WiNCom
ILLINOIS INSTITUTE OF TECHNOLOGY

NSF Workshop on

Spectrum Measurements Infrastructure

Workshop Report

NATIONAL SCIENCE FOUNDATION

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1. Executive Summary

The NSF Spectrum Measurement Infrastructure Workshop was sponsored and funded by the National Science Foundation and was hosted at Illinois Institute of Technology in Chicago, Illinois on the 6th and 7th of April 2016. This report summarizes the motivation, goals, format, material observations, conclusions and recommendations drawn from that Workshop.

Spectrum measurement and the understanding that comes from these efforts has become an increasing important topic as we seek to more efficiently and effectively utilize our nation's increasingly precious spectral resources. Several Federal Government initiatives, including two Presidential Memorandums[1], and the PCAST (Presidential Council of Advisors on Science and Technology) Spectrum Policy report[2], have advocated collaborative research, development, and testing in the area of enhanced measurement capabilities, to advance temporal spectrum sharing technology, and related regulatory rule-making. Currently there are spectrum measurement related efforts being pursued by advisory bodies for both the FCC (the Technological Advisory Council or TAC) and the NTIA (the Commerce Spectrum Management Advisory Committee or CSMAC) that further underscore the importance of this area.

Understanding the spectrum sharing environment is complex. While spectrum measurements are performed today by industry, academia, and government, these efforts usually tends to be narrowly focused to align with their respective mission, and/or current business interests. Depending on the specific purpose and method of data acquisition, spectrum observations tend to be diverse and scattered among many sources. Observations also vary widely 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, the data requirements themselves are highly variable and dependent on the intended use.

This Workshop was undertaken to bring together government, industry, and academia experts to discuss improvements in spectrum measurement techniques and infrastructure to better inform spectrum policy and management decisions, and to support more efficient and dynamic shared spectrum usage. The goals of the Workshop were to capitalize on the collective expertise of the spectrum measurement thought leaders to:

- Examine the current status of spectrum measurement efforts and related data capture and analysis efforts to improve spectrum utilization
- Establish meaningful and achievable national goals related to spectrum measurement
- Chart out a roadmap for scaling spectrum measurement efforts to a countrywide level.

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[1] *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.

[2] *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*).

1.1 Key Findings

There were a variety of important findings emanating from our two day session. These are provided throughout this now extensive report. Critical findings that were mentioned in many places and in many ways included that fact that "one size definitely does not fit all" when it comes to spectrum measurement systems. There are many different goals that are being pursued or will be pursued by various groups using spectrum measurement systems as a means of accomplishing their objectives. As Paul Kolodzy, one of our Keynote Speakers noted, there are at least four key phases of spectrum measurement applications, namely measurements to: 1) quantify opportunities and support regulatory action **Prior to Sharing**, 2) **Operationally Support** the sharing process once the spectrum has been designated for sharing, 3) **Assess usage and interference trends** and to assess further rule modifications after shared spectrum operations are in place, and finally 4) support **Enforcement** requirements.

Beyond these phases, there are many other dimensions of spectrum measurement requirements including the range of spectrum to be measurement, the geographic area that the spectrum measurements are to cover, the duration for the measurement, the requirement resolution bandwidth, the measurement cycle requirements, the spatial consideration of the direction the signal is likely to be emanating from, the power level of the signal to name but a few of the considerations. Given the numerous considerations and decisions that have to be taken in properly designing an appropriate spectrum measurement architecture, it is critical that the objectives for the measurement effort be carefully considered and documented. This will enable a proper system architecture and implementation to be established.

This plurality of needs also suggests that there are many different kinds of spectrum monitoring systems elements that need to be developed and deployed. A System of Systems hierarchy of at least three classes of sensors: 1) high cost / high trust sensors at fixed locations, 2) mid-cost / mid trust sensors more widely deployed geographically between the first class of installations, and 3) crowd sourced sensors occupying the bottom tier of the structure. Critical to this structure is the software to enable the data gathered from these different classes to be effectively "graded and integrated" at an appropriate level of the data structure for the over-all system to support the analysis needed to satisfy various spectrum information requirements. This diversity of elements and structures in the spectrum measurement architecture suggests the need for a wide variety of hopefully collaborative or at least synergistic research efforts to support these varied spectrum measurement needs. It also suggests significant business opportunities for vendors to produce the wide variety of instruments that will be needed to support these spectrum measurements needs.

1.2 Priority Spectrum Measurement Research Topics

The Workshop did conclude with a solid set of focus areas for research efforts that would advance the state of the art in the spectrum measurement architecture arena. These are captured in greater detail in Section 13 of the report and are also available as presentations on the web at - http://www.cs.albany.edu/~mariya/nsf_smsmw/. The summary of the topical research areas as identified by the final two Focus Groups of the Workshop are listed below.

The Day 2 Focus Group on Spectrum Measurement Architecture highlighted the need for research in the following prioritized areas:

- Signal Identification Rate
- Signal Identification

- General Detection or Informed Detection
- Portable v Heterogeneous Processing Algorithms.

The Day 2 Focus Group examining the broader scope of critical spectrum measurement related research topics established the following list of research areas listed in priority sequence.

- Feature detection & extraction - known vs unknown signals
- RF Big Data analysis - metadata & schemas - lessons learned from radio astronomy
- Crowd sourcing of measurement - consumer vs provider - incentivized vs policy
- Measurement for directionality
- Role of edge processing
- RF front end considerations - costs, re-configurability, filtering, bandwidth
- Handling unplanned events and spectrum dynamics
- Compartmentalized measurement data - privacy and security
- mmW aspects of spectrum measurement
- Spectrum data for non RF applications.

In addition to accomplishing the major objective of identifying key research topics that requirement in-depth investigation, many valuable exchanges took place between the various government agency representatives, industry representatives, and university researchers present at the event. It is hoped that these relationships will flourish over time to enhance the over-all collaborative efforts in this important area.

2. Workshop Goals and Organization

Goals: As the demand for spectrum, the lifeblood of the wireless world, continues to exponentially increase, the interest in the efficient utilization of spectrum has seen a corresponding increase. This has naturally led to an expanded focus on spectrum measurement as an increasingly vital component of future wireless communication plans. This is true whether the plans are focused on mobile broadband, the Internet of Things, radar, or for passive scientific use. With incentives for spectrum sharing becoming increasingly lucrative, the need to accurately characterize the level of sharing and usage at a national scale is being felt acutely by all engaged stakeholders. The goal of this workshop was to bring together a cadre of top tier academic, government and industry researchers focused on the area of spectrum occupancy observation, and encourage these attendees to utilize their collective knowledge in the science of spectrum measurement to chart out a roadmap for scaling spectrum measurement efforts to a countrywide level. An important component of this effort focused on the means by which large-scale spectrum usage information is captured, maintained, curated, analyzed and disseminated to various stakeholders. This was accomplished through a format consisting of keynote addresses, panel discussions and focus group sessions. A key product of the workshop is this report that documents the high-level roadmap for a national spectrum measurement infrastructure, the architectural considerations, technical challenges involved in realizing such a vision and the identification of key areas of research needed to make this vision a reality. A tour of IIT's Spectrum Observatory was provided to illustrate one example of a prototype fixed observation station.

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:

1. How can increased availability of spectrum occupancy data better inform policy development?
2. Where can data be used most effectively to improve policy decisions?
3. In a data-driven approach to spectrum management, what policy areas require attention, such as privacy and security?
4. How will advances in monitoring techniques and data management including vastly lower costs, make spectrum enforcement more efficient and effective?
5. How can improvements in monitoring and access to data enable new paradigms of sharing, including automated dynamic spectrum access?

2.1 Welcome and Agenda - Dennis Roberson

Dennis Roberson, IIT Vice Provost for Research, Research Professor in Computer Science and workshop host, opened the meeting welcoming the 60+ attendees from across the U.S. and indeed the world. Professor Roberson summarized the rigorous agenda for the two days of the Workshop highlighting the anticipated engagement of all participants in the various Focus Group sessions to be held. He provided special thanks to the National Science Foundation for providing both the idea for the Workshop and the grant that enabled the Workshop to be held. He then introduced Dr. Thyaga Nandagopal, the NSF Program Director who personally served as the sponsor for the event. Thyaga outlined the objectives for the Workshop and reviewed the results of the Spectrum Measurement Requirements Survey that most of the attendees had filled out prior to the meeting.

2.1 Meeting Objectives and Survey Results - Thyaga Nandagopal

Meeting Objectives: Given the enormous societal and financially driven interest in efficient spectrum utilization, the goal of this meeting is to better understand how to enhance and apply advanced spectrum measurement and monitoring techniques to improve this utilization in the context of temporal spectrum sharing. Specifically, the meeting was meant to focus on what and how to deploy large scale measurement techniques to support advanced spectrum sharing approaches. In this context the measurement and monitoring techniques need to satisfy a variety of constituent needs (e.g. operational, regulatory assessments, enforcement, etc.) and satisfy these needs in an efficient and cost effective manner. This includes direct measurement and monitoring considerations, data management requirements, analytical techniques and visualization approaches. The Workshop was specifically not intended to explore general policy topics independent of the technological implementations. The work product of the Workshop was meant to be this report, importantly focusing on the actionable recommendations that the experts attending the session made in line with the Goals described above. These recommendations should guide both research investments and relevant technology based wireless policy decisions.

