Understanding the Spectrum Environment:
Data and Monitoring to Improve Spectrum Utilization

NITRD Wireless Spectrum R&D Senior Steering Group
Workshop V Report

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1. Executive Summary

The Wireless Spectrum Research and Development Senior Steering Group (WSRD SSG)[1] Workshop V titled: *Understanding the Spectrum Environment: Data and Monitoring to Improve Spectrum Utilization*, was hosted by the National Science Foundation (NSF) in Arlington, VA on March 31, 2014. This report summarizes the motivation, format, material, conclusions and recommendations drawn from that Workshop.

Spectrum sharing, as a means to enhance efficiency in spectrum use, has become a significant issue for the United States. Several initiatives by the Federal Government, including two Presidential Memorandums[2], and the PCAST (Presidential Council of Advisors on Science and Technology) report[3], have advocated collaborative research, development, and testing, to advance spectrum sharing technology and related rule-making. While researchers, investors, small business start-ups and well-established businesses have all made progress in this area, there are still significant issues to be addressed. For example, in order to operate successfully and reliably in a shared environment, the sharing entities involved need to trust that the data they receive is accurate and that the data they share will be handled properly, analyzed correctly, and only used for the purposes requested. One method of achieving this knowledge is by monitoring the spectrum, combined with an improved analysis of the resulting data.

Understanding the spectrum sharing environment is complex. While spectrum monitoring is performed today by industry, academia, and government, it usually tends to be narrowly focused to align with their respective mission and business incentives. Depending on the specific purpose and method of data acquisition, spectrum observations tend to be diverse and scattered among many sources. Observations also vary based on the methods used and the type of data requested. Although there are many approaches to measuring spectrum occupancy, no single method is applicable under all circumstances. Also, data requirements are highly variable and dependent on the intended use.

The WSRD Workshop V was conducted to bring together experts across government, industry, and academia to discuss how the use of spectrum data and monitoring can be used to better inform spectrum policy and management decisions, improve regulatory enforcement, and coordinate more efficient and dynamic spectrum usage. The goal of WSRD Workshop V was to

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[1] The Wireless Spectrum and Development Senior Steering Group (WSRD SSG) was established in response to the June 2010 Presidential Memorandum to assist the Secretary of Commerce in creating and implementing plans for spectrum research, development, experimentation, and testing to improve access for commercial broadband services. The WSRD SSG is a consortium of Federal employees with expertise in spectrum issues and engineering.

[2] *See* Presidential Memorandum: *Unleashing the Wireless Broadband Revolution*, http://www.whitehouse.gov/the-press-office/presidential-memorandum-unleashing-wireless-broadband-revolution, June 2010; and Presidential Memorandum: *Expanding America's Leadership in Wireless Innovation,* http://www.whitehouse.gov/the-press-office/2013/06/14/presidential-memorandum-expanding-americas-leadership-wireless-innovatio, June 2013.

[3] *See* Report to the President: *Realizing the Full Potential of Government-Held Spectrum to Spur Economic Growth*, at 49-50 (July 2012), *available at* http://go.usa.gov/k27R (*PCAST Report*).

capitalize on the collective expertise of the spectrum sharing thought leaders from government, industry, and academia in order to:

- Examine spectrum monitoring, data, and analysis to improve spectrum utilization
- Establish meaningful and achievable national goals related to spectrum monitoring
- Develop a roadmap with meaningful R&D outcomes to achieve these goals

1.1 Key Findings

Based on the workshop presentations, panels, breakout sessions, and discussions, the WSRD SSG concluded that the key findings are:

- ***Monitoring data has multiple uses:*** Workshop participants agreed that measurement and monitoring of the spectrum environment provides added value to facilitate:
    - Spectrum sharing
    - Policy development
    - Establishment of ex-ante approaches to inhibit interference events
- ***Spectrum data is band specific****:* The services and operations of systems within a specific band drive the data needs and its use, whether for policy, enforcement, or access. Therefore, spectrum monitoring and information development need to be band specific.
- ***Data standardization is critical****:* Regardless of how the data was collected and measured, the resulting information must mean the same thing to all stakeholders. This may require standardizing data, and data collection methodologies based on the desired use, such as: location information, comparing license/assignment data, aggregating bands, predicting interference events, etc.
- ***Monitoring for interference enables enforcement****:* Enforcement is a key component to resolving interference issues and, thereby, achieving dynamic spectrum sharing success.
- ***Increased coordination is needed****:* Existing spectrum monitoring programs that are currently employed or under development should be leveraged and expanded to improve coordination with academia and industry, benchmark capabilities, develop a roadmap for future developments, and establish a national infrastructure for aggregating different sources of spectrum data.

1.2 Priority Research and Development Topics

The workshop participants prioritized the following research areas for spectrum monitoring, data collection, analytics, and applications.

- ***Develop innovative tools and techniques to improve the way we measure spectrum usage:*** We need the ability to acquire data based on known signal descriptions, with consistency and quantified uncertainty, in order to create a virtual model of the environment.
- ***Improve spectrum data analytics****:* We need to apply new and innovative data analysis techniques to better understand the spectrum occupancy data collected by the various spectrum monitoring systems in a given geographic region.
- ***Adopt crowd sourcing techniques***: We need to leverage crowd sourcing techniques to gather secondary measurement data for enforcement use (e.g. the DARPA RadioMap Program extended to focus on enforcement).

- ***Focus monitoring for policy development:*** We need to focus monitoring in a few industry verticals (that can result in statistics and estimates) that are of high policy value.
- ***Use the model (test) city to test prototypes****:* We need to use the wireless model (test) city to build trust in long-term spectrum monitoring capabilities.

It is the recommendation of the WSRD SSG that these research and development themes serve as a template for funding research programs in this important and increasingly high profile space.

In addition to accomplishing the objectives set forth for the workshop, valuable exchanges took place between the various government agencies, industry, advocacy organizations and university researchers present at the event.

