Final Report:
The Second Enhancing Access to the Radio Spectrum Workshop

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Executive Summary

Wireless systems have proven to be significant productivity enablers in almost every sector of the national economy. Emerging applications such as the Internet of Things, wireless healthcare, and mobile cloud computing are powered by ubiquitous wireless Internet connectivity and fueled by user demands for increased mobility. However, these applications will place greater demands on precious spectrum resources.

To ensure the continuation of these benefits to society, new technologies and policies need to be adopted to enable more flexible and efficient access to the wireless spectrum. The Second Enhancing Access to the Radio Spectrum (EARS) Workshop brought together experts from the wireless community including academic researchers, industry professionals, and policy makers to address future barriers to ubiquitous shared spectrum access. The workshop focused on discussion of near- and long-term obstacles to shared spectrum access, recent research discoveries that can enable improved spectrum sharing between wireless devices, and identifying future goals that will ensure wireless technologies continue to enable national productivity and facilitate economic and societal progress.

The workshop culminated in the following recommendations for enhancing EARS research to meet the challenges of ensuring ample availability of spectrum resources:

1. Emphasize the necessity of interconnected research efforts that tie together science (e.g. astronomical science, computer science), engineering, policy, sociology, and economic domains
2. Encourage technology transfer from universities to the wireless industry and facilitate the collaboration between the two by creating funding mechanisms that foster such activities
3. Proactively disseminate and highlight the findings and the potential impact of EARS-supported projects
4. Use the EARS program to experiment with new forms of university and industry collaboration
5. Support the research and development of emerging technologies for access above 6 GHz

The workshop participants identified high-potential research areas that will enable future wireless systems to provide ubiquitous access to shared spectrum resources:

- Advances in Hardware and the Physical Layer to Improve Sharing and Efficiency
- Coexistence of Heterogeneous Wireless Systems and Applications
- Security, Privacy, Compliance and Enforcement Issues
- Wireless Policy Challenges and Opportunities: Economic, Regulatory, Technology, and International Factors
- Prototypes, Testbeds, and Community Research Infrastructure

Furthermore, the workshop identified several grand challenges as part of a future vision for ubiquitous spectrum sharing among diverse wireless applications and services:

- Achieving Harmonious Coexistence in Heterogeneous Wireless Networks and Systems
- Development of Automated Enforcement Mechanisms and Compliance Certification Methods
- Evolving Spectrum Sharing Architectures for Future Wireless Applications and Usage Scenarios
- Exploration of Emerging Technologies as a Vehicle for Bold New Approaches, including Academic-Industrial-Regulatory Interaction

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I. Introduction and Overview

Wireless systems have proven to be a major productivity tool for every sector of the national economy. Emerging applications, enabled by enhanced Internet connectivity and fueled by user demands and advanced technology, promise continuation of these benefits to society. However, these applications will also undoubtedly place greater demands on precious spectrum resources. To meet this challenge, new technologies and policies need to be adopted to enable more flexible and efficient access to the spectrum.

One of the keys to moving forward is the establishment of a comprehensive vision for future spectrum use. With the National Broadband Plan and other ongoing spectrum reform initiatives as backdrops, the National Science Foundation (NSF) funded the Second *NSF Enhancing Access to the Radio Spectrum (EARS) Workshop* which was held on October 19-20, 2015, in Arlington, VA. The primary purpose of the workshop was to assemble an interdisciplinary group of distinguished researchers, developers, and regulators from academia, industry, and the government in order to create a forum in which the assembled experts could create a vision for enhancing the efficiency of future spectrum use, identify the technical and policy challenges and opportunities implied by this vision, the research needed to realize this vision, and the financial and human capital resources required.

At the workshop, the participant discussions were organized into eight breakout groups, where each breakout group's discussion theme was predetermined by the Workshop Steering Committee. Participants of the breakout discussions debated the current state of wireless technologies and identified research and policy initiatives that will be essential to facilitate more efficient use of the spectrum. The breakout groups focused on the following topics:

- Hardware advances in circuits, devices, and antennas;
- The needs of passive spectrum users and the lessons learned from the astronomy and earth exploration communities in terms of spectrum sharing;
- Security, privacy, and spectrum enforcement;
- Physical layer and networking challenges in spectrum sharing and access;
- The role of large-scale testbeds and prototyping efforts;
- Facilitating interaction between economic/regulatory policy and technology communities, and international cooperation on spectrum management and allocation;
- Facilitating and encouraging technology transfer from universities to the wireless industry, and bolstering collaboration;
- Challenges and opportunities in the coexistence of unlicensed and license-anchored technologies.

From the breakout discussions, a number of important meta-themes emerged, including:

- The need for experimental testbeds and radio platforms that can support collaboration between government, industry, and academia;
- The need for open-source software research tools that can be jointly developed and maintained by academia, government, and industry (e.g., an open-source implementation of the Spectrum Access System (SAS));
- The need for more dialogue and multidisciplinary collaboration between relevant domain experts both within the relevant science and engineering disciplines (e.g., collaboration between experts in signal processing and wireless hardware development), as well as with relevant non-engineering domain experts in economics, law, sociology, and public policy. This is especially true for emerging technologies at higher frequencies above 6 GHz;

- The importance of incorporating security, privacy, and enforcement mechanisms into spectrum sharing technologies starting at the initial design stage instead of patching problems with add-on features;
- The need for more research to address the fundamental questions that remain unanswered, such as: metrics to quantify spectrum parameters relevant to efficiency and performance, and fundamental metrics related to hardware advances;
- The importance of *relevance*, *awareness* and *timeliness* for making collaborations between academia, industry and government more effective and impactful; focus on relevant "use cases" may facilitate such interaction.

A. Workshop Recommendations Summary

Based on the breakout group discussions, panels, and the meta-themes identified above, the Steering Committee formulated a list of recommendations to the NSF EARS program with the aim of raising the visibility and impact of the program by improving the intellectual merit and relevance of the funded projects. These recommendations are listed below:

1. *Emphasize the necessity of interconnected multidisciplinary research efforts that tie together science (e.g. astronomical science, computer science), engineering, policy, sociology, and economic domains*: Spectrum sharing is impacted by the interplay of factors across multiple domains. Interdisciplinary as well as multidisciplinary research, including industry-academia collaboration, will be key to addressing open challenges in spectrum sharing. It is especially important that the multiple communities (e.g., economists, engineers, regulators) engage with each other earlier in the research and development process. Appropriately focused interdisciplinary and multidisciplinary research that addresses commercialization challenges and incentive issues earlier in the R&D process can contribute to easing the transition to new sharing frameworks and help ensure the economic viability of needed innovations.
2. *Encourage technology transfer from universities to the wireless industry and facilitate the collaboration between the two by creating funding mechanisms that foster such activities*: Possible examples include funding collaborative efforts between the NSF EARS awardees and the NSF SBIR/STTR program awardees focused on spectrum issues and other funding mechanisms, such as the provision of supplementary awards to active grants for supporting "transition to practice" and testbed development objectives.
3. *Proactively disseminate and highlight the findings and the potential impact of EARS-supported projects, especially within industry.*
4. *Use the EARS program to experiment with new forms of university and industry collaboration*: Examples include EARS PI meetings in conjunction with other events or conferences; exchange of personnel between industry and academia, especially students (e.g., internships); new models for developing and sharing intellectual property between universities and industry; coalescing intellectual property across performing universities as a drawing card for industry engagement and participation.
5. *Support the research and development of emerging technologies for access above 6 GHz (e.g., centimeter-wave and millimeter-wave frequencies):* Supporting such endeavors provides a unique and timely opportunity for experimenting with new "clean slate" approaches to academic-industry-government interaction, since both regulations and standards are still nascent.