Spectrum Measurement Requirements Survey: After setting the Objectives, Thyaga provided an overview of the 40 Survey responses provided by the attendees. There was reasonably strong consensus on the application of the measurement systems to the processes of:

1. Validating analytical methods and assumptions;
2. Establishing the real-time availability of spectrum for entrants and incumbents for spectrum sharing decisions;
3. Identifying unauthorized spectrum use and enforcing spectrum regulations;

and that measurement systems would be required to perform many functions simultaneously. There was also a reasonable level of support for the view that these measurement systems should support the identification of instances of “ducting” and other anomalous propagation effects.

Geographically, there was reasonable support for a focus on urban deployments (i.e. where the spectrum needs and interference issues are most severe), though there wasn’t a strong disagreement that rural sites near DoD installations would also be interesting spatial areas for spectrum observation. In any case, there was strong agreement that any system should have near continuous coverage over the deployment area.

The support for transmission types ranged from:

1. **strong support** for measuring traditional fixed and mobile terrestrial transmitters
2. **reasonable support** for the requirement to be able to observe intermittent transmitter and highly directional transmission systems
3. **limited support** for the capability to support the measurement of man-made noise, spurious emissions, inter-modulation and other unintended signals
4. **very limited support** for airborne transmitter measurements.

From a spectrum perspective, there was very strong support for measuring the ranges of bands below 6 GHz and limited support for measurement systems exclusively focused on spectrum above 6 GHz or systems that cover all spectrum bands up to and including millimeter wave bands.

From a measurement perspective there was general agreement on the:

1. Need not to be time-synchronized as long as alignment is post-facto
2. Ability to determine the emission type of signals
3. Localization with 100 meter accuracy (as opposed to 10 m, 1 km, 10 km)
4. Localization accuracy ultimately being dependent on the signal being measured
5. Need to have a high dynamic range in the spectrum measurement system
6. Need to react to events within seconds (e.g. 30 seconds)
7. Ability to provide log files, I/Q history and detailed reports.

On the other hand, there was no agreement on the:

1. Calibration levels
2. Need to have tight time synchronization goals across units
3. Limiting I/Q data collection and retention (for privacy reasons).

There was moderate support for the need for high detection sensitivity levels (i.e. sub-noise floor detection).

Finally, there was no consensus on any of the proposed installation and operations costs categories offered to the group. This question was likely very premature since the meeting illustrated that there are a very wide range of possible and in many cases deployed (at least at the prototype level) spectrum measurement architectures and the fact that no single architecture is capable of covering the full range of signal types that need to be measured. The Survey can be found in Appendix E and the Survey results are available on the Workshop website (http://www.cs.albany.edu/~mariya/nsf_smsmw/docs/NSF_SMIW_survey_results.pdf).

Workshop Overview: The Workshop opened with an outstanding presentation provided by our First Keynote Speaker Dr. James Truchard, President, CEO and Co-Founder of National Instrument. Dr. Truchard is a legendary figure in the automated test equipment and virtual instrumentation software field and his company is one of the key providers of equipment and base level software for spectrum measurement. This session was followed by a Key Projects Panel and an Equipment Panel that led directly to a set of demonstrations and exhibits by key equipment providers through an extended lunch period. Dr. Paul Kolodzy, a fabled technologist who initiated numerous efforts in the spectrum measurement and sharing arena at DARPA and who led the FCC's Spectrum Policy Task Force in the early 2000s provided our after lunch Keynote address on the first day. This address was followed by our first of two Focus Group break-out periods featuring three groups working through very challenging questions that will be discussed later in the report.

After an enjoyable evening "on the town" in Chicago, we open Day 2 of the Workshop with our third illustrious Keynote Speaker, Dr. Joe Evans, who is currently serving in a critical role as a DARPA Program Manager in the Strategic Technology Office focusing on wireless technologies while on leave from his position as a Distinguished Professor at the University of Kansas. He was followed by Dr. Paul Tilghman, also a key DARPA Program Manager, who introduce the newly released DARPA Spectrum Challenge to the group. A Panel composed of the three pairs of Co-Moderators for the Focus Groups provided read-out for each of their Focus Groups followed by a Panel discussion on the results of the sessions. After a short break, this session was followed by our final pair of Focus Groups seeking to identify the "road map" of requirements for future spectrum measurement systems and the research priorities this area that the Workshop should recommend. After lunch these Focus Groups provided their read-out to the full Workshop in a final Panel Discussion. This lead to a short Wrap-up presentation by Thyaga Nandagopal and Dennis Roberson. An optional tour of the IIT Spectrum Observatory followed the conclusion of the formal session.

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

3. Opening Keynote Speech – Dr. James Truchard – National Instruments

Dr. Truchard (or Dr. T as he likes to be called) opened our Workshop with an expansive discussion of the work being pursued at National Instruments (NI) in support of spectrum measurement and considerably beyond. After briefly introducing himself and National Instruments he initially focused on the importance of hardware and software platforms to enable progress in a variety of domains. He then applied this principle to the important role that LabVIEW, National Instruments' popular software platform, plays in the design of communications systems. He illustrated this by describing the history, evolution and the capabilities of LabVIEW in various applications areas. He then described the array of products NI provides to meet a wide variety of communications systems and measurements requirements. In the closing portion of his presentation he described many of the numerous applications of the NI product family to a wide and diverse set of problems. In this segment he particularly focused on the wide range of partners that NI has established over time and the achievements that NI has been able to support. The talk was very well presented and very well received serving to kick the Workshop off on a very positive note.

4. Key Projects Panel

This opening panel was comprised of six thought leaders engaged in the various areas related to our focus on spectrum monitoring and analysis. The goal was to provide a current perspective on the "state-of-the-art" in various aspects of the spectrum measurement space including several critical and high profile applications.

4.1 Highlights of Panelists' Opening Remarks – Milind Buddhikot – Nokia – Bell Labs

Milind Buddhikot from Nokia – Bell Labs opened the panel with a short stage setting presentation highlighting the history of spectrum measurements and the challenges associated with the use of measurements and sensing to effect positive impact on the efficiency of spectrum utilization. He then moderated the opening presentations and the follow-on discussion between the subject matter experts on the Panel, offering opportunities for questions from the audience through the Panel time period. The following describes each of the panelists opening remarks.

4.1.1 Mike Cotton – NIST ITS

Mike described the major spectrum measurements / monitoring projects that are being pursued at ITS in Boulder and specifically the growing network of ITS spectrum monitors that are supporting a blend of rulemaking, engineering, spectrum management, and enforcement objectives with a current focus on the 3.5 GHz band. The presentation illustrated the architecture of the network, the implementation of key elements of the system and some of the challenges associated with these elements. Through the development and deployment of this network, a critical goal is to determine whether a more comprehensive monitoring program would positively impact the efficient use of spectrum through such approaches as more effective dynamic spectrum sharing. He closed by providing references for four of the studies the group has conducted over the past few years. This are captured as the last four entries in Appendix F of this report.

4.1.2 Preston Marshall – Google

Preston cautioned us that while fixed spectrum observation might be useful to some degree, the ultimate challenge is to understand the environment at a specific receiver to make appropriate decisions about its use, especially in a dynamic sharing environment. A fundamental challenge here is the uncertainty associated with the actual propagation of a signal vs. the various propagation models that are in use today. He illustrated this challenge though a slide showing the measured path loss vs. a Free Space Model predicted path loss which indicated that the modeled loss was very conservative. Use of the model would therefore have the effect of dramatically reducing the potential spectrum efficiency that might be attained if either a better model, or more importantly sensing at the receiver itself were in place. As a solution he suggested the forward looking approach of using micro- / nano- modeling for today transitioning to some form of mandated crowd-sourcing by receivers involved in a shared spectrum environment in the future.

4.1.3 Greg Buchwald – Motorola Solutions

Greg spoke to the importance of our migration to a Geo-location Database centric Spectrum Management approach. At the same time he noted some of the challenges associated with this direction, especially for mobile devices. To support this approach he proposed that a network of fixed sensing devices supplemented by crowd sourcing from devices desiring shared use of a spectral environment under a pay (sensing) to play (spectrum use) protocol. He further highlighted the numerous challenges associated with sensing including the classical hidden node issue, the need to (or at least the high desirability to) identify specific waveforms, the challenge of sensing low power signals based in part on classical "near-far" problems, and the variation in protection requirements by various user classes.

4.1.4 Bert Hochwald – Notre Dame

Bert described the characteristics of the RadioHound systems being developed and deployed at Notre Dame as a "low-cost, pervasive, persistent spectrum sensor". The goal for this spectrum sensing system development effort is to produce a highly capable spectrum sensing capability which is sufficiently low cost that it can be very widely deployed. This is a full system including a database with Internet access to enable enhanced visualization including a notional "heat map" illustrating the coverage areas for the various transmitters identified by the widely deployed sensors. The bulk of the presentation covered the details of the status of the development effort and the plans for the future work. Please see the website for additional details.