2. Workshop Background and Overview

The WSRD SSG was established in 2010 to assist the Secretary of Commerce in creating and implementing a plan to facilitate research, development, experimentation, and testing to explore innovative spectrum-sharing technologies. This was called for in the June 2010, *Presidential Memorandum: Unleashing the Wireless Broadband Revolution,* as part of the overall plan to improve access to broadband services. Eighteen Federal agencies participate in the WSRD SSG, which is convened under the auspices of the Networking and Information Technology Research and Development (NITRD) program. Realizing that progress in this area will require the involvement of the private and academic sectors as well as the agencies, the WSRD group focused on bringing together the various research communities to collaborate on solutions. WSRD SSG has held a series of workshops on critical spectrum research areas. Results of each workshop were delivered in a report (this document) to the White House Office of Science and Technology Policy, recommending collaborative research in support of future government needs. Additional information about WSRD, the planning for this workshop, and the previous workshops can be found in Appendix A.

WSRD Workshop V was organized to address two major developments. The first was the June 2013 *Presidential Memorandum: Expanding America's Leadership in Wireless Innovation* which identified the critical need to monitor spectrum usage in real time. The second was the realization by researchers that new capabilities to monitor our spectrum usage could be combined with "Big Data" storage and analysis techniques to create innovative tools to manage our spectrum resources.

With a few notable exceptions, past spectrum measurements have been short-term, ad hoc efforts that provide snapshots of incumbent spectrum usage in particular frequency bands. Advances and developments in sensor technology, computing speeds, applications, data storage capabilities, and information management (e.g., Big Data) have opened new possibilities for automated long-term monitoring and data reporting. With standardization and best practices to ensure data quality and security, measurements could be combined with spectrum license data to improve the information available to stakeholders. Further, in the spirit of the PCAST Spectrum Access System (SAS) recommendations, this spectrum data could enable an automated dynamic spectrum access paradigm for select scenarios. For example, performance metrics are acquired on a routine basis by wireless carriers, but there have been limited efforts to collect, extend, and collate this information. End-user devices could not only be enlisted to measure wireless performance (on a voluntary basis), but also be used for enforcement purposes to detect, identify, and locate interference events. However, data monitoring and exposure creates new security and privacy issues.

This workshop utilized the collective expertise of spectrum management thought leaders from industry, academia, various consortia, and Federal, state, and local government agencies to address the following questions:

- How can increased availability of data better inform policy development?
- Where can data be used most effectively to improve policy decisions?

- In a data-driven approach to spectrum management, what policy areas require attention, such as privacy and security?
- How will advances in monitoring techniques and data management make enforcement more efficient and effective?
- How can improvements in monitoring and access to data enable new paradigms of sharing, including automated dynamic spectrum access?

The Workshop began with two opening panels: one focused on policy, commercial opportunity, and enforcement; the second provided an overview of several current spectrum monitoring projects. Workshop participants were then given time to visit project exhibits and demonstrations before joining a breakout session to contribute perspectives, refine ideas, and develop research recommendations. Each of the sessions considered the application of spectrum monitoring and data within one of the following topics: (1) Informing spectrum policy and management, (2) Interference resolution and enforcement, and (3) Coordinating spectrum usage. The workshop then reconvened and concluded with a full group discussion refining, ratifying, and prioritizing the conclusions from the individual break-out sessions.

The following sections provide descriptions, details, and conclusions from each element of the workshop.

3. Opening and Keynote Speaker Panel

Byron Barker, Co-Chair of the WSRD SSG and Chief of the Strategic Planning Division at the NTIA, welcomed the group with special thanks to NSF for hosting the event. He also expressed gratitude for participation of the keynote speakers. Byron also provided an overview of the workshop goals and the organization of the day.

He then introduced Rangam Subramanian, NTIA, who served as the moderator for the Keynote Speaker panel. Rangam discussed the goals of the opening talks and panel discussion, and introduced the distinguished speakers:

- ***Tom Power*** - Deputy Chief Technology Officer for Communications for the United States - presented the U.S. Government perspective on spectrum sharing
- ***Mark Gorenberg*** - Founder and CEO of Zetta Venture Partners and member of the President's Council of Advisors on Science and Technology (PCAST) - presented an industry / venture perspective on spectrum sharing
- ***Dale Hatfield*** - Senior Fellow at Silicon Flatirons and Adjunct Professor at the University of Colorado - presented a long-studied perspective on the enforcement challenges associated with spectrum sharing

3.1 Keynote Speakers' Opening Contributions

3.1.1 Tom Power

Tom opened with a commendation for the FCC's efforts in the spectrum sharing/management arena noting the large volume of activity currently being undertaken (e.g., the AWS-3.5 GHz proceedings that were being addressed in an FCC meeting running in parallel with the WSRD V

workshop.) He pointed out the criticality of resource sharing in all aspects of society and how this related to the need for enhancements in our approaches to the dynamic sharing of spectrum resources. Tom also discussed the importance of identifying the actual usage of spectrum versus the registered or assigned usage of spectrum in specific geographies and at specific times. He noted that by better understanding the nature of spectrum usage, we should be able to utilize this increasingly critical natural resource more efficiently. He spoke to the historic value and desirability of having cleared spectrum for various uses such as commercial cellular applications. He also described the difficulty in terms of time, complexity and the cost of clearing spectrum that is currently in use by Federal users.

3.1.2 Mark Gorenberg

As the leader of the group that developed the PCAST report to the President on Spectrum Policy, *Realizing the Full Potential of Government–Held Spectrum to Spur Economic Growth*, [4] Mark first recognized those who participated in the development of the report, many of whom were in the room. He then summarized key points of the report observing the need to develop a wireless spectrum usage model that is analogous to the Nation's shared interstate highway system. He talked about the leadership that FCC Chairman Tom Wheeler is providing in the implementation of the PCAST report through the 3.5 GHz proceeding. Chairman Wheeler describes this band as the "Innovation Band" where the three-tiered spectrum usage model, the Spectrum Access System (SAS), described in the PCAST report would be implemented and tested. Mark also discussed the need to avoid "band balkanization" by creating larger, more flexible bands where dynamic spectrum sharing of broadband applications can be more readily supported. He also talked about the "Wireless Model City" to provide full-scale deployment opportunities for emerging technologies that have reached the critical point in their development cycle where "at scale" deployment and testing is critical. Beyond the spectrum discussions that have already taken place on the 1695-1710 MHz, 1755-1850 MHz, and 3550-3650 MHz bands, Mark believes that the 2700-2900 MHz band should also be carefully investigated for future sharing opportunities. Finally, Mark observed that while absolutely critical today, 10 years from now, the commercial cellular model may no longer be the dominant wireless usage paradigm.