The remainder of this report is divided into the following sections:

- Section II discusses critical research areas and open problems that are aligned with the mission of the NSF's EARS program. Addressing these challenges is paramount to enabling sustainable growth of wireless technologies and applications.

- The advent of wireless services has fostered a unique environment where discourse and collaboration between government, industry, and academia is essential to the goal of the EARS program. Section III outlines obstacles and opportunities to collaboration.
- EARS research is intended to help shape the future vision of how wireless services can be realized through interdisciplinary research. Section IV illustrates grand interdisciplinary challenges that, if addressed, would have a significant impact towards shaping future visions of spectrum access, sharing and wireless capabilities.
- Section V highlights the progress that has been made by the EARS program and discusses suggested future directions for the program.
- A list of workshop participants is provided in Section VI.A.
- Section VI.B includes biographical sketches of selected workshop participants, and
- Section VI.C provides a link for obtaining slides from selected panels and keynote presentations.

II. Advancing EARS Research: Critical Research Areas and Open Problems

The research recommendations made in this report represent the evolution of research conducted based upon the recommendations of the First EARS Workshop. It is also important to highlight that many recommendations made in this section are in agreement with the findings of the Federal-Commercial Spectrum Sharing Workshop[1], which was held earlier in 2015. Since 2010, steady progress has been made towards enabling efficient spectrum access, yet many research areas identified in the First EARS Workshop are still active topics of interest[2]. The fundamental knowledge gleaned through prior EARS research (discussed in Section V) is leading to more refined questions and new directions on the nature of spectrum access and sharing, most notably:

- Potential for spectrum access in the centimeter- and millimeter-wave frequencies;
- The identification of fundamental security and privacy issues and development of innovative security/privacy-aware spectrum sharing and access architectures;
- Experimental validation of spectrum sharing policies coupled with engineering and economic models for spectrum sharing; and
- Renewed emphasis on engagement and collaboration between academic, industry, and regulatory communities in future research.

A. Advances in Hardware and the Physical Layer to Improve Sharing and Efficiency

1. *Power efficiency* is an essential research area, regardless of use case, frequency band, or radio configuration. Research on analog filtering and interference rejection, as opposed to digital approaches, is a promising approach to minimize radio power consumption. The use of analog methods for power efficiency becomes more feasible at higher frequencies, and needs to be explored further.

[1] W. Lehr, C. Kahn, C. Kutsche, "Workshop VII Report: Federal-Commercial Spectrum Sharing: Models, Applications, and Impacts of Incentives for Sharing", Networking and Information Technology Research and Development Program, Hoboken, NJ, 2015.
[2] J. Bernhard, J. Reed, and J. Park, "Final Report on the First EARS Workshop", National Science Foundation, Arlington, VA, 2010.

2. *Fundamental limits* in the area of radio hardware need to be explored. At present, there is limited information on the fundamental performance thresholds that can be achieved in the hardware domain. This also applies to hardware reconfigurability.
3. *Wireless network scalability* will be important as wireless communications devices continue to proliferate. The increased number of wireless devices will raise the noise floor, and digital back-end processing complexity will increase as wireless systems expand both system bandwidth and the number of antennas utilized. In the near future this trend will be more pronounced at frequencies below 6 GHz driven by the expected proliferation of wireless devices in the “Internet of things”. Interdisciplinary research is needed to address the resulting challenges.
4. *Interdisciplinary research* and increased collaboration between hardware, communications, and signal processing experts is essential to future research and must be encouraged. Similarly, increased collaboration between communications and networking experts is needed.
5. New technologies and applications above 6 GHz are a promising emerging area under current exploration, but several challenges remain unaddressed. Power consumption is a critical issue due to the additional digital-backend processing required for high bandwidth applications and multi-antenna applications. Furthermore, coordinating multi-beamforming and tracking in mobile scenarios is another challenging problem that needs to be addressed. The fundamental design of the analog-digital interface needs to be revisited at these higher frequencies.
6. Improving *spectral efficiency* and *radio configurability* to enhance spectrum sharing will be key in enabling the creation of spectrum sharing devices. Methods for rapidly detecting unused spectrum and reconfiguring front-end radio hardware over broad swaths of spectrum are paramount for enabling efficient spectrum sharing. This will likely require joint hardware-software innovations.
7. Future wireless systems (i.e., 5G and beyond) are expected to be highly frequency agile, and they will leverage multi-band techniques such as spectrum aggregation. Research efforts need to focus on enhancing radio frequency agility from 1 to 100 GHz to utilize available spectrum and to improve spectrum aggregation techniques.
8. Research needs to explore potential economic/regulatory functionality that might be explicitly embedded in wireless hardware and system designs. This might include such ideas as incorporating time-limited leases, support for real-time markets, crowd-sourced sensing, and radio "black boxes" to support ex post enforcement audits.

B. Coexistence of Heterogeneous Wireless Systems and Applications

1. One of the key hurdles in realizing spectrum sharing in the Citizens Broadband Radio Service (CBRS) band (3.5 GHz band) is enabling the harmonious coexistence between radar and communication systems, such as the coexistence of DoD radar systems and LTE-based small cell networks. Even with the adoption of beamforming technologies, this coexistence scenario poses a number of challenging problems, which have yet to be addressed.
2. Passive sensing applications may be very sensitive to even low levels of additional signal energy in the band. Furthermore, passive applications have limited flexibility to relocate to other frequencies since passive sensors are searching for RF signatures at particular frequencies where physical phenomena can be observed, and the phenomena of interest are not under direct control of the sensing systems. Research needs to identify sharing challenges and opportunities between passive and active wireless applications, and explore frameworks and models for coexistence between these applications:

    2.1. Spectrum usage requirements and regulatory mechanisms for active and passive wireless applications are drastically different. For example, passive users are not directly detected by active users and so some sort of explicit coordination mechanism may be needed to enable coexistence. How can these differences be reconciled in a spectrum sharing framework?

2.2. Receiver sensitivity for some passive applications is -250 dBW/m^2/Hz below the noise floor of most active sensors. Can we quantify a tolerable and measurable level of interference that would be acceptable to passive users?

2.3. Research should investigate the possibility of nulling transmitted signals at a receiver instead of at a transmitter, and the potential to enable coexistence via direction-based spectrum sharing.

3. Frequency bands reserved for Radio Astronomy Services (RAS) and Earth Exploration Satellite Services (EESS) may not be continuously utilized. Furthermore, phenomena of interest for RAS are in bands that are increasingly congested from use by other users (e.g., L-band spectrum is assigned for satellite usage, and is therefore no longer widely usable for RAS). Research is needed to investigate frameworks for sharing spectrum access between passive and active users. How can bands reserved for passive applications be shared with secondary users, while ensuring the needs of the passive users are met? What sharing frameworks could enable passive users to scan for phenomena of interest in bands used by commercial operators?

