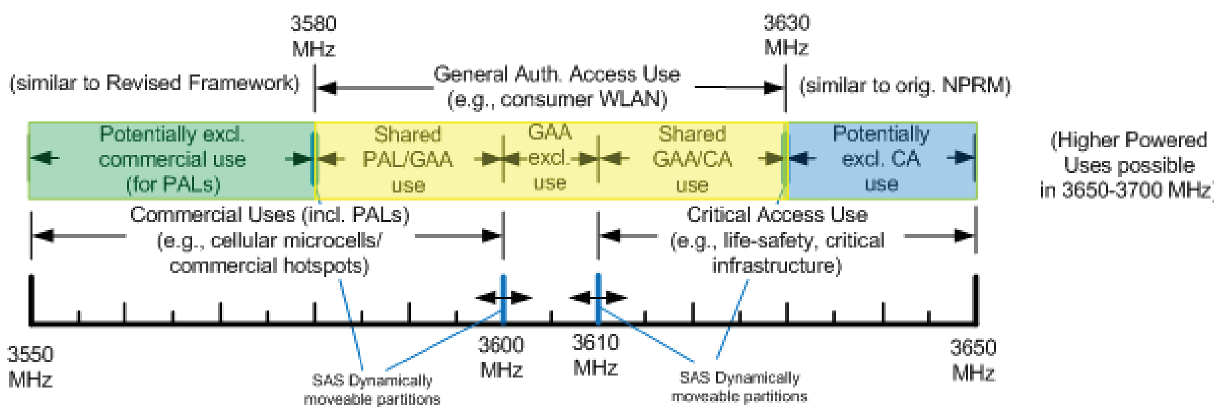


Figure 34: Motorola's Flexible Band Plan Accommodates the First Responder Community

Many other systems engineering, network, and device technology challenges were articulated in the Workshop proceedings.

11

Gap Analysis

Most major wireless industry players now characterize spectrum sharing as "inevitable" but still are not sure how to get there most effectively. In reviewing the analysis and conclusions presented in this document, certain gaps emerge in establishing dynamic spectrum sharing as a mainstream concept. It is clear that investment in dynamic spectrum sharing technologies is often limited to government funded research and development in advance of regulation, and regulatory uncertainty in already existing spectrum sharing bands has inhibited growth. At the same time, new regulations for dynamic spectrum sharing cannot be made unless there is a clear understanding the actual spectrum occupancy in the band of interest, that incumbents in that band can be protected by the spectrum sharing technology employed, and that there is a valid business model under which investment can occur. The development of new business models is driven by an understanding of the technology potential and limitations, and the regulator environment under which they will operate.