3.1.3 Dale Hatfield

Dale opened his discussion by pointing out that in a dynamic spectrum sharing or commons scenario, the increased proximity of transmitters and receivers dramatically increases the potential for destructive/harmful interference, which, in turn, requires improved enforcement capabilities. He stressed that enforcement cannot be an afterthought; it must be 'baked into' the regulations and thus considered very early and seriously in developing regulations. He also highlighted the unique directional demands for interference resolution and enforcement since source identification (in contrast to the observation of usage or even interference) is the primary focus of efforts in this area. He also noted that trust is critical to the wide-scale adoption of dynamic spectrum sharing. Entrepreneurs will not be willing to develop the needed technologies and products, investors will not be willing to invest, and incumbents will not want to share their spectrum. In this context, Dale discussed the enormous challenges that the Enforcement Bureau of the FCC deal with today versus the more manageable historic era of high power AM/FM

[4] http://www.whitehouse.gov/sites/default/files/microsites/ostp/pcast_spectrum_report_final_july_20_2012.pdf

transmissions. Dale acknowledged the DARPA RadioMap program for its innovations in "crowd sourcing" spectrum usage information. Finally, he identified the need to make public and ultimately fuse the enormous amount of spectrum monitoring information that is currently being collected by cellular providers, wireless tower companies, satellite providers, wireless research organizations, the Federal Government, and even universities.

3.2 Summary of the Keynote Speaker Panel

Dynamic spectrum sharing is a critical issue for the U.S., and the current Administration is giving it adequate attention. There is a great deal of technical and business progress being made in the area driven in part by the wide-spread adoption of the PCAST recommendations by the Federal Government, the investment community, wireless researchers, and various start-up and well-established businesses. However, there are still significant issues to be addressed. For example, in order to operate successfully and reliably in a shared environment, the parties involved need to trust that the data they receive is accurate and that the data they share will be handled properly, analyzed correctly, and only used for the purposes requested. Gaining an improved understanding of the spectrum environment through observation and the careful analysis of spectrum information is critical if we are to resolve these issues and achieve the full potential of dynamic spectrum sharing.

4. Key Projects Panel

This panel was comprised of thought leaders in the area of spectrum monitoring. The goal was to provide a current perspective on the "state-of-the-art", moderate a discussion between the subject matter experts, and offer opportunities for questions from the audience. This panel was moderated by Peter Tenhula, NTIA.

4.1 Highlights of Panelists' Opening Remarks

The following describes the panelists opening remarks.

4.1.1 Jesse Caulfield

Key Bridge Global is a certified TV White Space database administrator (located in McLean VA) that has developed a spectrum monitoring capability (based on low-cost sensors, data collection, and storage) to characterize the whitespace spectrum for the benefit of licensed and unlicensed users. Licensed data, installation parameters, monitoring data, and propagation models help licensed users determine if a secondary user is encroaching and help unlicensed users determine if available frequencies are suitable for their use. Key Bridge has also developed useful data visualization and mapping tools. Data is geo-tagged at a low level, which allows for the database user to query for a general area and frequency range. All data is made available via a web-based database Application Programming Interface (API), which allows for the data to be downloaded in bulk or mapped with a browser-based application. Predictive coverage can be compared with empirical data.

4.1.2 Mike Cotton

NTIA, an agency of the U.S. Department of Commerce, manages the Federal Government's use of the radio spectrum and serves as the President's principal advisor on telecommunications policy. NTIA's new Spectrum Monitoring Pilot Project, started in March 2014, will be conducted by the newly formed Center for Advanced Communications (CAC) within the NTIA's Institute for Telecommunications Sciences (ITS). Since the 1970's, the ITS has developed the expertise, hardware and software tools to perform measurements of complex signal environments across all bands from 100 kHz to 20 GHz. The primary goal of the new pilot program is to simplify and reduce costs for the required hardware and automate acquisition, processing, and presentation processes in order to make spectrum data less costly and more quickly accessible for spectrum policy decisions. Partnered with NIST's Information Technology Lab (ITL), ITS will: (1) Implement a centralized database for storage and analysis of standardized data sets acquired by continuously operating remote sensors, (2) Maintain a cost-capability matrix for the wide range of commercial off-the-shelf sensors, and (3) Establish a network of RF sensors with control and data uploads to be performed over an IP network. In FY2014, end-to-end functionality of the overall sensor network and prototype ITS-customized sensors for pulsed radar signals and typical communications environments (e.g., LTE, LMR) will be demonstrated. In FY2015, ITS plans to deploy the ITS-customized radar sensor at ten locations along the East, West, and Gulf coasts to monitor spectrum usage in the 3.6 GHz maritime radar band.

4.1.3 Anoop Gupta

Founded in 1975, Microsoft is a worldwide leader in software, services, and solutions that help people and businesses realize their full potential. The Microsoft Spectrum Observatory was created with the purpose of providing an intuitive presentation of the usage of the wireless spectrum. This project is sponsored by Microsoft's Technology Policy Group. Collected spectrum data is made freely available to the researchers in academia, government, and industry. The data and project outputs are expected to help inform spectrum policy and management. Data is recorded through global spectrum monitoring stations. Data is stored, processed and visually presented using the Windows Azure cloud. Spectrum monitors collecting spectrum usage data have already been installed by Microsoft and their partners in various locations around the world. Microsoft's philosophy in developing this program has been to keep costs low and deliver open, flexible solutions to the global community. Microsoft's solution is sensor-technology agnostic and has achieved continuous monitoring from 50 MHz to 6 GHz with sensors that in some cases cost less than $5,000. Source code for the entire solution has been released to open source. Microsoft is currently working with a number of university research groups and is looking for collaborators from government and industry as well.