3.1. EESS users are especially interested in exploring spectrum sharing opportunities in the 500-600 MHz band. Research is needed to evaluate potential sharing opportunities between incumbent users (e.g., television broadcasters) and passive users.

4. There are significant open challenges to the coexistence of multiple wireless technologies which are influenced by different regulatory frameworks for managing spectrum access. This is illustrated by the on-going challenges of reconciling barriers to coexistence between wireless systems influenced by unlicensed versus license-anchored frameworks (e.g., Wi-Fi vs. LTE-U, respectively). The research community should aim to address the following:

4.1. What constitutes “harmful interference,” and what mechanisms can be used to quantify and measure interference? How might these definitions vary with the form of a regulatory model? Research is needed to provide comparative analysis of the technical and economic benefits and efficiency of decentralized versus centralized spectrum management and resource governance, and to explore the transaction and overall efficiency implications of alternative spectrum rights regimes.

4.2. As new wireless systems and technologies emerge, it is possible to encounter the scenario where established and emerging wireless systems cannot be operated in harmony. Under these scenarios, how should the benefits and drawbacks of the competing wireless systems be quantified and valued?

4.3. What is the appropriate mix of ex ante and ex post enforcement of interference protection, and how can these mechanisms best be reconciled?

C. Security, Privacy, Compliance and Enforcement Issues

1. The use of the Spectrum Access System (SAS) enables a pragmatic approach for enabling spectrum sharing, but at the same time, it may pose a serious threat to the operational security (OPSEC) of the incumbent, priority, and secondary users by unintentionally facilitating the collection and aggregation of sensitive information by adversarial users. This is a key challenge since critical services (e.g. critical infrastructure operators, healthcare users, and military users) will operate in shared spectrum, such as the 3.5 GHz and AWS-3 bands. In such scenarios, there is an inherent tradeoff between the spectrum user’s OPSEC and spectrum utilization efficiency, and this issue needs to be studied further.

2. Methods for ensuring that radios conform to spectrum sharing policies when operated in the field is an open challenge. This includes detecting when a radio transmission in shared spectrum bands is violating policy, identifying which radios are violating policy, and enforcement actions and mechanisms that can be used when policy violations are detected. In general, enforcement mechanisms can be classified into two categories: *i.)* ex ante (preventive)

mechanisms, and *ii.)* ex post mechanisms (punitive measures or incentives/credits based on observed actions). Striking an optimum balance between these two enforcement schemes in terms of cost, efficiency and complexity is a challenging problem. Furthermore, advances in technology open up new opportunities for enabling enforcement that need to be explored. More research is needed to address spectrum sharing enforcement, and to identify new and novel enforcement approaches enabled by technology advances in areas such as cognitive radio and millimeter-wave radios.

3. There exists an inherent trade-off between enforcement and privacy. More reliable and effective enforcement regimes often result in greater infringement of the user's privacy rights. A multidisciplinary research effort is needed to quantify this tradeoff, and explore the technical and sociological solution approaches for achieving the two, seemingly opposing, goals of enforcement and privacy.

4. The key steps of ex-post enforcement are: detect harmful interference events, identify rogue or malfunctioning radios, adjudicate intentional interference events, and resolve interference disputes. Performing these steps manually becomes prohibitively expensive as wireless systems proliferate and become more advanced. More research is needed to investigate the feasibility of automating some of the enforcement steps.

5. Testing a Software Defined Radio (SDR) node for compliance is non-trivial because of the radio's reconfigurable and frequency-agile nature. Research is needed to study efficient and reliable mechanisms for certifying SDR compliance.

6. In SAS-driven spectrum sharing, the SAS needs to store information about incumbents as well Secondary Users (SU). Storing more information about SUs provides forensic evidence during the adjudication process, if needed, but it also exponentially increases the data retention burden. Research is needed to identify the types of data that must be stored to achieve a desired level of adjudication.

D. Wireless Policy Challenges and Opportunities: Economic, Regulatory, Technology, and International Factors

1. The transition to new and more efficient sharing models must balance diverse stakeholder interests and so presents a complex collective choice decision-making challenge for policymakers and industry. Multidisciplinary research is required to better understand stakeholder incentives and private/societal cost-benefit implications of transitioning to new sharing models. We need better techno-economic models to understand how to best balance alternative spectrum usage models for society and industry. This includes improved models for valuing spectrum uses.

   1.1. Economic research should support better evidence-based decision-making; there is a need for better information on ground truth and forecasts of market trends, economic/societal impacts, and how those relate to the technology. A key deficit in current research is adequate empirical data to value spectrum resources, wireless usage, and the societal opportunity costs of using spectrum resources for one use instead of another.

   1.2. RAS and EESS provide valuable data for basic research and society. Valuing the long-term benefits to society of basic science research or public safety (e.g., storm tracking) and justifying and securing research funding to support these activities poses a difficult challenge. Uses and benefits of passive sensing for society are not well understood (e.g., surveillance for drug trafficking, environmental sensing and monitoring, etc.). More research is needed to demonstrate and assess the value to society of using spectrum for passive sensing applications.

2. Coexistence between heterogeneous wireless systems can be facilitated through a variety of market-based approaches. Research on the following issues is needed: *i.)* strengths, weaknesses, opportunities, and tradeoffs of different coexistence approaches, and *ii.)*

prospective regulatory frameworks that incentivize spectrum brokers in achieving the aforementioned objectives:

2.1. Research needs to identify design strategies for market and regulatory institutions to be incentive compatible so that stakeholders when acting in their private interest behave as intended (e.g., comply with rules, report spectrum requirements and usage truthfully, etc.).

3. Economic research methods such as game theory, mechanism design, and new econometric techniques for Big Data analytics need to be applied with appropriate cognizance of the wireless propagation characteristics that facilitate or prevent coexistence in a given spectrum band. Accomplishing this is unlikely to be successful without active collaboration between engineers and economists engaged in such research.

4. Currently, the FCC and the NTIA are working on rules and regulations for AWS, CBRS, 5 GHz and millimeter wave spectrum bands. The research community needs to focus on identifying and elucidating spectrum usage rights, specifically: how we define these rights, and the cost-benefit analysis (i.e., technical performance analysis, economic efficiency assessment) of these rights in different realistic scenarios. Engaging economists in design of the 3.5 GHz auction and SAS is a potential avenue of interest.

5. Existing spectrum frameworks provide limited protection for passive sensing users. There are no dedicated sensing bands, and at most, passive sensors are noted as "protected" users with ambiguous protection rights. Much of the focus on spectrum reform management has neglected to address the unique requirements of passive sensing, instead focusing on active spectrum users. Research needs to evaluate opportunities and challenges in scenarios where passive users are granted primary status in shared spectrum bands.

6. Some stakeholders may see future spectrum sharing as a threat to their own use. Emphasizing that spectrum sharing can also provide opportunities, including for incumbent users whose spectrum demands also continue to grow, might incentivize them to actively participate in spectrum sharing. Policy research efforts along with engineering creativity should focus on incentivizing spectrum sharing opportunities for both incumbent and secondary users.