4.1.5 Paul Brown – Paradigm4

Paul shifted the focus to the critical challenges associated with the management of the spectrum measurement data and not just the "gathering" of the data. He pointed to the need to capture data (often referred to as metadata or data about the characteristics of the collected data) from a variety of sources (e.g. geographic, temporal signal, non-signal data…) to be able to support the spectrum management desires. He also pointed out that there are a very wide variety of database systems available for storing the data. Even worse these systems are each useful, but for different purposes so aligning your selection of a single or more likely a set of database technologies that match your requirements is critical. From Paul's perspective there is a great deal of work to be done to enhance the base set of analytical tools (R, Python custom solutions, MATLAB…), on the server side functionality, on the integration of file formats (e.g. HDF5) and more generally the scale, performance and reliability of the systems deployed in the spectrum storage, management and analysis space. Paul closed by proposing that a carefully constructed and proven relevant Benchmark is needed to be able to measure the relative merit of the various proposed approaches to spectrum data management. This Benchmark would at minimum need to include the data characteristics, size, throughput requirements, analytic workflow and the Quality of Service expectations.

4.1.6 Joydeep Acharya – Hitachi

Joydeep was our final speaker for the Opening Panel Season and he continued the focus on the data characteristics and importantly the analytics aspect of the spectrum measurement challenge with a focus on Hitachi's efforts in this area. Specifically he highlighted the difference between traditional "Data at Rest" where data is "ingested, stored, indexed and later analyzed" vs. "Data in Motion" where data is analyzed as it is ingested and used with low latency to make decisions and take action in real time. Applying this to the spectrum measurements environment, Dr. Acharya suggested that these two data storage approaches needed to be merged to enable the use of historic data to provide trend information to supplement and contextually enhance the newly acquired data to direct for example spectrum sharing decisions. He further suggested the potential for a hybrid storage architecture where the "Data at Rest" was centralized while the "Data in Motion" and the results of the analysis of the "Data at Rest" were merged in an edge processing environment. This should enable better informed decisions to be made with very low latency enabling related actions to be taken in a more timely manner. He closed by providing an architectural view of how this might be implemented. Again, please see the website for additional details.

4.2 Summary of the Key Projects Panel

The challenges the panel highlighted in the discussion period included Mike Cotton's observations on the operational challenges of maintaining spectrum measurement systems. Here he highlighted the seemingly mundane, but very real challenge of restarting remote (and potentially very remote) systems when the need arose. With a widely deployed system this can entail plane flights to resolve a 30 second processor restart issue.

Preston pointed out the challenges of insuring that the data from various monitoring sources can be properly compared and synergistically utilized. Key to this is the need to standardize data formats and to insure the capture of descriptive metadata to enable the rationalization of discrepancies in the data from various sources (e.g. IIT Spectrum Observatory on top of a tall building vs. Google data gathered at street level).

Greg Buchwald pointed out the extreme value associated with the densification of sensors. As an example, this would allow overloaded sensor data to be discarded and more generally the identification and rationalization of spectrum measurements from various sensors to draw a more accurate understanding of the spectral environment. Bert Hochwald added the need for a baseline set of specifications for sensors that would enhance the ability to share spectrum data that had been obtained from large numbers of low cost sensors.

Paul Brown moved the discussion to issues with the data itself highlighting two challenges. First as with any large data management program, some of the data will be "dirty" based on the inherent "noise" in any data collection system. Therefore the data needs to be "cleansed" first before it can be truly useful. Second is the information integration challenge with the data. Given the variety of data sources, the diversity in the characteristics of these systems, likely 70 percent of the time associated with analyzing the data will be devoted to rationalizing the various data sources to a common format so the combined results can be shared. Joydeep Acharya highlighted the machine learning aspect of the data analysis problem and per Paul Brown the need to insure that the data is rationalized so the powerful modern "big data" tools can be applied to the analysis of the data.

Milind followed up on Greg Buchwald's observation asking the Panel to opine on the challenges associated with the emerging world of a "sea" of inexpensive and less functional sensors which can supplement or even replace the current world of a few carefully place and managed expensive sensors. Preston pointed out the challenge of the diversity of the environments where the sensors may be placed having a potentially dramatic effect on the observed outcomes.

Privacy is another critical issue associated with the wide scale gathering of data since a great deal of information about individuals and their habits can be gleaned from this data. Greg Buchwald suggested that the privacy issue may be one of several important reasons for deploying a hybrid system of fixed sensors augmented by crowd sourcing. In line with Joydeep's earlier comments, Greg also highlighted the high value of being able utilize historic data, even crude data to derive "deeper knowledge" about the spectrum utilization. Burt Hochwald also spoke to the value of "anchor points" to help rationalize and "ground truth" for the data coming from a sea of inexpensive sensors. Paul Kolodzy and Milind pointed out the critical importance of understanding what the data is to be used for, e.g. localized decision making vs. macro scale understanding of the spectral environment. This understanding can be very helpful in the privacy area as well since the detailed data need for localized decision making can be "processed and used at the edge" and need not ever be promulgated and accumulated in a permanent centralized database.

Preston made the somewhat radical point that in 20 years spectrum sensing as an independent activity should go away! The sensing should instead be built into the radios themselves (i.e. the original Joe Mitola concept) where the real understanding of the spectral environment is needed. The understanding of the macroscopic spectrum environment in this context will become less and less important from his perspective. Milind and others disagreed with lack of importance of the accumulation of macroscopic data for over-all understanding of the spectral environment and the opportunity to make macroscopic improvements, but did acknowledge the importance of the "smart radio" point that Preston raised. This concluded this important and thoughtful session.

5. Equipment Panel

5.1 Highlights of Panelists' Opening Remarks – Ivan Seskar – Rutgers University

Ivan provided a brief overview of our Panel composed of representatives of the most of the leading providers of spectrum measurement related equipment. The intent of this panel was to talk about the current state of the art in spectrum measurement equipment ranging from sophisticated, high function, performance and cost equipment to very inexpensive equipment with ever improving functional capabilities. The Panel was also asked to provide whatever insights they felt comfortable sharing on future capabilities and performance recognizing that they were in the presence of many of their prime competitors.

5.1.1 Abhay Samant – National Instruments

Abhay expanded on the themes developed in the opening presentation by Dr. Truchard and applied these more explicitly to the challenge of developing Spectrum Monitoring Systems. The talk initially focused on NI's emphasis on platforms and specifically the importance of building a product family that is built on and therefore compatible with this platform. In NI's case this is obviously LabVIEW which Abhay characterized as supporting the "Hard Part" in the development of Spectrum Monitoring systems. Abhay also pointed out that this virtual instrumentation software is the most important part since it is what enables the integration of all the unique spectrum observation hardware components and the connection of the system to the related storage system and analysis capability. Abhay then highlighted the scalable platform NI has developed to cover the full range of spectrum observation needs and budgetary capacity providing "spec sheet" descriptions of many of these products and the supporting elements of NI's product families.

5.1.2 Raymond Shen – Keysight Technologies

Raymond highlighted the significant change that is occurring in the spectrum monitoring arena. Even as cellular systems are moving from large, expensive macros cells covering large geographic areas to achieve coverage goals to inexpensive "small cells" to meet the growing capacity needs, the need for monitoring must move in a similar direction. Raymond reviewed a couple of physically compact Keysight products that are suited for this evolving requirement. His primary focus for the presentation was on the sensor applications that Keysight believes are most important namely: Network Planning and Deployment, RF Survey and Signal Classification, Emitter Location Identification, Signals Analysis, and Spectrum Data and Report Generation. Raymond identified the Keysight hardware and software products that focused on supporting each of these important and somewhat unique application areas.

5.1.3 Steve Satoh - PCTEL

Steve describe PCTEL's sensor business as primarily supporting the cellular carriers in the understanding of their coverage characteristics and increasingly also meeting their needs for identifying anomalies, interference sources and in some cases rogue carriers attempting to utilize spectrum that they aren't entitled to use. Today's challenge for any equipment provider is how to deal with both the macroscopic issues of size, weight and power while preparing for the future demands for a full range of sensors that will handle much lower latency, higher reliability, and high data throughput requirements. PCTEL will need and is planning to continue to scale their product line to meet the ever evolving and ever more demanding needs of the future (especially 5G) while also offering derivative products that meet the wide variety of specialized needs of the marketplace.

5.1.4 Steve Stanton - Tektronix

Steve introduced the important notion of the "Interference of Things" as he talked about the ever more crowded spectrum environment, the need for answers (and not more data) even when the signals at issue are transient and finally the need for more cost effective solutions. Steve describe the critical requirements to be able to scan the environment, classify the signals found in the environment, locate the source of transmissions and to record and playback captured signals. Steve highlighted the Tektronix RSA family of low to midrange spectrum analyzers as having the capabilities to handle most environments. Finally he emphasized that the full range of Tektronix spectrum analyzers are supported by SignalVu, a single powerful and easy to use software package that covers most of standard requirements for spectrum monitoring and analysis.

5.1.5 Randy Neal – Rohde & Schwarz

Randy focused on the importance of sensitivity, especially in the "Wild West" environment of ever more densely packed transmitters and the need to be able to "see" signals even in a neighborhood of many more powerful transmissions. He pounded home the notion that receivers must be "fit for purpose" and that the proposed need must be well understood in order to be able to identify the right solution for the measurement / monitoring activity. Randy focused on several application areas including basic recording (with the question – Recording what being key?), direction finding, and signal classification. Since "one size definitely does not fit all" requirements in the spectrum measurement arena Randy strongly encouraged the audience to understand the objectives they are trying to achieve prior to defining a solution. Further, that we be cognizant of the additional requirement that the measurements must be efficiently gathered, reproducible, and easily reportable to those who ultimately need the information.