4.1.4 Dennis Roberson

The Illinois Institute of Technology (IIT) in Chicago is a private Ph.D.-granting research university, with wireless spectrum research interests. IIT has been operating spectrum sensors in the IIT's Spectrum Observatory since July 2007. Funded by the National Science Foundation and partnered with Shared Spectrum Company, the program started with a single observatory station on the top of a 22-story and operating between 30 and 6000 MHz (which has been running continuously since). The goal has been to support dynamic spectrum sharing by measuring

spectrum usage trends and anomalous events, providing data sets for cognitive radio studies, and supporting the development of related models, simulations, and analyses. IIT has expanded to a second measurement site and has pursued several mobile measurement campaigns. The project was originally spectrum analyzer based but has expanded to three other sensor types in order to improve temporal and spatial resolution, and to reduce cost. IIT's Spectrum Observatory has demonstrated the benefit of long-term continuous monitoring by, for example, quantifying differences in band occupancy before and after policy decisions (e.g., 2009 digital television transition), observing human activity through a spectrum "lens" (e.g., observing consistent, cyclical, and anomalous activity levels), and identifying opportunities for shared spectrum usage (e.g., Public Safety usage in the LMR band was at record levels during a blizzard while the adjacent commercial usage in the LMR band dropped to low levels of usage).

4.1.5 Marja Matinmikko

VTT is the main research organization in Finland and Marja's group is specifically focused on dynamic spectrum sharing. She referenced the ECC (Electronic Communications Committee) January 2014 workshop "How Measurement of Spectrum Occupancy can help Spectrum Management" that was held in Mainz, Germany.[5] Marja felt European regulators presented a cautious view, suggesting that:

- Focused studies were needed with careful selection of measurement parameters (e.g., bandwidth, scan speed, antenna location) on a band-by-band (and service-by-service) basis
- High-quality measurement equipment and filters were deemed essential
- Measurements cannot be used as a basis for decisions on whether a particular frequency can be used at a certain location
- To give a detailed inventory of the spectrum usage in a big city, a vast amount of fixed receiving stations or other methods (e.g., mobile data) would be necessary

The workshop identified other practical roles for spectrum measurements as well, e.g. to improve system internal performance, to help in the development of new spectrum sharing approaches, and to identify interference protection criteria in order to protect incumbents. Marja also discussed the work VTT has been doing to build a Licensed Shared Access demonstration system that was demonstrated at the IEEE (Institute of Electrical and Electronics Engineers) DySPAN (Dynamic Spectrum Access Networks) 2014 Conference.

4.1.6 Georg Schone

LS Telcom is a private German company and a worldwide market leader in the provision of integrated spectrum management systems and their integration with monitoring systems. Their portfolio includes hardware and software solutions for spectrum monitoring, capture, storage, analysis, and display. Their monitoring system can be deployed in either standalone or networked configurations to give wider coverage. LS Telcom deploys a variety of RF front ends on their sensors to cover the different requirements that different locations and frequency bands require. LS Telcom has resolved the data incompatibility that comes with different RF front ends,

[5] http://www.cept.org/ecc/groups/ecc/client/introduction/ecc-statement-on-spectrum-occupancy-workshop

and is able to aggregate data from multiple sources side-by-side. Georg presented a comparison between the US and UK TV White Space approaches. Georg mentioned that the UK approach has a sophisticated computation layer that predicts interference events in a probabilistic manner.

4.2 Summary of the Key Projects Panel

There is not a one-size-fits-all approach to measuring spectrum usage. Industry, academia, and government perform spectrum monitoring according to their respective goals and incentives and they each employ a wide variety of methods and equipment. It is important to understand the signals one intends to measure, to standardize the data and the data collection methodologies in order to achieve full value (e.g., to approximate locations, compare with license/assignment data, aggregate and predict interference events). Also, open-source software development appears valuable as a means to develop and update software-based spectrum measurement capabilities, collaborate with consistency, respond to continuously changing requirements with new bands and services to be measured, and support software reliability and security efforts.

5. Breakout Sessions

The workshop included three break-out sessions designed to gather perspectives and refine ideas for how spectrum monitoring and information might be utilized for targeted applications in the following three areas:

- Session I: Informing Spectrum Policy and Management
- Session II: Interference Resolution and Enforcement
- Session III: Coordinating Spectrum Monitoring and Usage

5.1 Session I: Informing Spectrum Policy and Management

This session was co-moderated by John Hunter from T-Mobile and Howard McDonald from the Defense Spectrum Office (DSO).

5.1.1 Applications of Data for Policy

The group agreed that spectrum data, with a special focus on monitoring, would be useful for policy development. The data should be viewed as part of a technical approach to inform the development of policy, and should be directly related to a specific issue and frequency band. Potential policy-related examples for using data include:

- Comparing existing assignment and license databases, with monitoring data as part of efforts to identify under-utilized spectrum
- Developing realistic spectrum usage characteristics of candidate sharing bands so that new entrants can more effectively assess the potential for dynamic sharing
- Enhancing propagation and aggregate environmental models that are increasingly being used in policy and rules development

The technical approach would identify the specific monitoring requirements (e.g., needed parameters, data collection and reduction architectures) to generate the desired data. The data would then be analyzed to determine appropriate policy responses to an issue.

5.1.2 Challenges

The principal challenge mentioned was the identification of sufficient resources to gather and process data. Currently, policy and regulatory agencies (e.g., NTIA's Office of Spectrum Management) have limited resources for capturing and analyzing data even if data from other government agencies or commercial companies were made available. Other challenges discussed by the group included:

- Prioritizing data collection (e.g., what bands, what parameters, etc.) when each issue and/or band has its own challenges
- Defining the amount of data that would be necessary and sufficient to inform policy development
- Development of data analytical methods (e.g., turn data into information)
- Overcoming technical challenges for data monitoring (e.g., equipment configurations, threshold levels, etc.)