E. Prototypes, Testbeds, and Community Research Infrastructure

1. Community shared testbeds will be key to evaluating and validating innovative solutions. An ideal wireless testbed has, but is not limited to, the following characteristics: *i.)* provides introspection into each wireless technology layer, *ii.)* provides a common programmable experimentation environment, *iii.)* facilitates time-sharing and virtualization of wireless devices, *iv.)* enables node mobility control, and *v.)* provides robust remote management capabilities.

2. Ad hoc and uncoordinated efforts to construct and operate wireless testbeds will likely fail to meet the needs of the research community and hamper the development of innovative and pragmatic solutions. International collaboration and close interaction between the government, industry, and academia will be essential and should be encouraged for the development and operation of testbeds of sufficient size and capabilities.

3. Compared to testbed experiments, simulations are less resource intensive to carry out. However, in general, the research community deems simulation results, by themselves, insufficient to validate new technologies or solution approaches. When possible, simulation results should be validated by relevant experimental testbed results. New simulation models, approaches, and tools are needed to enable rapid and low-cost evaluation of new wireless technologies.

4. Prototypes and testbeds in emerging technologies—e.g., for spectrum access and applications above 6 GHz or testbeds aimed at dense network scaling below 6 GHz—can provide a useful platform for impactful collaboration between academia and industry.

III. Bolstering Collaboration Between Government, Industry, and Academia

In addition to fundamental research challenges, wireless and spectrum research presents challenges that cross organizational boundaries in academia, government and industry. To facilitate any type of wireless innovation there *must* be significant communication and collaboration between regulators, researchers, and commercial parties. This section outlines organizational issues that inhibit research and innovation efforts in the wireless arena that could be addressed in future EARS solicitations.

A. Improving Communication Between Government, Industry and Academia

1. The emergence of new forums that bring together policy makers and engineers, such as the IEEE Dynamic Spectrum Access Networks (DySPAN) conference and the Wireless Innovation Forum Conference on Communications Technology and Software Defined Radio (WInnComm), need to be nurtured and can be venues for encouraging technology transfer.
2. Additional cross-domain discussions need to be fostered by creating new technical journals focused on wireless policy to further encourage discourse between stakeholders in academia, industry, and the government. One example implementation would be to create a Letters on Wireless Policy Management topic in a technical organization, such as the IEEE.
3. Research sponsors in industry and government need to emphasize the need for research solutions that are compatible with regulatory policy, or research that proposes new techniques and a pathway for evolving regulatory policy to accommodate new uses of wireless technologies.

B. Facilitating and Encouraging Technology Transfer between Industry and Universities

1. Differences in organizational goals and expectations are negatively affecting collaboration and technology transfer efforts between academia and industry. The following challenges must be addressed to enable improved collaboration between academia and industry:
   - 1.1. Disputes over intellectual property (IP) when academia and industry work together is a vexing dilemma; there are very different expectations about IP rights between parties which stymie industry-academia collaboration. Work needs to focus on identifying differences in both parties' expectations of IP rights as well as IP policy initiatives that facilitate and encourage collaboration.
   - 1.2. Some of the most successful collaboration between industry and academia has resulted when academia and industry have shared staff members (e.g., student internships, students moving into industry, and shared research infrastructure where academics and industry professionals physically work together). Understanding lessons learned from successful collaboration is key to expanding collaboration and technology transfer pathways between industry and academia.
2. Research sponsors should consider encouraging deliberate interaction between industry and academia in advancing EARS research goals (Section II) by specifying collaboration expectations and requiring deliberate industry-academic interaction in requests for proposals.

IV. Grand Challenges

Based upon the discussions in the panel and breakout sessions, the workshop participants identified a number of grand challenge projects. These grand challenges serve as highly desirable future capabilities, and they illustrate the need for synergistic collaboration between experts from several areas. Addressing these grand challenges could provide disruptive new capabilities, but it requires highly interdisciplinary teams and significant resources to achieve. The grand challenges discussed here should not necessarily be considered mutually exclusive, but instead complementary and interconnected issues in spectrum utilization that are motivated by technical, policy, and economic considerations illustrated by the wireless system model in Figure 1.

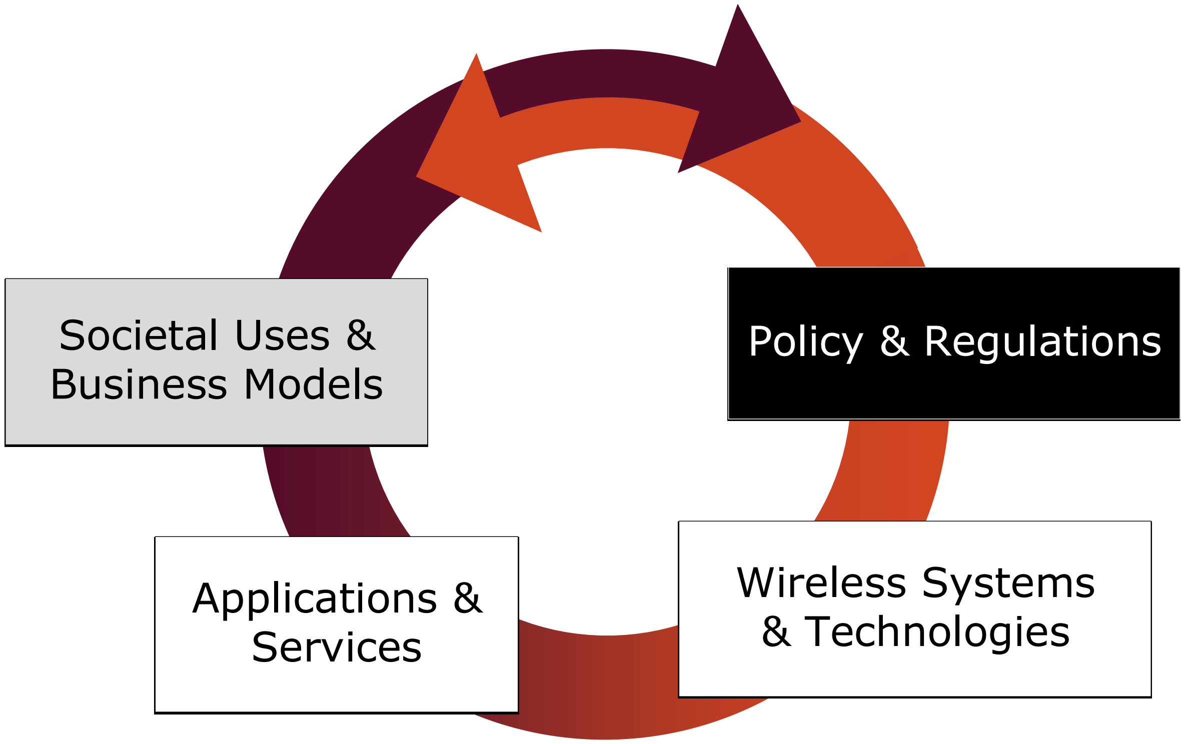

Figure 1. Layered wireless ecosystem model reflecting the interplay of technical, societal, and policy factors: Modern wireless systems are impacted by socio-technical issues from adjacent layers while societal and policy layers directly affect each-other. The model reflects the feedback and evolution cycle of wireless technology, services provided through wireless systems, regulatory policies, and societal uses. The socio-technical nature of contemporary wireless systems is indicative of the critical role that the interplay between the academic, industrial, and regulatory stakeholders plays in advancing wireless research.