5.1.6 Bruce Devine – Signal Hound

Bruce introduced his portion of the agenda by indicating his personal interest in hearing from the distinguished audience on the requirements that are most important to the group. He pointed out that today there are $1000 and $100,000 spectrum sensing solutions. Signal Hound's place in the ecosystem is to supply as much functionality as possible for the lowest possible cost. This means including a significant processor (Intel i5) in the unit to provide desired functionality, but there is a cost trade-off associated with the provision of this functionality. The dynamic range and the performance of the receiver including appropriate filters is very important as well. He is a strong believer in the 80/20 rule, i.e. 80% of the functionality for 20% of the cost that 100% of the desired functionality would cost to deliver. The trade-off of what to include "in the box" and what to make available outside the unit for specific purposes is one of the significant challenges for all vendors and the Workshop attendees input should be of great value to the vendors in attendance.

5.2 Summary of the Equipment Panel Interactions

The Panel addressed two important questions at some length. First, the importance of storing the sensor results vs. the real-time use of the sense information and second the value and availability of different kinds of antennas for the sensors. Most of the Panelists spoke to both points creating a very robust discussion. The net of both conversations, and something of a theme of the Workshop was the fact that "one size does not fit all", so there is a need for both real-time and long-term capture of spectrum data and there is a requirement for a wide variety of antenna solutions.

Specifically in the case of data storage the amount of sensed data to be stored and the amount of back-end analysis to be conducted is highly dependent on the task to be performed, i.e. why is the data being collected in the first place. In some cases real-time decisions are required and of necessity these will largely be made directly from the sensed data. At the opposite end of the continuum, there are applications in, for instance, the regulatory environment where the availability of long-term data with extensive analysis will be critical. It was pointed out that it is not just the direct sensor information that is important in that the metadata or the information about how the data was collected, where it was collected, when it was collected, etc. are all very important. In many cases the data needs to be delivered in layers since there are a variety of users of the data. Each user will have specific components of the information that are important to them while this information has no relevance to others who in turn have other portions of the data that is critical to them. It was also pointed out that the security of the data will be critical in many cases since important decisions will be made based on the information derived from the sensed data. All this led to the important comment that given the breadth and diversity of the needs for sensed information, many different kinds of spectrum sensor systems are and will be required.

Commercially this provides the opportunity for a variety of different vendors to each flourish in a segment of the spectrum sensor and sensor system marketplace.

On the question of antennas, it was noted that most spectrum sensors have standard ports that enable a wide variety of antennas (in one vendor's case over 100 antennas are offered by the vendor) to be connected to and used by the spectrum sensors. This specifically includes rotating antennas, steerable antennas and beam forming antennas each of which can be of specific value in the geo-location of the source of transmissions. Again, the antenna selection must be carefully tied to the task that the user of the sensor is attempting to perform.

A final observation was that the broad deployment of spectrum sensors is now feasible and even relatively economical given the high price that spectrum now demands. The case was made that at a one kilometer spacing, Chicago could be adequately covered with 1500 wide bandwidth sensors that would provide a solid perspective on spectrum utilization in all sections of the City. Similar systems could be deployed in other major metropolitan areas of the country and indeed the world to both aid in ensuring efficient utilization of the spectrum and to assist with the challenging task of enforcing spectrum regulations in an ever more complex spectrum environment.

6. Lunch and Demo / Exhibition Session

Following the Equipment Panel Session the audience was given the opportunity to interact with the presenters and in many cases additional supporting personnel from their equipment companies at demonstration tables set up on either side of the auditorium. This provided an excellent opportunity for the Workshop attendees to obtain a "hands-on" perspective on the hardware and software products that had just been described and to see other related offerings as well.

7. Spectrum Pop Quiz

Following lunch the Workshop attendees were "treated" to a Pop Quiz from Professor Roberson consisting of a set of unlabeled multi-month spectrum "waterfall" charts with the goal that the audience identify the spectrum band being plotted. The group did reasonably well with the initial chart of the 600 MHz television band, but had considerable difficulty with most of the rest of the bands including the 700 MHz LTE and Public Safety band, the 2.4 GHz Unlicensed band, the 3.5 – 3.7 GHz band, the 4.2 – 4.4 GHz radio altimeter band, the 4.945 – 4.99 GHz Broadband Public Safety band, and the final charts showing the spectrum usage in the 5 GHz band. Since the afternoon Keynote Address was focused on the 5 GHz band, these final "quiz" charts served as an introduction to the afternoon talk.

8. Keynote Speech – Dr. Paul Kolodzy – Kolodzy Consulting

Paul based much of his interesting and informative talk on the Commerce Spectrum Management Advisory Committee (CSMAC) subcommittee he co-chaired focusing on Spectrum Measurement and Sensing in the 5 GHz Band. This work was aimed both at better understanding the opportunities for spectrum measurement and sensing systems in general and specifically how they could be applied to the proposed new spectrum sharing initiatives in the U-NII-2B (5350-5470 MHz) and U-NII-4 (5850-5925 MHz) bands. Paul initially identified the four key application areas for spectrum measurements, namely measurements to: 1) quantify opportunities and support regulatory action **Prior to Sharing**, 2) **Operationally Support** the sharing process once the spectrum has been designated for sharing, 3) **Assess usage and interference trends** and to assess further rule modifications after shared spectrum operations are in place, and finally 4) support **Enforcement** requirements.

Paul then turned to a discussion of what actually needs to be measured, how it must be measured, and the limitations on measurements and how to ameliorate these limitations in each of the four application areas. He described seven emission parameters that need to be considered when making spectrum measurements and the complexity that emerges from the consideration of these seven independent parameters. He next pointed out the obvious conclusion that no single spectrum measurement architecture would be capable of covering this broad set of potential emission types. This leads directly to the consideration of a wide variety of different spectrum measurement architectures which Paul described as having at least four sets of independent parameters. To further emphasize the measurement challenges Paul showed a spreadsheet identifying examples of some of the specific applications and their characterization relative to the seven emission parameters and a second spreadsheet identifying the applicability of the various measurement architectures to observe a sample of the emission profiles.

Using this information and knowledge of the various options that have been advanced, Paul described specific remediation techniques that might be applied to support the four application areas described above. He followed this by talking about some of the current and future challenges for measurement systems citing Distributed Multiple Input / Multiple Output (MIMO) systems as a particularly challenging emerging area. This led to the proposal of several significant measurement research challenges that the NSF should consider in future funding efforts including: the use of statistical analysis methods to support the measurement work in the various application areas, the challenges of spatial considerations including Beamforming, MIMO and propagation models in environmentally challenging areas, advanced measurement architectures applying the parameters mention above in unique configurations, and sorting through the policy aspect of measurements including sorting through the critical balance between improved measurements and more comprehensive databases on the one hand, and security and privacy issues on the other.

9. Focus Groups - Day 1

The real "work" of the first day of the Workshop commenced after our second Keynote Address. The attendees were divided into three roughly equal sized groups each with roughly equal proportions of government, corporate and academic attendees. These were particularly lengthy sessions (3 hours including a break in the middle) with high expectations for significant outcomes from the groups. The Focus Group sessions were designed to gather perspectives and refine ideas in three distinct aspects of the Spectrum Measurements Infrastructure ecosystem. The three specific areas of focus were:

- Optimal Future Spectrum Monitoring Architecture
- Spectrum Monitoring Data Management Architecture
- Role of Spectrum Measurement in the various applications

The remainder of this section with provide a brief outline of the tasks that were undertaken by each of the Focus Groups while the results of their efforts will be reviewed in Section 11.

9.1 Optimal Future Spectrum Monitoring Architecture

This session was co-moderated by Craig Partridge from Raytheon / BBN and Yang Weng from the NTIA. The specific question the Focus Group was asked to pursue was: *What is the optimal future* *architecture for spectrum monitoring – fixed sites, aero platforms, distributed sensors, crowd sourcing, etc. and why is this optimal?*

9.2 Spectrum Monitoring Data Management Architecture

This breakout session was co-moderated by Phil Fleming from Nokia and Preston Marshall from Google. The topic that they were asked to consider was: *What is the data management architecture in large-scale spectrum monitoring of the future, to ensure adequate support for measurement / analysis / dissemination / curation / standardization / repeatability, etc.? To what extent can the Big Data community help?*

9.3 Role of Spectrum Measurement in the Various Applications

This group was co-moderated by Walter Johnston from the Office of Engineering and Technology (OET) at the FCC and Randall Berry, a Professor in the Dept. of Electrical Engineering and Computer Science at Northwestern University. The focus of this group was to answer the question: *How are the various roles of spectrum measurement related and different – pre-allocation, operational use (especially for spectrum sharing), post deployment assessment and enforcement?*

10. Keynote Speech – Dr. Joe Evans – DARPA

Joe provided us with an overview of the Advanced RF Mapping technology being developed under the DARPA RadioMap program. Through the talk he highlighted the threefold purpose of the program focusing on: 1) Spectrum Management, 2) Spectrum Situational Awareness (directly supporting various DoD organizational needs) and 3) Technical Innovations. RadioMap effectively provides a DoD "crowd sourcing" capability by adding software to many existing DoD RF devices to enable them to observe and report on their local spectral environment. This has the potential to greatly enhance the spectral situational awareness for a geographic area of interest (e.g. a battlefield). Beyond the significant multiplier in the number of available sensors (albeit with varying levels of availability and functionality), new software has been created to assist in the geo-location of emitters, the determination of the calculated field strength for the emitters and the interpolation or extrapolation of this data to estimate the spectrum intensity (and hence the availability of spectrum for shared usage) across an environment. Additional sensors and/or sensors in motion can test and refine the calculations as part of the overall deployed system. This system is now being demoed and evaluated by the Marine Corp for a potential formal transition in due course. This description of the application of spectrum sensing in an area relative unfamiliar to most members of the audience was extremely valuable in expanding the thinking of the group.