5.1.3 Candidate Actions

Specific candidate actions discussed included:

- Benchmark monitoring capabilities to provide acceptable validity. There is a need to create a standard platform and add structure to the overall framework
- Provide best practices and data standards by leveraging the work of the new Center for Advanced Communications (CAC), including existing NTIA/ITS efforts, to define data formats, capabilities, and acceptable validity for spectrum monitoring
- Research and develop data analytics targeted to extract information from large scale spectrum data including monitoring data and other spectrum-related data sources (e.g., licensing databases)

5.2 Session II: Interference Resolution and Enforcement

This breakout session was co-moderated by Dale Hatfield (University of Colorado) and Thomas Dombrowsky (Wiley Rein LLP).

5.2.1 Applications of Data for Enforcement

The group agreed that measurement and monitoring of the spectrum environment is useful for establishing ex-ante approaches to interference issues. However, it was less clear how to utilize data to provide appropriate levels of enforcement while still ensuring that stakeholders retain the flexibility to reach their own agreements concerning interference limits.

They discussed several cases where data could be useful for enforcement and agreed on two principal cases that would require distinct approaches: (1) Shared access where the goal is to reduce unintentional interference events; and (2) Malicious interference (e.g., jamming), where the goal is to eliminate occurrences.

Within the sharing context, there was a broad discussion on monitoring for discovering interference events, and the need for ensuring that recurrence of the same events ceased. One suggestion to prevent repetitive interference was incorporating monitoring requirements directly into the sharing agreements reached by the negotiating parties. Under this approach, parties would agree on standards for monitoring and the monitored data could be used by either party for dispute resolution. To reduce interference in shared environments, a database could be used to eliminate registered users as potential interferers by, in effect, shutting them down sequentially and isolating the sources of interference. They agreed that a level of interference protection should be established for sharing parties to comply with, but there will be a need for some level of government (FCC/NTIA) enforcement of those requirements.

The group indicated that intentional interference, or jamming, should be treated more harshly than non-intentional interference. They agreed that monitoring will help to identify jamming, but it was unclear how to determine what bands should be monitored for jamming, who would benefit from the monitoring, and, most critically, how to get those that benefit from the monitoring to pay for it. Participants discussed an effort related to intentional interference in the United Kingdom (UK) where spectrum detectors were deployed throughout the country to detect jamming. These detectors are tied to the national camera system, and a photograph can be taken to identify the violator.

There was also discussion on requiring annual certification of the equipment used in the shared spectrum environment to demonstrate that it is still complying with the technical requirements. There were arguments made that the focus should be on the software used by the device, rather than the hardware, where a spectrum sharing database could automatically (and remotely) monitor the software used by any registered device to ensure compliance with the technical requirements. A variety of suggested actions, as outlined in the "Candidate Actions" section below, related to software and machine-to-machine interfaces were identified.

Overall, they supported the use of spectrum data, including monitored data, software registries, and other forms of data, for resolving interference and enforcing spectrum rules. However, the participants indicated that enforcement through monitoring alone did not seem sufficient. Associated with these identified enforcement applications, the group also identified challenges and candidate actions as discussed in the subsequent sections.

5.2.2 Challenges

The group identified a number of challenges associated with using monitoring for enforcement actions:

- It is often difficult to determine whether interference is unintentional or malicious, but the answer is significant in choosing the appropriate enforcement action
- Interference from other bands and intentional modifications of equipment will remain difficult to police despite extensive efforts to harden software, prevent modifications to devices, and provide unique identification of devices
- The cost of monitoring for enforcement is significant and will remain a barrier.
- Monitoring and enforcement systems must be flexible enough to allow users to reach mutually agreeable outcomes

5.2.3 Candidate Actions

The participants identified three main areas for future research and actions that would lead to a better understanding and use of monitoring and other spectrum data and enable more effective interference resolution and enforcement:

- Increase understanding of enforcement challenges and underlying causes of interference:
    - Analyze existing enforcement issues by gathering data from the FCC and commercial entities on the enforcement issues that are experienced in the field[6]
    - Research international efforts associated with monitoring for enforcement, such as that conducted in the UK
    - Review social science research including the motivations of people who want to interfere or modify the shared spectrum device, and how to judge consumer reactions to the hardening of software on devices in a shared spectrum network

- Develop appropriate enforcement techniques and technology:
    - Research the establishment of unique identifiers (such as a call sign) and the legal issues associated with that (including privacy concerns)
    - Investigate the techniques and costs to "harden" the software layer of shared spectrum devices to prevent interference
    - Research the use of secondary monitoring by devices on the shared spectrum network, such as the capabilities of devices to gather data that could be used to detect anomalies on systems and networks
    - Research the capability to dynamically decertify a device as well as the legal issues associated with this approach
    - Research incentives that can be used to reward desired behavior, such as grants to encourage secondary monitoring of the network
    - Research the ability to automate enforcement mechanisms for devices on the shared spectrum network

- Enable effective spectrum data processes and programs to enhance enforcement:
    - Create a sharing agreement framework that would include monitoring as part of dispute resolution
    - Identify resources, such as device user fees, to help fund the costs associated with monitoring

5.3 Session III: Coordinating Spectrum Monitoring and Usage

This group was co-moderated by Peter Stanforth (Spectrum Bridge) and John Chapin (DARPA).

[6] This data would show what the current trends are in the enforcement arena and allow the crafting of monitoring techniques that could alleviate interference. It was suggested that companies be sought out for their internal data on enforcement issues.