Once addressed, these grand challenges will provide fundamental knowledge that will be instrumental in advancing seamless and efficient access to the radio spectrum for passive, active, and future wireless applications. Undertaking these grand challenges will undoubtedly require input and collaboration that spans the gamut of the wireless community. Interactions between communications researchers and engineers, economists, radio astronomers, spectrum regulators, computer scientists, sociologists, etc. will be critical to addressing the grand challenges. NSF's Astronomical Sciences, Engineering, and Computer & Information Science & Engineering organizations should encourage discourse, collaboration, and partnerships among different members of the wireless community towards investigating these grand challenges through conferences, PI meetings, and other forms of discussion described in further detail in Section III.A.

A. Achieving Harmonious Coexistence in Heterogeneous Wireless Networks and Systems

There is an ever increasing demand for spectrum, and a diverse array of wireless technologies vying to access the spectrum has resulted in numerous challenges in many areas, including: radio hardware design (Section II.A), coexistence of wireless devices and systems (Section II.B), spectrum policies (Section II.D), and methodologies for testing potential spectrum access technologies and devices (Section II.E). The exploding demand for spectrum is being fueled by the proliferation of existing and new wireless applications—e.g., an increasing number of automobiles are being equipped with radars to aid drivers; and the Internet of Things is expanding where everyday items such as locks, light bulbs, large appliances, and wristwatches are being equipped with wireless transceivers to enable novel applications that were not previously imagined.

In the case of automotive radar, shared access to the 77-81 GHz band is being considered between incumbent radio astronomy services (RAS), radiolocation services, and amateur radio operators[3]. In another case, shared access between commercial and government radio operators in the 3.55-3.7 GHz band is being implemented[4]. It is likely that sharing of spectrum will increase in both the short and long term. It is imperative that multiple operators' applications coexist harmoniously so that each operator can carry out their mission, whether that mission is communications, active sensing (e.g., radar), passive sensing (e.g., radio astronomy), or a future wireless application.

Specific goals in this grand challenge include:

1. *Creating Metrics to Assess How Well Devices can Coexist Together*: With the potential for multiple heterogeneous applications and networks operating in a shared band, it becomes increasingly important to understand how each application or network would define interference. Once an application-specific view of interference is reached, it becomes possible to investigate metrics that enable quantitative assessment of coexistence performance between applications, where coexistence performance could be defined as how efficiently a particular application can meet a given objective while sharing spectrum with one or more other wireless applications.

2. *Risk Assessment Techniques for Evaluating When and How to Share Spectrum Resources Between Users*: The heterogeneous nature of different wireless applications (i.e., communications, sensing) results in varying demands being placed upon spectrum resources. In some cases, an application sharing the spectrum may degrade another application's performance. It is important that the different spectrum communities come together to investigate and evaluate the demands their applications require of spectrum resources, communicate spectrum needs throughout the community, and identify paths by which heterogeneous applications can coexist while maximizing wireless application performance.

3. *Identifying Policies for Resolving Disputes*: There are times when wireless applications may interfere with other spectrum users. In the case of these events, spectrum users must come together and decide what spectrum rights each user has in a given band, and how to mediate and resolve sharing disputes between different users.

4. *Interference mitigation techniques:* It is paramount that spectrum users collaborate to find mechanisms by which multiple wireless applications and networks can achieve harmonious coexistence when sharing the same spectrum band. Mitigation could be protocols to minimize undesired interference that may be encountered when sharing wireless resources among many homogeneous (i.e., multiple communications systems) or heterogeneous applications (i.e., passive and active wireless services). Mitigation techniques could also be policies that address sharing through wireless right-of-way definitions and approaches for time sharing wireless applications.

5. *Large-scale Simulations that Assess Potential Coexistence Techniques and Policies:* High-fidelity simulation experiments will be an essential first step in understanding the interplay of multiple diverse spectrum applications (i.e., coexistence simulations of both heterogeneous and homogeneous wireless networks and systems) operating together in shared spectrum

[3] U.S. Federal Communications Commission. (2015 Feb). FCC 15-16, Operation of Radar Services in the 76-81 GHz Band.
[4] U.S. Federal Communications Commission. (2015 Apr). FCC 15-47, Amendment of the Commission's Rules with Regard to Commercial Operations in the 3550-3650 MHz Band.

bands. These simulations should incorporate measurements from relevant testbeds to best simulate wireless conditions that sharing applications could encounter.

Technical and policy approaches that address this grand challenge would yield results applicable to challenges in compliance and enforcement (Section II.C) and wireless policy (Section II.D). Furthermore, this grand challenge would fuel future research in wireless hardware (Section II.A) and new dynamic spectrum access mechanisms and systems (Section II.B).

B. Development of Automated Enforcement Mechanisms and Compliance Certification Methods

This grand challenge arises from the need for frequency agile radios (Section II.A) combined with compliance and enforcement requirements (Section II.C) to achieve spectrum-sharing goals. Each member in the spectrum community must clearly define their desired spectrum use cases, and under which conditions they can achieve their desired uses. Once defined, the different communities can come together to design and assess technical and policy incentives and deterrents that allow for efficient spectrum sharing between different wireless networks and applications.

Radio agility has been identified by some Federal users as essential to achieving future goals[5]. One path to spectrum sharing is through software defined radio's frequency agility features. Yet, with increased frequency agility comes increased certification and enforcement complexity (see Section II.C) to ensure that spectrum sharing incentives and deterrents are swiftly applied.

Specific goals in this grand challenge include:

1. *Evaluating the Sociology of Privacy, Enforcement Mechanisms, and Potential Penalties*: Different groups of spectrum users (e.g. commercial users, radio astronomers, wireless researchers, federal agencies) will have varying needs for utilizing spectrum resources. As such, these needs will be one factor that motivates incentive and deterrent mechanisms to sharing the spectrum. Wireless users need to come together to suggest and evaluate spectrum sharing policies.

2. *Automating the Detection and Identification of Interference Sources*: The effectiveness of spectrum sharing policies require that these policies be rapidly enforced (whether through ex ante, ex post, or a combination of both mechanisms). Collaborative research on wireless hardware, regulation mechanisms, and wireless system composition will be essential.

3. *Creating Mechanisms for Rapidly Enforcing Policy Changes on Radio Devices*: Spectrum sharing policies will undoubtedly change as spectrum users' needs change and as wireless technology evolves new capabilities. Research is needed to understand what enforcement mechanisms are possible for wireless hardware, what systems or infrastructure are needed to enable dynamic policy updates, and the regulatory effects that dynamic policy mechanisms could have in balancing spectrum sharing policy as the needs of different wireless users ebb and flow over time.

4. *Evaluating the Economic Tradeoffs in Ex Ante and Ex Post Mechanisms*: The means by which spectrum sharing policies are applied will influence the perceived value of incentive and deterrent policies by different spectrum users. Research into the tradeoffs between ex ante and ex post spectrum sharing mechanisms is needed to inform the diverse community of spectrum users on how spectrum policies could be applied, and how policies would impact technical operations.