11. The DARPA Spectrum Collaboration Challenge (SC2) – Dr Paul Tilghman – DARPA

Paul provided us with a very timely presentation on the details of the newly launched DARPA Grand Challenge. This Challenge was issued on 23 March or only two weeks prior to our Workshop, so the news truly was very fresh for the group. The primary goal of SC2 is to give radios advanced machine-learning capabilities so they can collectively develop strategies that optimize use of the wireless spectrum in ways not possible with today's inefficient approach of pre-allocating exclusive access to designated frequencies. The challenge is expected to take advantage of recent progress in the fields of artificial intelligence and machine learning and also spur new developments in those research domains, with potential applications in other fields where collaborative decision-making is critical.

Paul told us that DARPA Challenges have traditionally rewarded teams that dominate their competitors, but in the electromagnetic spectrum arena being a good neighbor is of optimal import. Therefore, the team that shares most intelligently will win this Challenge. The Challenge will run for three years with checkpoints at the end of each year. It will conclude with a live competition in a large testbed environment. The team whose radios collaborate the most efficiently and effective with the other fielded radios will win the Grand Challenge prize of $2M.

This presentation provided more details about the Challenge than most of the audience had previously been aware of (indeed many were unaware of the Challenge all together) so it engendered a considerable degree of excitement and numerous questions.

12. Day 1 Focus Group Read-out

The next agenda item was the Panel Read-out on the three major Focus Groups that had meet for roughly three hours on the afternoon of the first day of the Workshop. The results were obviously of considerable interest, especially as roughly two-thirds of the attendees had their first opportunity to hear about the efforts and conclusions from the other one-third of the group. The outputs from each of the three groups are described below followed by the Panel discussion of these findings.

12.1 Optimal Future Spectrum Monitoring Architecture

What is the optimal future architecture for spectrum monitoring – fixed sites, aero platforms, distributed sensors, crowd sourcing, etc. and why is this optimal?

The First Focus Group began their deliberations by deciding that the future architecture must be one that scaled with the ability to handle up to 500k devices per square kilometer in dense urban environments at one end and could handle very rural areas where the metric might more appropriately be a square kilometers per device. To achieve this flexibility, architecturally a System of Systems with a Hierarch of Trust would seem to be the most appropriate approach. This would imply:

1) the deployment of high quality, special purpose, trusted measurement platforms which because of cost considerations would likely be distributed sparsely (1 per sq. km or less);

2) the deployment of medium quality, less trusted measurement platforms including carrier equipment on cell towers, "volunteer" spectrum sensing from universities and others, and potentially other sources of spectrum measurement data; and

3) the use of purely "volunteer" Group/Crowd Sourced approaches like the use of individually owned smartphones, Wi-Fi, etc. devices.

The challenge will be in integrating information across these "levels" to yield pervasive and cross-verified sensing capabilities. After considerable discussion there was unanimity within the Group that this was "the way to go forward" from a high level structure perspective.

Looking more deeply at the spectrum measurement systems architecture the Group identified that there will likely be the need to support at least two modes of use namely, long running sensing activities to, for example, understand the change in the noise floor over time, and focused activities to identify "anomalies" and to support enforcement needs such as the location of the pizza delivery car using GPS blocking. Importantly, the sensing should not be restricted to passive sensing only since in some instances active sensing (i.e. pinging) may be of considerable value. The systems must not only be capable of handling static sensing, but must have the ability to handle reactive tasking, that is the ability to modify their focus and sensing capability over time as the spectrum sensing needs change. There is also a critical need for a strong capability to manage the collected data. The DARPA RadioMap program illustrates one way to do the reactive sensing tasking in the context of a platform independent passive sensing and collection environment.

There are a range of choices for the specific structure of the architecture. These include the use of:

1) local devices working cooperatively to accomplish the sensing task;

2) proximity controllers in local cloudlets to direct the senses in a local area; and

3) more centralized controllers to direct the sensors over a wide area.

An example that would illustrate how a specific structure might be selected was that of an airport suffering from GPS jamming. In this case it was noted that there would be too many local devices for local coordination (passengers and their mobile devices). At the same time, coordination from a national center would seem to be too remote. By process of elimination (and instinct), the local cloudlet solution would seem to be most appropriate sensing approach.

The storage and dissemination of the sensed data is also a very critical topic. Key areas of focus from the Group's perspective include the direction that most of the data for distributed sensing be processed locally to reduce the backhaul capacity requirements and costs. For those instances where specific data is required from a sensor or group of sensors, a set of predefined criteria to trigger the data transfer should be utilized (e.g. sampling sensed data at specific time intervals to enable the determination of the change in the noise floor over time). Finally, standardizing the data interfaces and storage format for the various sensors devices is a critical task that needs to be completed.

With these architectural principles in place the Group decided to "Test Drive" this structure with various applications (several of which are referenced above). The first application is measuring noise temperature (noise floor rise). Here in order to obtain "really good measurements" specialized equipment with limited sensing range (due to front end requirements) will be needed. Therefore the architectural choice would be the use of specialized, trusted devices in selected areas around the country, whose data provides baseline/ground truth that can also leverage mobile self-reported data

A second application is to find the GPS blocker in the pizza delivery vehicle. In this case a trusted device would be required to report a GPS interference issue. Crowd source devices could be used to both confirm the trusted devices observation and to greatly assist in identifying the specific location of the offending jammer. It should be noted that the loss of accurate clock is a significant issue that may require a robust "GPS applet" that will assist the distributed crowd source devices in maintaining an accurate clock while suffering interference. The Group observed that the system of systems architecture should work under this scenario. At the same time, this application highlights some of the challenges associated with both identifying the parameters of the challenge and in identifying the challenges to be resolved by the architecture.

The Focus Group concluded by noting that the above does not describe a "solution" per se, rather it is a "sturdy architecture framework" where many of the detailed elements of the architecture must be instantiated through research efforts that are well beyond the scope afforded by a three hour Focus Group. At the same time the Group is confident that the measurement infrastructure described in the report is both feasible and desireable. From a cost estimate perspective, the assumptions will have major impact on the resulting estimate. In particular, the density of deployment of trusted nodes and the willingness of others to freely permit use of their devices will have a dramatic impact on the resulting estimate. To provide a rough order of magnitude estimate, if we assume 1 trusted device per urban square kilometer, using the rest of the assumptions described earlier in this section, the cost would be $500M or less than 0.1% of the annual U.S. telecom revenue. The Group's assessment was that this was truly a terrific investment with beneficial returns based on the improvements in spectrum utilization that would accrue.

12.2 Spectrum Monitoring Data Management Architecture

What is the data management architecture in large-scale spectrum monitoring of the future, to ensure adequate support for measurement / analysis / dissemination / curation / standardization / repeatability, etc.? To what extent can the Big Data community help?

The group first focused on Data Collection Models (or "how do we make the data most useful") making the obvious observation that identifying the planned use for the data up front is critical. The group felt that the four use classes identified by Paul Kolodzy in his Keynote were a very appropriate starting point, namely:

1. Preparing to share (how will we make sharing work?)
2. Sharing (what can be shared right now?)
3. Post-sharing (how is sharing working?)
4. Enforcement (who's cheating?)

The group suggested that localized network optimization could be a fifth key use case.

As to the data itself, it was first identified that how the data was collected and maintained is critically important to know the level of credibility to assign to the data and the value that it will have for the intended application. This led to a discussion of the notion of Data Provenance or the origin, source and chain of ownership or custodianship for the data. This latter notion is particularly important for use of the data in enforcement proceedings. To make the spectrum measurement data valuable a full specification is required that identifies the details of the measurement system itself, the process utilized in obtaining the data and the system for storing and maintaining the data. This is critical to pass the standard scientific test reproducibility criteria that is a part of the rigor that must be applied for the data to have true value for any significant application.

The elements of the spectrum measurement data that should ideally be captured include such elements as the:

- Location where the data was captured
- Topography of the environment
- Time of capture (year, month, day, hour, minute, second…)
- Frequency being captured
- Resolution Bandwidth
- Distance from the transmitter (if available).