5.3.1 Challenges

- Measurements are not well-defined and converting measurement data into useful information is difficult
- Despite the low cost, ad hoc monitoring does not produce a great deal of value and fails to generate the necessary trust in the measurements
- Monitoring systems need to be coherent, interconnected, and scalable to enable effective access to raw or derived data
- Cost of sensors for monitoring and associated data systems need to be significantly reduced to enable wide spread deployment and use
- Recognizing a fundamental tradeoff between spectrum efficiency and protection of privacy and security, challenges exist to ensure effectiveness of data while not revealing more than is necessary. Challenges discussed included:
    - Carefully defining the characteristics of both the data that is necessary to collect and the data that should not be collected
    - Aggregating data over time or space (or both) that preserve privacy and security, but also retain the data's effectiveness
    - Taking into account the regulatory, social, and technical challenges and then tailoring the solutions for different bands and purposes

5.3.2 Candidate Actions

Participants discussed actions that fell into three main categories:

- Core policy goals and related activities:
    - Identify services that are candidates for spectrum sharing and determine what information is necessary to assess interference in the associated bands
    - Describe what is to be monitored and what procedures need to be used so that companies can innovate on the least expensive way to produce useful data for government needs
    - Develop standards and architectures for a sensor "system of systems" to enable horizontal sharing and efficient processing of data

- Specific technical or experimental projects to achieve policy-oriented goals and actions:
    - Create models that can recreate and predict the interference environment and statistically indicate the parameters required for measuring and monitoring
    - Develop techniques to integrate sensor information from heterogeneous sensor networks
    - Conduct monitoring in a "vertical" service area (e.g., public safety) and develop specific monitoring methods and systems[7]
    - Utilize the activities associated with the FCC AWS-3 proceedings to encourage users to help deploy a sensor network, using auction revenues to help fund it
    - Test monitoring capabilities in limited or controlled situations such as:

[7] Such data would be of high policy value in areas such as public safety: time variation of usage (ramp up/down) for example.

        - A spectrum "test" city or region
        - A dynamic sharing testbed in a "safe" environment (not a complex city)
        - An underutilized spectrum band (e.g. 60 GHz)
    - Sponsor a "Sensing Challenge" using hundreds of radios where the winner is the one who can identify the usage most accurately
    - Sponsor an event on spectrum monitoring (like WSRD Workshop V, but larger and broader in scope) to help stimulate and develop the ecosystem

- Societal-level considerations and candidate actions:
    - Analyze the privacy and security needs of systems and organizations that use spectrum today
    - Explore mechanisms that can enhance privacy and security of spectrum data while retaining its effectiveness for the purposes of spectrum sharing
    - Assess ways to quantify the risk to privacy and security from spectrum data

6. Concluding Panel and Candidate Action Plan

With the summary of challenges and proposed actions in place for each of the breakout sessions, the goal of the concluding panel was to use their expertise and input from the larger group to create a prioritized list of proposed research areas that the government should consider pursuing.

6.1 Summary R&D Candidate Action Plan

The following list of potential research areas were presented, discussed, and in many cases enhanced by the full group. Following the discussion, a vote was taken with each attendee having the opportunity to vote for their top 3 research topics. The results of this vote are indicated at the end of the description of each of the research proposal below.[8]

- ***Informing Spectrum Policy and Management***
    - Leverage and expand the NTIA Spectrum Monitoring Program to benchmark capabilities, improve collaboration with academia and industry, develop a roadmap for future developments and capabilities, and establish national infrastructure for aggregating different sources of spectrum data (0 votes)
    - Leverage the Center for Advanced Communications to find what the monitoring best practices are (2 votes)
    - Perform Data Analytics to make sense out of the collected data (38 votes)
- ***Interference Resolution and Enforcement***
    - Research on boundaries of trust and hardening platforms (10 votes)
    - Conduct social science research to understand the motivations that drive people to cheat or hack devices etc., and understanding the willingness of users to play by rules (2 votes)

[8] Wording and grammatical errors were retained in the following section to preserve the exact statements that were voted on during the workshop. The authors discussed and reviewed the items and edited them for clarity for the Executive Summary.

    - Research on using crowd sourcing to gather secondary user measurement data for enforcement (18 votes)
    - Model the costs of enforcement, and contributing sources of funding to implement enforcement (10 votes)
- ***Coordinating Spectrum Usage***
    - Use AWS-3 Auction proceeds to fund encourage users who want access to help deploy a sensor net (1 vote)
    - Deploy monitoring in a few industry verticals to gather data of high policy value (16 votes)
    - Deploy pilot monitoring in the spectrum test city (14 votes)
    - Perform monitoring and sharing experiments in a safer engineering test environment (3 votes)
    - Link monitoring and sharing in an underutilized spectrum band (0 votes)
    - Research on measuring better to create a virtual model that can recreate an environment and predict what will happen (24 votes)
    - Conduct a "Sensing challenge" (9 votes)
    - Interaction - pick a realistic system using spectrum and analyze privacy and security needs (6 votes)

6.2 Recommended Priority Research and Development Topics

Based on the vote, the most popular research topics for the WSRD Workshop V attendees, ordered by number of votes received were:

- Perform data analytics to make sense out of the collected data (38 votes)
- Research on measuring better to create a virtual model that can recreate an environment and predict what will happen (24 votes)
- Research on using crowd sourcing to gather secondary user measurement data for enforcement (18 votes)
- Deploy monitoring in a few industry verticals to gather data of high policy value (16 votes)
- Deploy pilot monitoring in the spectrum test city (14 votes)

In addition, the workshop organizing committee felt that the following research topic should be included in the final list of recommendations:

- National spectrum monitoring programs, such as the NTIA's Spectrum Monitoring Pilot Project[9], should be leveraged and expanded to benchmark capabilities, improve collaboration with academia and industry, develop a roadmap for future developments and capabilities, and establish a national infrastructure for aggregating different sources of spectrum data.

[9] The National Telecommunications and Information Administration (NTIA) is an agency of the U.S. Department of Commerce. NTIA manages the Federal government's use of the radio spectrum and serves as the President's principle advisor on telecommunications policy. NTIA's new Spectrum Monitoring Pilot Project began in March 2014 and will be conducted at its research and engineering lab, the Institute for Telecommunications Sciences (ITS).