[5] U.S. Department of Defense. (2013 Sep). A Call to Action: Electromagnetic Spectrum Strategy

C. *Evolving Spectrum Sharing Architectures for Future Wireless Applications and Usage Scenarios*

Spectrum management approaches and systems will be essential to the progress of spectrum sharing across users and devices. Current research has been promising and has enabled initial spectrum sharing through a database-driven Spectrum Access System (SAS). Yet, technological research and advances in hardware (Section II.A) will enable new and innovative dynamic spectrum sharing and access scenarios. Two example scenarios are discussed in greater depth in goal 5 of this grand challenge. New spectrum sharing architectures will need to differ from contemporary solutions to address sharing challenges in different scenarios (Section II.B), including the transition of additional federal spectrum with different types of legacy users and applications, while providing mechanisms to ensure spectrum is being economically utilized based on local and national needs (Section II.C, II.D, and II.E).

Specific goals in this grand challenge include:

1. *Assessing the Economic Trade-offs of Incentivizing Spectrum Sharing Under Multiple Scenarios*: These scenarios should represent the unique spectrum needs within the community of wireless users, including (but not limited to) commercial, research, radio astronomy, and federal wireless users. Future wireless scenarios encompass new and novel ways of utilizing shared spectrum, which will likely require technical and policy updates to contemporary spectrum sharing systems. Some examples of innovative future scenarios for spectrum sharing include: high mobility wireless (e.g., commercial delivery via unmanned aerial vehicles communicating in shared spectrum), dynamic spectrum access within contained access facilities (e.g., enabling shared spectrum bands inside buildings to be repurposed by occupants, as long as indoor wireless users' signals do not radiate outside the building), and celestially scheduled and interruptible shared spectrum (e.g. scheduling active wireless systems' access to shared spectrum based on scheduled, unscheduled, and intermittent passive sensing applications).

2. *Devising Models and Processes that can Operate on Huge Datasets of Wireless Feedback, Rapidly Assess Spectrum Usage, and Adjust Spectrum Sharing Parameters in Real-time:* Future spectrum access systems' adaptation to the ebb and flow of demand for access to spectrum will likely depend on real-time analysis of multiple data points (e.g. noise floor observations at a particular location, spectrum access requests over time, spectrum service parameters requested by multiple applications). It is imperative to understand what parameters a spectrum access system can glean individually, from external sources, and from wireless users in a given region. When presented with a plethora of data points, how can these seemingly disparate data points be analyzed to provide useful situational awareness to a spectrum access system? Finally, how should situational awareness information be used with economic, sociological, and engineering models to respond to spectrum demands while promoting efficient use of spectrum resources?

3. *Understanding what Data from Spectrum Usage can be Collected and Analyzed to Assess Spectrum Utilization without Infringing on Users' Privacy:* In the process of collecting information on the utilization of shared spectrum (discussed in IV.C.2) it is likely that a spectrum access system may be collecting privileged data directly from spectrum users, or will have access to enough data points to make accurate inferences about sensitive user information. In these scenarios it is essential to define *i.*) what data points a spectrum access system may collect (i.e., what is necessary versus useful data points), *ii.*) asses the sensitivity of information that can be derived by the spectrum access system as individual data points are aggregated and interpreted, and *iii.*) define the allowable uses of each individual and aggregate data point collected or created by a spectrum access system. Situational awareness data generated from shared spectrum operations is insightful for optimizing how spectrum is shared, but the utility of situational awareness data must be balanced with users' security and privacy interests. Again, input from the diverse community of wireless users will be essential in both

understanding the utility that can be gleaned from various datasets generated from spectrum uses in conjunction with defining privacy requirements and expectations.

4. *Facilitating Radio-Frequency Propagation Measurements that Provide a Baseline for Expected Sharing Efficiency in Different Bands*: Understanding wireless signal propagation characteristics in a particular band is essential to assessing coexistence performance between multiple wireless networks and applications in addition to identifying sources of interference when multiple users operate in the same frequency band. Once signal propagation characteristics are understood, it is possible to design coexistence models for heterogeneous and homogeneous wireless networks at a given frequency. Addressing this challenge can reduce mission risks and coexistence uncertainty for wireless users who are considering opening up licensed spectrum bands to other secondary-licensed or unlicensed users. Collaboration between radio astronomers, hardware engineers, signal processing engineers, and computer scientists could yield new and innovative models that inform sharing between active and passive networks in the same band.

5. *Researching Protocols, Policies, Models, and Frameworks to Enable Future Spectrum Sharing Architectures*

   5.1. *Enabling Rapidly Moving Wireless Devices in Shared Spectrum Bands*: Wireless technologies are enabling advances in high mobility cyber-physical systems applications such as high speed vehicular communications and unmanned aerial vehicles (UAV). While today's shared systems make the simplifying assumption about incumbent, primary and secondary users being stationary or slowly moving, shared spectrum bands are likely to be needed for emerging high mobility applications. Due to the high mobility nature of these applications, it is reasonable to presume that high mobility wireless devices would need to be granted spectrum access at different locations representing the device's anticipated position at any given instant in time. The complexity of assessing spectrum availability for high speed applications may be compounded by human safety issues when device operation is conditioned on the availability of shared spectrum (e.g., A UAV requires telemetry sent from a wireless ground station to operate, and would therefore be unable to fly if the UAV's communications system is unable to secure spectrum in a shared band at a given time and location). To enable new and novel services (e.g., commercial delivery service UAVs) in shared spectrum bands, research needs to investigate the impacts of coexistence between stationary, low- and high mobility applications and potential frameworks for achieving sharing between devices operating at different speeds and with different priorities.

   5.2. *Passive and Active Wireless Coexistence via Celestial Scheduling and Spectrum Preemption*: Passive sensing applications are both scheduled and unscheduled. For example, many RAS or EESS users are amenable to being scheduled, raising the possibility of time-based sharing. However, there are also continuous monitoring scenarios and many passive applications involve a mix of both scheduled and unscheduled uses of the spectrum. Sharing spectrum between active and passive wireless users may be facilitated by exploiting spectrum sharing based on the celestial location of EESS observation satellites. With EESS, known orbits can be used to identify blocks of time when EESS spectrum may be able to be shared with active users. Yet, synchronizing the time slots when EESS satellites are inactive may pose a significant technical challenge and will likely require accurate geolocation details of terrestrial wireless users. Furthermore, an open challenge exists where research needs to illuminate protocols and policies to enable spectrum preemption, whereby secondary users rapidly relinquish the spectrum to accommodate unscheduled and intermittent passive sensing applications. Research on spectrum preemption would need to identify economic models that appropriately value and incentivize the services provided by both active and passive users in conjunction with engineering approaches to coordinate and enforce spectrum preemption.

D. *Exploration of Emerging Technologies as a Vehicle for Bold New Approaches, including Academic-Industrial-Regulatory Interaction*

One of the meta-themes in the context of collaboration between academic, industrial, and governmental stakeholders, as discussed Sections II.D and III, is the importance of relevance, awareness, and timeliness for the collaboration to be impactful. Often times, academic researchers are working on problems that may have very limited impact due to existing regulations or standards. On the other hand, standards and regulations can be misguided if not fully informed by relevant research and innovations from academia. The needed interactions have traditionally occurred in ad hoc fashion. However, emerging technologies for which standards and regulations are still nascent provide a unique opportunity for exploring new approaches for streamlining such interactions between academic, industrial and regulatory stakeholders.