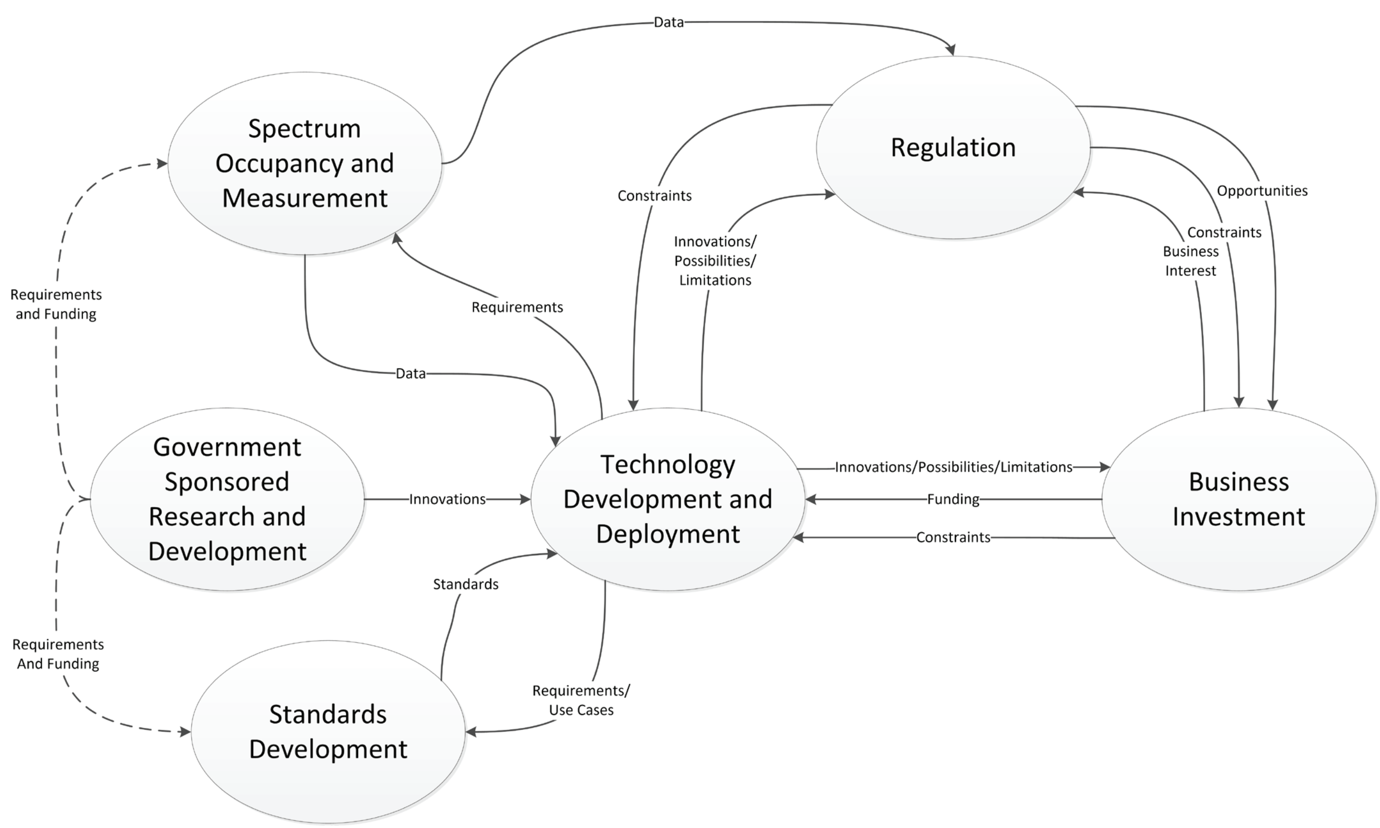


Figure 35: Adoption of Dynamic Spectrum Sharing is Driven Equally by Technology, Regulation, and Business Model

Given these opposing dynamics, a number of elements would help in facilitating the broader adoption of dynamic spectrum sharing in mainstream markets:

1. A common model should be established for determining spectral occupancy at a given location and a given time to provide a consistent mechanism for regulators to understand what bands lend themselves to sharing, and what the potential is for harmful interference in each band.
2. Government should continue strategic investment of joint research and development between industry and academia; in particular to address industry needs identified in the Wireless Innovation Forum's ten most wanted innovations list[240]. Such research should be harmonized, where possible, across agencies and between nations, to reduce repetition of effort and focus on advancing the state of technology.
3. A "spectrum sandbox" should be established for each band of interest to demonstrate the readiness level of dynamic spectrum sharing technologies and different business and regulatory models in an operational setting to help cross the "credibility gap".
4. A common set of broadly agreed upon architectural, business and regulatory models should be developed that can be tailored to the specific requirements of each band of interest. Such models can include databases, sensing systems, etc. Such models will help to better define what standards are needed and where additional research it required.

Ultimately, these and other innovative concepts will help in accelerating the convergence of regulation, technology and business models toward rapid market uptake of dynamic spectrum sharing.

240 http://groups.winnforum.org/d/do/6206