For the data collection itself, capturing the abstractions (i.e. the metadata) first is a critical notion. It was suggested that Microsoft's extensible schema might be a good tool for this purpose. So as not to "re-invent the wheel" gaining an understanding of the approach being taken by other data intensive disciplines such as astronomy and high-energy physics seems very appropriate. It is also important to utilize "edge processing" in this effort to facilitate the processing of the data near its capture as opposed to shuffling enormous amounts of data back and forth between various sites. As an aside, the group suggested that getting this right would be very challenging and could lead to the "blooming of a thousand dissertations." This is therefore an important area where further research is required.

It was also noted that there are a variety of applications for the data and many different communities with needs for elements of the data. Therefore trying to anticipate all the needs is not worthwhile. Instead the data should be rendered as open as possible to allow the various needs to be satisfied. Since there are many approaches to spectrum measurement resulting in many different kinds of data, the data needs to be "graded" or classified by its characteristics. Examples of this might include:

- I/Q samples (Security/privacy issues need to be addressed)
- Decimated I/Q samples
- Energy or Power Spectral Density
- Spectrum Occupancy (the presents or absence of a signal independent of form or power)
- Level of metadata supporting the measurement data.

The group then turned its focus to the Data Architecture itself, i.e. what kind of data architectures are or will in the future be needed. Again, are there existing data architectures that are appropriate for re-use in this environment (e.g. astronomy data storage and retrieval methods) or are there unique requirements that exist today or are likely to come into play over time that either can't be met by existing methods or not optimally handle by existing methods. Some of the basic elements that need to be explicitly included in the architecture and the more particularly in the implementation of the architecture would include:

- Storage size
- Access (latency and frequency)
- Formatting
- Archiving needs and characteristics
- Unique hardware architectural characteristics or requirements
- Unique software architectural characteristics or requirements
- Specialized query languages
- Streaming/Real-time data analysis
- Detection/Classification of anomalous behavior.

Beyond the base requirements, some of the ideas and questions advanced on how to construct and test the architecture included:

- Starting with a benchmark –
    - a sample of 10 common queries
    - QoS goals – data integrity, completeness, accessibility…

- What are the numerical "building blocks" that will be used by researchers and practitioners?
- Should there be an interpretation of the data included in the data?
- How can the results be made more accessible?
- What is needed for Visualization? For Machine Learning?
    - This will require some serious investigation but should be done in the course of research questions rather than independently
- How can we reduce the learning curve for doing analytics on the collected data?
- How do we address the real-time data analysis use cases?
- How to effectively use spectrum based on spectrum monitoring?
- How do we do predictive analytics?

Fleshing out this list to include quantitative details and a hierarchy of importance for the various identified parameters represents another research area that requires work beyond the time available to the Focus Group.

Though it was somewhat beyond the original scope of the charter for the Focus Group, the Group decided to explore the cost structure for a full Spectrum Measurement System deployment. The Group's perspective was that at least one and possibly two or more sensors are needed per AP or BS in dense urban environments and likely less for less dense networks environments (e.g. rural areas). The assumed sensor cost would was $100. Backhaul costs would be high unless a fiber infrastructure was already in place. Wireless backhaul was not viewed as ready for deployment by the group, but more investigation would be helpful on this. It is further estimated that it will cost between $13 and $60 per sensor per month to store and process the data. There are likely significant Operation and Management costs that need also need to be investigated. Based on this set of assumptions, the bill for a large city Spectrum Monitoring System would therefore be as much as $300/year per sensor, especially for the initial deployment year (yikes!).

Based on the above, a level of creativity will be needed to make sensor-supported spectrum sharing work. Examples of areas to be explored include the potential for some form of low bitrate reporting of the results of the measurements as opposed to capturing and centrally storing the spectrum data itself. Another important consideration is understanding the potential strengths and weaknesses of using extensive spectrum measurements based systems relative to the database oriented spectrum sharing systems that are currently being developed and tested.

The "business" models or more directly "who pays" models also need to be explored and understood. Various options include:

- government pays (directly or indirectly) to collect the data in an ad-hoc manner
- it is a non-profit enterprise with volunteers providing data to a broker (e.g. Weather or Wikipedia)
- Someone makes a profitable business out of collecting, storing, preparing (and etc.) the data and makes it available to people who pay to access it

12.3 Role of Spectrum Measurement in the various applications

How are the various roles of spectrum measurement related and different – pre-allocation, operational use (especially for spectrum sharing), post deployment assessment and enforcement?

The third Focus Group concentrated its efforts on the development of the following detailed requirements chart which focuses on the four use cases listed above and presented in Paul Kolodzy's keynote address. The chart compares and contrasts the required characteristics of the spectrum measurement system for each of these application areas. As noted below, some of the requirements are consistent across all four application areas (e.g. frequency resolution), while others are very different (e.g. test duration interval). The obvious observation here is that once again, "one size clearly doesn't fit all" when it comes to spectrum measurement systems so either a variety of discrete systems or the "system of systems" approach described by the first Focus Group will be required to satisfy the full range of requirements.

Attributes	Pre-allocation	Operational Use	Post Deployment	Enforcement
data refresh rate	Months	seconds or subseconds	seconds to months	seconds to days
age of data/latency	Months	miliseconds possibly microseconds depending on architecture	months	seconds to months depending on architecture
Duration of interval required	Months	10-100 milliseconds to seconds	seconds to months	seconds to years
Spatial scale (Area surveyed)	100 m to 10 Km	100 m to 10 Km	100 m to 10 Km	100-500 m
Spatial resolution/density	meters to several 100 meters	meters to several 100 meters	meters to several 100 meters	meters to several 100 meters
cost sensitivity per unit	low	high	low	medium to low
directionality	?	?	?	yes
time resolution	seconds or more	seconds or less	seconds or more	seconds or more
frequency resolution	7.25 Khz - 10 Mhz	7.25 Khz - 10 Mhz	7.25 Khz - 10 Mhz	7.25 Khz - 10 Mhz
receiver sensitivity	depends on primary and sensing architecture	depends on primary and sensing architecture	depends on primary and sensing architecture	depends on primary and sensing architecture
storage capacity	large	very low	large	medium
environmental requirements	non-critical	hardened	non-critical	includes portable outdoor
type of measurement	detailed	simple	detailed	detailed/multiresolution
remote access/integration	desireable	mandatory	desireable	mandatory
calibration across sensors	open problem	open problem	open problem	open problem
on board processing	n/a	depends on cost and architecture	n/a	n/a
dynamic range		cost constrained if distributed/ could be less constrained if levereaged service provider architecture		

13. Focus Group 2 Sessions

The second and final round of Focus Group session commence after lunch with the following two focus areas that both built on the first day and second morning's Keynote talks and on the Focus Groups from the first day. The goal for the Focus Groups was to come to closure in identifying some of the key issues facing the Spectrum Measurement Infrastructure environment and the resulting research topics that should be address to assist in resolving these issues. The charters for the two Focus Groups were: *a) Define and prioritize requirements for future measurements systems and* *architectures, led by Co-Moderators: Mark McHenry – Shared Spectrum / Mike Cotton – ITS, and b) Identify the critical research opportunities and associated deployment efforts that are needed to move our spectrum measurements capabilities forward led by Co-Moderators: Mark Gibson - Comsearch / Paul Tilghman – DARPA.* After the Focus Groups met independently for 90 minutes and after a lunch break that enabled the Co-Moderators to consolidate and refine the presentation of their conclusions, Monisha Ghosh from the University of Chicago served as Moderator for a report out session and associated Panel of the Co-Moderators enabling the full Workshop attendee group to opine on the conclusions drawn by the two Focus Groups.

13.1 Recommended Research Topics in Spectrum Measurement Systems and Architecture

The co-moderators for the first Focus Group used a relatively sophisticated approach to identify and prioritize the potential research areas in the spectrum measurements systems and architecture space. In sequence, the individuals in the Focus Group were asked to:

1. Prepare a list of requirements for an RFP for a spectrum measurement system
2. Quiz a "virtual customer" to see how much and where research effort would be required
3. Categorize the results into RF, Algorithm, Network, etc. categories
4. Rank the results according to both Cost and level of required Research.

Using this process and ranking the categories using a simple popularity approach (i.e. how often did a category appear on the attendees list of priorities), in order, the perceived cost drivers from an RFP perspective were:

- Installation (including - network, site access, antenna mount, power)
- Dynamic range (hardware and software)
- Signal Parameters (what signals need to be captured)
- Signal Identification
- Sensitivity
- Directionality.

In similar fashion the top technical challenges that require research focus were identified in priority order as:

- Signal Identification Rate
- Signal Identification
- General Detection or Informed Detection
- Portable vs. Heterogeneous Processing Algorithms.

The challenge is that while these were clearly the top research areas that were identified with signal identification appearing in both the cost and the research lists, there were numerous additional areas that were identified by individuals or small numbers of attendees as requiring additional attention (i.e. the candidate research list had a distribution with a very long tail).

13.2 Recommended Priority Research and Development Topics

The second Focus Group used an open format to solicit priority research topics from those who chose to be a part of this critical Focus Group. The group identified the following ten areas where additional research would be very valuable. After a great deal of discussion, the group used a simple voting approach (3 votes per Focus Group participant) to prioritize these identified areas. The results are shown in priority sequence.