7. Conclusion

In addition to the research areas described above, several key findings and common themes emerged from WSRD Workshop V that help define a candidate action plan to utilize spectrum and monitoring data:

- Measurement and monitoring of the spectrum environment is useful for a variety of applications. Spectrum monitoring and data:
    - Can and should inform policy development
    - Can help establish ex-ante approaches to inhibit interference events
    - Will be necessary to enable spectrum sharing
- The services and operations of systems within a specific band drive the data needs and its use whether for policy, enforcement, or access. Hence monitoring data challenges and uses are band and policy specific
- Enforcement through monitoring alone is not sufficient for spectrum sharing between parties. However, resolution of interference issues through enforcement is a key component to achieve success in a dynamic spectrum sharing environment.

It is the recommendation of the WSRD SSG that these research and development themes serve as a template for funding research programs in this important and increasingly high profile space.

In addition to accomplishing the objectives set forth for the workshop, valuable exchanges took place between the various government agencies, industry, advocacy organizations and university researchers present at the event.

Appendix A: WSRD and WSRD Workshop Organization

The Wireless Spectrum Research and Development Senior Steering Group (WSRD SSG) was established in 2010 to assist the Secretary of Commerce in creating and implementing a plan to facilitate research, development, experimentation, and testing to explore innovative spectrum-sharing technologies. Such an effort was called for by the June 28, 2010, *Presidential Memorandum: Unleashing the Wireless Broadband Revolution* as part of the overall effort to improve access to broadband services. Some 16 agencies participate in the WSRD SSG, which is convened under the auspices of the Networking and Information Technology Research and Development program (NITRD) Program. Realizing that progress in this area will require the involvement of the private and academic sectors as well as the federal agencies, the WSRD group was asked to focus on how to bring together the various research communities to collaborate on solutions.

Table 1: Prior WSRD Workshops		
WSRD I	Boulder, CO	July 26, 2011
WSRD II	Berkeley, CA	January 17-18, 2012
WSRD III	Boulder, CO	July 24, 2012
WSRD IV	Cambridge, MA	April 23-24, 2013

The four earlier workshops brought together key individuals from industry, academia, and the public sector with WSRD members to discuss research projects underway or proposed. The focus of the first three workshops was on technology based research. While technology is a key ingredient in promoting wireless broadband growth and innovation, ensuring timely commercialization of technologies, creating successful business models, and establishing spectrum sharing practices also will require addressing a host of business, legal, and policy issues. This was therefore the primary focus of the fourth Workshop.

By focusing on the economic and policy R&D agenda, the fourth workshop complemented the charter of the WSRD Steering group and its work in the earlier workshops directed at:

- Helping facilitate the 500 MHz transition outlined in the Presidential Memorandum, in a manner that can be implemented in a reasonable timeframe, and
- That is consistent with the Federal Government's role in sponsoring "high-risk high-reward" research innovation and experimentation.

This, our fifth workshop, was hosted by the National Science Foundation and held in Arlington, VA on March 31, 2014. It was attended by 97 named participants (see Appendix E) and included a full day of presentations, demonstrations, breakout sessions, and panels.

The following were members of the workshop planning committee:
Dennis Roberson (IIT) Chair
Byron Barker (NTIA)
Mike Cotton (NTIA/ITS)
Dale Hatfield (U of Colorado/Silicon Flatirons)
Joe Heaps (DOJ/NIJ)
Bill Horne (NASA)
Min Song (NSF)

Rangam Subramanian (NTIA)

Appendix B: Workshop Agenda

I. 9:00-9:10- Introduction and Overview: Byron Barker

II. 9:10-10:15- Keynote Speaker Panel moderated by Rangam Subramanian
   a. Tom Power
   b. Mark Gorenberg
   c. Dale Hatfield

III. 10:15-10:30- *Break*

IV. 10:30-11:45- Key Projects Panel moderated by Peter Tenhula
   a. Jesse Caulfield: Key Bridge
   b. Mike Cotton: NTIA NOI review – ITS work
   c. Anoop Gupta: Microsoft Spectrum Observatory
   d. Dennis Roberson: IIT Spectrum Observatory
   e. Marja Matinmikko: VTT, Technical Research Center of Finland:
   f. Georg Schone: LS Telecom

V. 11:45-1:30- *Lunch* and Demo/Exhibit Session (for information on Exhibitors see Appendix E)

VI. 1:30-3:45- Breakout Sessions
   a. Room II-515: *Informing spectrum policy and management*: Co-moderators: *John Hunter and* Howard McDonald
   b. Room II-595: *Interference resolution and enforcement*: Co-moderators: Dale Hatfield *and* Thomas Dombrowsky
   c. Room II-555: *Coordinating spectrum usage:* Co-moderators: Peter Stanforth *and* John Chapin

VII. 3:45-4:15- *Break*

VIII. 4:15-5:45- Concluding Panel moderated by *Dennis Roberson*

IX. 5:45-6:00- Wrap-up: *Byron Barker*

Appendix C: Exhibitors

Teams representing fourteen different organizations set up demonstrations and exhibits of state-of-the-art spectrum monitoring equipment, systems, and observatories. The companies and organizations were chosen by the planning committee.

Agilent Technologies, Inc. demonstrated the N6841A RF Sensor for Signal Monitoring Networks that features a wide range of Sensor applications to meet specific monitoring, analysis, and location requirements, including Signal LOOKback memory to enable reliable detection, processing and location of short duration signals or interference.

CRFS demonstrated their RFeye® Node, the robust IP-networkable remote distributed spectrum monitoring station and its real time ability to monitor spectrum, demodulate signals, generate alarms, alerts, geolocate target transmitters and build a database of captured data for analysis. The node and can be cost-effectively deployed over wide areas for a range of regulatory, defense and security applications. http://www.crfs.com/

FCC Enforcement Bureau engineers presented information on the technical tools used in spectrum monitoring, interference investigations, and radio direction finding activities in support of the FCC's regulatory mission. This included direction-finding vehicles and future direction for portable systems, as well as how monitoring and measurement tools are used in the field for interference investigations and other spectrum activities.
http://www.fcc.gov/encyclopedia/regional-field-offices
http://www.fcc.gov/

ICF International demonstrated a spectrum profiling solution that measures and characterizes noise floor and identifies sources of external interference over large geographic areas. They use high fidelity spectrum recordings to extract signals even in congested spectrum. The solution assists with planning of spectrum and networks, interference identification, and network performance optimization.
www.icfi.com/broadband

IIT's Wireless Networking and Communications Research Center (WiNCom) showed their web accessible, real-time spectrum occupancy information from their Spectrum Observatory in Chicago, including a You-Tube video showing the spectrum occupancy in the 700 MHz band through its recent transition. This data is available to support research efforts and to inform policy discussion.