Consider that wireless technology is undergoing an unprecedented transformation driven by the operational needs of existing and emerging applications. This is manifested in current discussions and debate on 5G systems, including: gigabit and low latency communication at frequencies in the centimeter- and millimeter-wave frequencies, billions of connected devices in the “Internet of things”, and new cloud-based applications and approaches to network optimization and deep understanding of complex and pervasive data sets. This transformation is being fueled by hardware innovations (Section II.A) for taming the complexity of emerging heterogeneous networks (Section II.B); enabling new modes of secure communication (Section II.C); new devices and architectures for spectrum agility (Section II.B); and new approaches to efficiency and scalability by revisiting the traditional analog-digital divide (Section II.A).

The full potential of these advances can only be realized by cross-disciplinary engineering research spanning hardware developers, communication engineers, and networking experts. Suitably trained communication engineers and signal processing experts can play an important role by providing a bridge between hardware developers and networking researchers. Appropriately designed experimental testbeds (Section II.E) can greatly facilitate such efforts as well as foster close interaction between academia and industry (Section III.B). The results of collaboration across the gamut of wireless communities towards emerging technologies could be significant.

V. Progress of the EARS Program and Future Directions

One of the key success factors in EARS research is discourse and collaboration between a diverse set of stakeholders in the academic, industrial, and regulatory fields. The EARS workshops have been instrumental as a forum for stakeholders to discuss recent developments and ponder philosophical issues (e.g. technical advances, spectrum rights, and societal perception of wireless systems) which affect the direction of industrial activity, policy initiatives, and fundamental and applied research.

The First EARS Workshop was held in 2010, where the workshop participants identified the following areas for further investigation[6]:

- Metrics to Quantify Spectrum Parameters Relevant to Efficiency and Access
- Interdisciplinary Technology Innovation to Enable Spectrum Efficiency
- Spectrum Security and Enforcement
- Spectrum Allocation/Assignment: Market and Nonmarket Mechanisms
- Green Technology
- New Frontiers and Research that May Lead to Transformational Improvements in the Use of the Radio Spectrum

[6] J. Bernhard, J. Reed, and J. Park, “Final Report on the First EARS Workshop”, National Science Foundation, Arlington, VA, 2010, sec. 7

- Technology Transfer of Next-Generation Developments in Smart Radios
- Creation of Wireless Test Beds and Demonstration of New Concepts
- Development of Methods to Create and Maintain a Comprehensive Spectrum Survey and Inventory
- Education and Workforce Development

While many of the findings and recommendations from the Second EARS Workshop (Sections I.A, II, and III) echo the recommendations from the First EARS Workshop, the recommendations from the Second EARS Workshop are significantly refined due to the research discoveries of NSF EARS funded research collaborations from the past half-decade. Since the First EARS Workshop, seminal research work on spectrum sharing architectures and privacy and security models have been influential in enabling spectrum sharing systems as well as identifying promising future directions for dynamic spectrum access techniques. Research in RF circuits and antenna array architectures has illuminated new and improved opportunities for spectrum sharing in the centimeter- and millimeter-wave frequencies. The recommendations of the Second EARS Workshop are influenced by the impact of new fundamental and applied research endeavors in many areas[7] including, but not limited to:

- RF Circuits and Antennas for Spectrum Sensing and Access
    - Reconfigurable RF Electronics and Antennas
    - Millimeter-wave Circuits and Devices
    - Beamforming Architectures for Massive Multiple-Input Multiple-Output (MIMO) Communications at Millimeter-wave Frequencies
    - Full-Duplex Cognitive Radios
- Medium Access Control (MAC) and Network Layer Support for Emerging Physical Layer Technologies
- Cognitive Radio Networking and Dynamic Spectrum Access Frameworks
    - Sharing between Passive and Active Wireless Systems and Services
    - Interference Aware Passive Wireless Systems
- Exploration of Spectrum Coexistence Theory and Models
    - Algorithms and Protocols for Dynamic Spectrum Access
    - Economic Models, Policies, and Regulatory Issues in Wireless System Coexistence
    - Societal and Behavioral Aspects of Spectrum Sharing
    - Security and Privacy Dilemmas and Solutions

Building on these research discoveries and developments, the EARS workshop has formulated new future visions for wireless technologies and policies, which are outlined as grand challenges (Section IV). Furthermore, researchers have been able to utilize discoveries since the First EARS Workshop to assist regulators, through events such as policy workshops[8,9], in formulating new and effective policies. Future interdisciplinary research in wireless hardware and circuits, wireless coexistence architectures for passive and active users, economic and regulatory frameworks, and community wide wireless

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[7] National Science Foundation. (2015). *EARS Program Overview* [Online]. Available: https://earsworkshop.wireless.vt.edu/pdfs/EARS_workshop_NSF_PD_presentation_public_release.pdf

[8] U.S. Federal Communications Commission. (2013, Mar 13). *3.5 GHz Workshop* [Online]. Available: https://www.fcc.gov/events/35-ghz-workshop

[9] U.S. Federal Communications Commission. (2014, Jan 14). *3.5 GHz Spectrum Access System Workshop* [Online]. Available: https://www.fcc.gov/events/35-ghz-spectrum-access-system-workshop

testbeds will be key to further developing fundamental scientific knowledge that will unlock the economic potential from increased spectrum availability.

VI. Appendices

A. Workshop Participants

1. General Participants

Name	Affiliation
Jennifer Bernhard	University of Illinois
James Buckwalter	University of California, Santa Barbara
Milind Buddhikot	Alcatel-Lucent Bell Labs
John Chapin	Defense Advanced Research Projects Agency
Andrew Clegg	Google
Sandra Cruz-Pol	University of Puerto Rico at Mayagüez
Pierre de Vries	Silicon Flatirons Center, University of Colorado
Zhi Ding	University of California, Davis
Samir El-Ghazaly	National Science Foundation
Joseph Evans	Defense Advanced Research Projects Agency
Phil Fleming	Nokia Networks
Michael Flynn	The University of Michigan
Ralph Gaume	National Science Foundation
Hossein Hashemi	University of Southern California
Chris Helzer	Federal Communications Commission
Tom Hou	Virginia Tech
Walter Johnston	Federal Communications Commission
Peter Kinget	Columbia University
Edward Knightly	Rice University
J. Nicholas Laneman	University of Notre Dame
John Leibovitz	Federal Communications Commission
Sidharth Misra	Institute of Electronics and Electrical Engineers: Geoscience and Remote Sensing Society, Frequency Allocations in Remote Sensing Committee
Bruce Mueller	Motorola Solutions
James Neel	Federated Wireless
Jeyanandh Paramesh	Carnegie Mellon University
Robert Pavlak	Federal Communications Commission
Dimitrios Peroulis	Purdue University
Dipankar Raychaudhuri	Rutgers University

Continued on next page

General Participants (Continued)

Name	Affiliation
Phillip Regalia	National Science Foundation
Dennis Roberson	Illinois Institute of Technology
Jessica Rosenberg	National Science Foundation
Anant Sahai	University of California, Berkeley
Sayed Shah	Office of the Secretary of Defense
Peter Steenkiste	Carnegie Mellon University
Rangam Subramaniam	National Telecommunications and Information Administration
Vahid Tarokh	Harvard University
Peter Tenhula	National Telecommunications and Information Administration, Office of Spectrum Management
John Volakis	Ohio State University
Martin Weiss	University of Pittsburgh
Guoliang Xue	Arizona State University
Charlie Zhang	Samsung