(16) Feature detection & extraction - known vs. unknown signals

(15) RF Big Data analysis - metadata & schemas - lessons learned from radio astronomy

(12) Crowd sourcing of measurement - consumer vs. provider - incentivized vs. policy

(8) Measurement for directionality

(6) Role of edge processing vs. central processing

(5) RF front end considerations - costs, re-configurability, filtering, bandwidth

(4) Handling unplanned events and spectrum dynamics

(3) Compartmentalized measurement data - privacy and security

(3) mmW aspects of spectrum measurement

(1) Spectrum data for non RF applications

13.3 Recommended Priority Research and Development Topics

Following the presentation of the outcomes of the two Day 2 Focus Groups, Monisha convened the Co-Moderator Panel to respond to questions from the audience, Monisha and the other Panelists. As an initial focus, Monisha looked for areas of commonality between the prioritized lists from the two groups. Though not fully comprehended by the group, it should be noted that signal identification and the related topic of feature detection & extraction did appear on all three prioritized lists. This highlights the importance of this research topic.

The challenge of doing long-term, large scale collaborative research in these areas was discussed by several of the Workshop attendees with funding being a major inhibitor. Thyaga challenged the attendees to submit proposals that would comprehend the scope of the projects that needed to be addressed. Thyaga also challenged the group to focus on opportunities for collaboration between institutions to achieve the needed scope to address some of the more challenging research issues. The duration of NSF funding and the nature of the research, i.e. performing research in a single thread of activity related to a solicitation, then preparing appropriate papers and reports to document the results, were highlighted as being inconsistent with the long-term fundamental efforts that now need to be pursued.

This lead to a discussion of the Wireless Model City that had originally been proposed in the context of the PCAST Spectrum Policy Proposal[2] and how implementation of this proposal might help support the long-term foundational efforts that were identified in this Workshop. Walter Johnston from the FCC requested that the Panel and the Workshop attendees in general provide their inputs on the characteristics that should be part of the Wireless Model City since the FCC and the NTIA are currently working to put these requirements together. Thyaga challenged the attendees to establish long-term collaborative relationships that can be productive over a long period of time. These will result in better proposals that will more frequently be funded establishing a "virtuous research cycle".

Concerns about the regulatory challenges associated with spectrum sharing and especially the speed of regulation approval were voiced first by Monisha and subsequently others especially as it relates to the TV White Space sharing issue. Preston Marshall spoke up in defense of the FCC particularly citing the rapid action taken on the PCAST recommendation concerning the 3.5 GHz band. Thyaga also spoke to the speed and support that the FCC was providing in recent sharing proceedings. Mark Gibson spoke to the AWS-3 process that was initially undertaken by the NTIA and through the CSMAC group advising the committee. This paved the way for rapid execution in the FCC. Extending the partnering theme that Thyaga started, Mark pointed to the value of academic / industry partnerships and how these can be extremely valuable in making rapid progress on key research fronts. This was a positive end point for the Panel as it concluded.

14. Wrap-Up – Thyaga Nandagopal and Dennis Roberson

Thyaga concluded the workshop by pointing out that this Workshop is building on the efforts that have been initiated in other previous gatherings both under NSF auspices and those supported by others. The challenge is to come together to focus our research efforts toward meeting the needs of a consolidated spectrum measurement architecture. We made good progress through the Workshop on the characteristics of the common sensor and data structure architecture and the research goals that were established are definitely worthy of funding. Thyaga will look forward to receiving and funding proposals that are focused on the topics coming out of the Workshop. Thyaga's biggest challenge is reading volumes of proposals many of which are neither properly focused, nor written at level that merits funding. Beyond NSF funding, given the constituency of the attendees representing academia and industry, other means of collaboratively funding research should be available to this group. Thyaga is clearly looking for additional thoughts on this Workshop and feedback on needed future Workshops. He also invited Summer School proposals that would support the education of graduate students in this important area. Thyaga concluded his remarks by thanking all those who had come out to the Workshop for their time and thoughtful engagement.

Dennis provided his additional words of thanks to the Keynote Speakers, Panel Moderators and Panelists, the Co-Moderators for the Focus Groups that provided the core work products for the Workshop, the Steering Committee for their significant planning effort leading up to the Workshop. Dennis thanked Maggie Garcia for her efforts to coordinate the session. He also expressed his appreciation to Mariya Zheleva for developing the Workshop website. Finally, Dennis thanked Thyaga for providing the inspiration for the Workshop and of course the vital funding to enable the Workshop to take place.

15. Optional Spectrum Observatory Tours - Dennis Roberson

Following the formal agenda, the group was provided with the opportunity to visit Illinois Institute of Technology's Wireless Networks and Communications Research Center (WiNCom) and specifically the World's First permanent Spectrum Observatory and the International Spectrum Observation Center (ISOC). Though the weather was very uncooperative (i.e. cold, rain, hail and even snow all in the matter of a few minutes and in April no less), many members of the group braved the elements to visit the antenna farm on the top of the 22 Story IIT Tower. They also saw the control room for the spectrum data capture, the lab where the data is stored and of course the six large flat screen displays that provide the surface used to display the processed spectrum information generated by the Spectrum Observatory. This was supplemented by a set of posters describing the specific research efforts (primarily with funds from NSF) being undertaken in the WiNCom Research Center. This event was primary set up and conducted by the WiNCom Research Assistants who deserve Kudos for their efforts!

16. Acknowledgements

Obviously this Workshop could not have taken place without the vision and the funding provided by our patron organization, the National Science Foundation and specifically Thyaga Nandagopal who additional served with distinction on our Organizing Committee. The other members of our Organizing Committee also deserve praise for their considerable efforts to set the agenda, to establish both the structure of the meeting and its objects, determine the appropriate invitee list, recommend and approve the keynote speakers, Panelists and Moderators for the Panels, Focus Group Co-Chairs and finally to establish and implement the survey that was conducted prior to the meeting. The Steering Committee is listed in Appendix A. The Keynote speakers did an outstanding job in providing enlightening ideas and information for the attendees at the Workshop to absorb and consider. In similar fashion the Moderators and members of the two opening Panels help set the context for the meeting and provided us with much to think about as we entered the Focus Group phase of the event. The spectrum measurement equipment vendor representatives provided us with concrete examples of instruments and tools (often unknown or at least unfamiliar to the audience) to consider in the context of the future spectrum measurement opportunities. The Co-Chairs of the five Focus Groups skillfully steered these efforts to produce interesting and useful results to be considered well beyond the conclusion of the Workshop. The Workshop artifacts (agenda, plans, presentations, etc.) were very effectively captured by our webmaster, Mariya Zheleva from the University of Albany. Behind the scenes there were a cadre of students often invisibly supporting various aspects of the event including its filming and of course the tour of the Spectrum Observatory and related International Spectrum Observation Center. Finally, what would we have done without Maggie Garcia who handled the multitude of logistics leading up to the event and supporting the various needs of the attendees at the event?

Appendix A: Workshop Organizing Committee

The following were members of the workshop planning committee:

Phil Fleming - Nokia

Walter Johnston - FCC

Mark McHenry – Shared Spectrum Company

Thyaga Nandagopal – FCC

Dennis Roberson – IIT

As noted in the Acknowledgement session, many thanks to this group for their efforts to organize and implement this important meeting.

Appendix B: Workshop Agenda

DAY 1 – 6 April

8:00-9:00 - Demo set up

8:15AM - Registration, Mingling and Continental breakfast

I. **9:00-9:05 - Welcome and Overview: Dennis Roberson - Illinois Tech**

II. **9:05-9:20 -** NSF Welcome, Meeting Objectives and Results of Spectrum Measurement Requirements Survey**: Thyaga Nandagopal - NSF**

III. **9:20-10:00 - Keynote Speaker 1 - Dr. James Truchard – National Instruments**

IV. **10:00-10:15 - *Break***

V. **10:15-11:15 - Key Projects Panel moderated by Milind Buddhikot – Nokia** (*Goals: 1. Communicate the state of current spectrum measurement efforts. 2. Describe the plans for the immediate future (what is in the charted roadmap, and what are the wish list features that you cannot have at this time). 3) Identify how these measurements efforts are informing analytical spectrum usage models, and where do such measurement efforts fail)?* Panelists:

a. **Mike Cotton – ITS**

b. **Joydeep Acharya – Hitachi**

c. **Greg Buchwald – Motorola Solutions**

d. **Preston Marshall – Google**

e. **Paul Brown – Paradigm4**

f. **Bertrand Hochwald – Notre Dame**

VI. **11:15-12:30 - Equipment Panel moderated by Ivan Seskar** (*Goals: 1. Describe the current state of the art in spectrum measurement tools from sophisticated / costly instruments to widely deployable low cost equipment. 2. Describe the direction for the emerging and future tools).* Panelists:

a. Abhay Samant – NI

b. Raymond Shen – Keysight

c. Steve Satoh – PCTEL

d. Steve Stanton – Tektronix

e. Randy Neal – Rohde & Schwarz

f. Bruce Devine – Signal Hound

VII. **12:30-2:00 - *Lunch* and Demo/Exhibit Session**

a. Lunch set up in UTP Atrium

b. Equipment Demos in UTP Atrium

i. Keysight Technologies - **Raymond Shen**
ii. National Instruments - **Abhay Samant + Tanim Taher**
iii. PCTEL - **Amir Soltanian, Matt Laurich, Steve Satoh**
iv. Rohde & Schwarz - **Randy Neal**
v. Test Equipment Plus - Signal Hound - **Bruce Devine**
vi. Tektronix - **Steve Stanton - Tektronix**