ISCO International demonstrated a solution to deliver cleaner spectrum featuring Proteus with PurePass, a proprietary RF digital signal processing algorithm. Proteus monitors the RX uplink for interference and removes the interference when found by automatically creating up to five simultaneous notch filters. The Spectrum Monitor feature provides a view of the spectral activity on up to six RF paths simultaneously.
www.iscointl.com .

Key Bridge teamed with AVCOM of Virginia to demonstrate their SM-3500 Wideband Spectrum Monitoring system as a solution to gain detailed spectral awareness across large geographic areas and over extended periods. The integrated software suite is

designed to transform incoming data streams received from an extensive radio frequency sensor network into meaningful, actionable information in near real-time.

LS Telcom demonstrated LS Observer, a system designed to connect spectrum monitoring with analysis and decision-making that captures, stores, analyzes, and displays data, MONITORplus, for forwarding monitoring information to Spectrum Management was also shown. Focus is on the needs of regulators for a scalable system that also controls costs.

Microsoft Spectrum Observatory provided information on their ability to provide an intuitive presentation of the usage of the wireless spectrum. Data is recorded through monitoring stations throughout the world and made freely available to the public. The data is stored and processed for visualization for the purpose of informing policy discussions and spectrum management decisions. http://observatory.microsoftspectrum.com

National Instruments: Ettus Research demonstrated three products from their Universal Software Radio Peripheral (USRP) platform, USRP X300, USRP B200, and USRP N210 (currently being deployed by the Microsoft Spectrum Observatory). The USRP platform is designed for rapid prototyping, spectrum monitoring, signals intelligence, and research in the area of cognitive radio and dynamic spectrum access.

Rohde & Schwarz demonstrated a highly automated, workflow driven spectrum monitoring software suite designed to interface with spectrum management databases as well as perform complex spectrum measurements by controlling sensors either remotely or locally. On board evaluation tools perform in-depth analysis tasks such as occupancy/gap/transmission statistics. http://www.rohde-schwarz.us/en/products/radiomonitoring/

S2 Corporation presented its novel photonic approach to address the challenge for systems to detect and analyze the presence of signals over a wide bandwidth, out to 40 GHz and scaling to 120 GHz, in real time, without any scanning in frequency, and with dynamic range that far exceeds that of wideband digitized solutions currently available. www.s2corporation.com

Signal Hound demonstrated their BB60C Spectrum Analyzer that is designed to provide a high-performance low-cost monitoring platform with user customized software. A key element is the use of a low cost Intel vPro enabled PC. This technology makes it possible to: A) securely power cycle the PC, B) perform a system recovery if the PC or BB60C crashes or locks up, and C) manage software updates.

The Wireless Innovation Forum presented information on their Dynamic Spectrum Sharing Annual Report. This report is being created for Regulators, Policy Makers, Spectrum Managers, Network Planners, and Wireless Researchers to act as a reference guide on spectrum sharing, identifying what is new from a technology, business and regulatory perspective, what is in development and what issues remain to be addressed. **http://www.wirelessinnovation.org/**

Appendix D: Participant List

Atkins, Paige
Barker, Byron
Bertuna, Dan
Bishop, Don
Bonneau, Robert (Bob)
Bose, Vanu
Brinkoetter, Thomas
Bulthuis, Kyle
Caulfield, Jesse
Causey, Stan
Chan, Serena
Chan, Serena
Chandramouli, Mouli
Chapin, John
Cirbo, Leo
Clancy, Charles
Clegg, Andrew
Cotton, Mike
Devasirvatham, Daniel
Devine, Bruce
DiFazio, Robert (Bob)
DiFrancisco, Mike
Dombrowsky, Thomas
Eggerl, Braden
Evans, Joseph
Fell, Barry
Gibson, Mark
Gilmore, Michael
Giorgio, Paul
Glossner, John
Goldberg, Lawrence
Golmie, Nada
Gorenberg, Mark
Graulich, Dave
Grunwald, Dirk
Gupta, Anoop
Hatfield, Dale
Haug, John
Heaps, Joe
Higgins, Jim
Hood, Cynthia
Horne, William (Bill)
Hunter, John
Joseph, Don
Keltz, Ira
Kilbourne, Brett
Krenz, Thomas
Laneman, Nicholas (Nick)
Loera, Jose
Luker, Mark
Markwalter, Brian
Marshall, Preston
Matinmikko, Marja
McDonald, Howard
McHenry, Mark
Medin, Milo
Melvin, Jon
Merkel, Kris
Mody, Apurva
Molina, Steve
Monie, Joe
Myers, Ted
Nebbia, Karl
Nelson, Eric
Parker, Scott
Pavlak, Robert (Bob)
Peha, Jon
Perry, Loyd
Power, Tom
Ranganathan, Mudumbai
Rappaport, Ted
Reddish, Mark
Reed, Jeff
Reichard, Gordon
Rezaeinia, Paria
Roberson, Dennis
Schneider, Robert (Bob)
Schone, Georg
Song, Min
Souryal, Michael
Srihari, Dileep
Stanforth, Peter
Stine, John
Subramanian, Rangam
Taylor, Jesse
Taylor, Tom
Tenhula, Peter
Tian, Zhi (Gerry)
Tillman, IC
von Bredow, Oscar
Wassel, Joe
Weiss, Martin
Weston, David
Williamson, Steve
Yi, Byung

* Note that since the event was webcast, it is expected that there are others that likely attended portions of the workshop.

Appendix E: Resources and References

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