VIII. 2:00-2:30 – Keynote 2 - Paul Kolodzy – Kolodzy Associates

IX. **2:30 - 5:30 - Focus Groups**

a. *What is the optimal future architecture for spectrum monitoring – fixed sites, aero platforms, distributed sensors, crowd sourcing, etc. and why is this optimal?* **Co-moderators: Craig Partridge – BBN / Yang Weng – NTIA**

b. *What is the data management architecture in large-scale spectrum monitoring of the future, to ensure adequate support for measurement / analysis / dissemination / curation / standardization / repeatability, etc.? To what extent can the Big Data community help?* **Co-moderators: Phil Fleming - Nokia / Preston Marshall – Google**

c. *How are the various roles of spectrum measurement related and different – pre-allocation, operational use (especially for spectrum sharing), post deployment assessment and enforcement?* **Co-moderators: Walter Johnston – FCC / Randy Berry – Northwestern University**

X. **[3:30-3:45 - *Break for Focus Groups with the opportunity to switch groups for cross fertilization]***

XI. **Dinner (A night out on the town in Chicago!)**

DAY 2 – 7 April 2016

XII. **8:00 – Continental Breakfast**

XIII. **8:30 – 8:35 – Second Day Welcome and Logistics – Dennis Roberson**

XIV. **8:35 – 9:15 – Keynote Speaker 3 – Joe Evans – DARPA**

XV. **9:15 – 9:30 – DARPA Spectrum Challenge – Paul Tilghman – DARPA**

XVI. **9:30 – 10:45 – Focus Group Read-outs Panel – Moderated by Dennis Roberson**

Co-Moderators from session IX

XVII. **10:45 – 11:00 – Morning Break**

XVIII. **11:00 – 12:30 – Focus Groups Two** (Atrium conference rooms)

a) Define and prioritize requirements for future measurements systems and architectures ***Co-Moderators: Mark McHenry – Shared Spectrum / Mike Cotton – ITS***
b) Identify the critical research opportunities and associated deployment efforts that are needed to move our spectrum measurements capabilities forward ***Co-Moderators: Mark Gibson - Comsearch / Paul Tilghman – DARPA***

XIX. **12:30 – 1:30 – Lunch (in the Atrium)**

XX. **1:30 – 2:15 – Read-out from Focus Group 2 - Moderated by: Monisha Ghosh**

a. Co-Moderators from session XVII

XXI. **2:15 – 2:30 - Wrap-up: Thyaga Nandagopal / Dennis Roberson**

XXII. **2:30 – 5:00 - Optional Tours of Illinois Tech Spectrum Observatory**

Appendix C: Exhibitors

Teams representing six key measurement equipment providers set up demonstrations and exhibited of state-of-the-art spectrum monitoring equipment and systems. As noted in the agenda, these demonstrations where available through the extended lunch hour and at the breaks on the first day. The companies and organizations were chosen by the planning committee.

i. Keysight Technologies - **Raymond Shen**
ii. National Instruments - **Abhay Samant + Tanim Taher**
iii. PCTEL - **Amir Soltanian, Matt Laurich, Steve Satoh**
iv. Rohde & Schwarz - **Randy Neal**
v. Test Equipment Plus - Signal Hound - **Bruce Devine**
vi. Tektronix - **Steve Stanton - Tektronix**

Appendix D: Participant List

NSF Workshop on Spectrum Measurement Infrastructures - April 6-7, 2016 - Illinois Institute of Technology - Chicago

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Brief biographies for most attendees are available at:
http://www.cs.albany.edu/~mariya/nsf_smsmw/docs/nsf_smiw_bios.pdf

Appendix E: Spectrum Measurement Survey

Survey Objective: The objective of this survey is to obtain the workshop participant's opinion on the requirements of distributed spectrum measurement systems. This includes the application, the deployment area, the types of signals to be measured, the measurement system capabilities, and the system costs. The survey results will be used to set a context for the workshop and will be discussed in the opening section of the workshop.

Instructions: The survey has 20 questions (plus sub-questions). Please provide your view of the importance of each requirement on a scale of 5 to 0. A value of 5 means that the requirement is critical. A value of 0 means that the requirement is not important or even counterproductive. Please add your name on the bottom if you want.

Spectrum Measurements Infrastructure Requirements Survey		
ID	**Requirement**	**Importance (5=Agree, 0 = Disagree**
	Application Area	
1	Measurements should inform the process of identifying and prioritizing bands for potential relocation or sharing by validating analytical methods, assumptions, and analysis approaches	
2	Measurements should inform entrant users of the spectrum availability and the specific incumbent system operating locally to make near real time spectrum use decisions	
3	Measurements should support spectrum enforcement where unauthorized or out –of-spec operations are characterized and localized	
4	Measurements should support the identification of “ducting” and other anomalous propagation loss estimation	
5	Measurements should support determining users with assigned spectrum that are not using the spectrum	
6	The measurement system in any given geography will likely have to perform many functions simultaneously	
	Deployment Area	
7	Measurement systems should be located mostly in urban areas where there is high commercial and private spectrum use	
8	Measurement systems should initially be located mostly in rural areas where there is a transition between commercial and DoD spectrum use	
9	Measurement systems should provide near continuous spatial coverage in the deployment area	
	Types of Signals to Be Measured	
10a	Measurement systems should focus on measuring airborne (including satellite) transmitters	
10b	Measurement systems should focus on measuring ground mobile transmitters	
10c	Measurement systems should focus on measuring terrestrial fixed transmitters	
10d	Measurement systems should focus on measuring transmitters with highly directional antennas	
10e	Measurement systems should focus on measuring intermittent and/or difficult to detect signals	
10f	Measurement systems should focus on measuring man-made noise, spurious emissions and inter-modulation emissions and other unintended signals	
11a	Measurement systems should focus on the 100 MHz to 1,000 MHz frequency range	
11b	Measurement systems should focus on the 1,000 MHz to 3,000 MHz frequency range	
11c	Measurement systems should focus on the 3,000 MHz to 6,000 MHz frequency range	
11d	Measurement systems should focus on >6,000 MHz frequency range	

11e	Measurement systems should not be focused and should cover the full frequency range to millimeter wave bands	
	Measurement System Capabilities and Features	
12a	Measurement systems need to be calibrated to within 0.5 dB accuracy (including antenna gain and power measurement)	
12b	Measurement systems need not be calibrated so long as they provide consistent measurements	
12c	Measurement systems need to be time synchronized to within 5 us accuracy	
12d	Measurement systems need not be time synchronized so long as they are means of there are means of aligning events after the fact.	
13	Measurement systems need to determine the emission type of signals (aka the signature of the signal) and other detailed parameters (e.g., bandwidth, burst length, etc.)	
14a	Measurement systems need to localize signals to within 10 meter accuracy	
14b	Measurement systems need to localize signals to within 100 meter accuracy	
14c	Measurement systems need to localize signals to within 1 km accuracy	
14d	Measurement systems need to localize signals to within 10 km accuracy	
14e	Measurement localization accuracy will depend on the signal being analyzed	
15	Measurement systems need to have high dynamic range to avoid inter-modulation and image signals	
16	Measurement systems need to react to events within seconds. For example, if an unauthorized user is detected, a report needs to be generated within 30 seconds.	
17	Measurement systems need to provide log files, I/Q signal history, and other detailed reports on events	
18	Measurement systems need to limit the amount of data collected to avoid privacy issues and therefore should not collect and store I/Q data	
19	Measurement systems need to have very high detection sensitivities (i.e., sub-noise detection)	
	System Costs	
20a	Measurement system costs (including sensor, installation, backhaul, etc.) for a major city like Chicago needs to be less than $1M (for all of the sensors) to install and $0.5 M per year to operate	
20b	Measurement system costs (including sensor, installation, backhaul, etc.) for a major city like Chicago needs to be less than $10M (for all of the sensors) to install and $1.0 M per year to operate	
20c	Measurement system costs (including sensor, installation, backhaul, etc.) for a major city like Chicago should be integrated with other sensors that measure for instance, pollution, noise, auto traffic, etc. with an incremental installation cost of less than $1M and incremental operational cost of less than $250k.	
	Name (Optional):	

Appendix F: Resources and References

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- *Spectrum Occupancy Measurements of the 3550-3650 MHz Maritime Radar Band Near San Diego, CA*, Michael Cotton and Roger Dalke, NTIA Report TR-14-500, Jan. 2014.
- *Spectrum Sharing Research and Development*, Telecommunications Industry Association (TIA), December 2013.
- *TAC Enforcement Slides, Preliminary Thoughts on Enforcement: Background, Questions, and Proposed Deliverables*, Dale Hatfield, Spectrum and Receiver Performance Work Group, Apr. 10, 2013.

- Souryal, et al., "Real-Time Centralized Spectrum Monitoring: Feasibility, Architecture, and Latency," in *Proc. IEEE DySPAN*, Sep. 2015.
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- Cotton, et al., "An Overview of the NTIA/NIST Spectrum Monitoring Pilot Program," IEEE International Workshop on Smart Spectrum, New Orleans, Mar. 9, 2015.
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