2. National Science Foundation EARS Program Officers

Name	Division
Lawrence Goldberg	Electrical, Communications and Cyber Systems
George Haddad	Electrical, Communications and Cyber Systems
Glen Langston	Astronomical Sciences
Hao Ling	Electrical, Communications and Cyber Systems
Wenjing Lou	Computer and Network Systems
Thyagarajan Nandagopal	Computer and Network Systems
Chengshan Xiao	Electrical, Communications and Cyber Systems

3. Workshop Steering Committee

Name	Affiliation
Jeff Reed	Virginia Tech
Jerry Park	Virginia Tech
William Lehr	Massachusetts Institute of Technology
Akbar Sayeed	University of Wisconsin-Madison
Laura Woodney	California State University, San Bernardino

4. Workshop Coordinators and Assistants

Name	Affiliation
Nancy Goad	Virginia Tech
Joyce Donathan	Virginia Tech
Sudeep Bhattarai	Virginia Tech
Thaddeus Czauski	Virginia Tech
Gaurang Naik	Virginia Tech
Abid Ullah	Virginia Tech

B. Biographical Information for Selected Participants

1. *Jennifer Bernhard*

University of Illinois
Moderator, Panel 3

Jennifer Bernhard is currently a professor in the Department of Electrical and Computer Engineering and the Associate Dean for Research in the College of Engineering at the University of Illinois, Urbana-Champaign. She has been a faculty member in the Electromagnetics Laboratory in the Department of Electrical and Computer Engineering at the University of Illinois since 1999. Her research group focuses on the development and analysis of multifunctional reconfigurable antennas and their system-level benefits as well as the development of antenna synthesis and packaging techniques for electrically small, planar, and integrated antennas for wireless sensor and communication systems. In addition to the NSF CAREER Award, the IEEE Antennas and Propagation Society H. A. Wheeler Prize Paper Award and other research recognitions, she has been honored with a number of teaching and advising awards. In 2008-2009, Prof. Bernhard was a member of the Defense Science Study Group, sponsored by DARPA. In 2010, she co-chaired the National Science Foundation Workshop on Enhancing Access to the Radio Spectrum (EARS). She also served on the President's Council of Advisors on Science and Technology (PCAST) Working Group on Realizing the Full Potential of Government-Held Spectrum to Spur Economic Growth in 2011-2012. She is a Fellow of the IEEE, and in 2008, she served as the President of the IEEE Antennas and Propagation Society. Dr. Bernhard received her Ph.D. in electrical engineering from Duke University.

2. *Milind Buddhikot*

Alcatel-Lucent
Member, Panel 1; Moderator, Panel 2

Milind M. Buddhikot is currently a Distinguished Member of Technical Staff (DMTS) in Alcatel-Lucent Bell Laboratories, where he conducts research in next generation of wireless networks. In a research career spanning 22+ years, he has made significant contributions, scientifically as well as to the business aspects of wireless, IP and multimedia networking.

Milind's recent work is in the area of high capacity wireless networks, in particular small cells that exploit shared spectrum via dynamic spectrum access (DSA) technologies. He has authored 45+ technical papers and holds 15 US or international patents. According to Google Scholar, Milind's research publications have recorded 5000+ citations and are well recognized within the research community. Two concepts he pioneered and researched, namely the concept of database coordinated dynamic spectrum access (2004) and ultra-broadband small cells using shared spectrum (2009) have now emerged as promising new technology and spectrum policy directions.

Milind is a recipient of the Bell Labs President's Silver Award for outstanding innovations and contributions (2003), Bell Labs Team Award (2003), Lucent Chairman's Team Award (2006) and DMTS award (2012). Milind is a co-founder of the IEEE DySPAN symposium which has emerged as a premier conference on the topic of Dynamic Spectrum Access. He has served as an Associate Editor of IEEE/ACM Transactions on Networking and Elsevier's Computer Networks Journal, secured 1.2+ million dollars in research funding and regularly participates in FCC, NSF and conference panels and TPC committees of major IEEE and ACM conferences. Milind has frequently delivered invited presentations and tutorials on future technology directions to audiences in top-tier research forums and trade shows and to business customers worldwide.

3. *James Buckwalter*

University of California, Santa Barbara
Leader, Breakout Session 1A

James F. Buckwalter (S'01-M'06-SM'13) received the Ph.D. degree in electrical engineering from the California Institute of Technology, Pasadena, in 2006. He is currently a Professor of electrical and computer engineering with the University of California - Santa Barbara (UCSB), Santa Barbara. From 2006-2014, he was an Assistant and Associate Professor with the University of California – San Diego (UCSD), La Jolla. From 1999 to 2000, he was a Research Scientist with Telcordia Technologies. During Summer 2004, he was with the IBM T. J. Watson Research Center, Yorktown Heights, NY. In 2006, he joined Luxtera, Carlsbad, CA. In July 2006, he joined the faculty of UCSD as an Assistant Professor. Dr. Buckwalter was the recipient of a 2004 IBM Ph.D. Fellowship, 2007 Defense Advanced Research Projects Agency (DARPA) Young Faculty Award, 2011 NSF CAREER Award, and 2015 IEEE MTT-S Young Engineer Award.

4. *Andrew Clegg*

Google (now Alphabet)
Member, Panel 1; Moderator, Panel 2

Andrew Clegg is the Spectrum Engineering Lead for Google. He is presently focused primarily on identifying spectrum sharing opportunities for commercial wireless networks. Prior to joining Google, he served as the spectrum manager for the U.S. National Science Foundation. At NSF, he founded the Enhancing Access to the Radio Spectrum (EARS) program, a funding program dedicated to supporting academic and small business research focused on improving spectrum efficiency and access. Prior to NSF, he was a Lead Member of Technical Staff at what is now AT&T Mobility. He has over 25 years of experience in national and international spectrum management for both government and commercial applications, and was a member of the U.S. delegation to two World Radiocommunication Conferences.

Andrew holds a PhD in radio astronomy (major) and electrical engineering (minor) from Cornell University, and a BA in physics and astronomy, with highest distinction, from the University of Virginia.

5. *Sandra Cruz-Pol*

University of Puerto Rico at Mayagüez
Leader, Breakout Session 2A

Sandra Cruz-Pol is a Professor in the Department of Electrical and Computer Engineering at the University of Puerto Rico at Mayagüez since 1991. She was the NSF Program Director for the EARS program and was also a Spectrum Manager. As part of her job at NSF within the Electromagnetic Spectrum Division in 2014-15, she was appointed the NSF Representative to the IRAC and was a member of the U.S. Delegation at the ITU Radiocommunication meetings in Geneva. She obtained her Ph.D. in Electrical Engineering from Pennsylvania State University working with passive satellite sensors in the K_u, K and K_a bands for the calibration of absorption models of atmospheric gases and the sea surface emissivity model using satellite radiometer and ground-based radiometers and ancillary global data. She worked with polarimetric radars and ocean K-band radars at the University of Massachusetts.

Her research interests include microwave remote sensing (active and passive) of the Earth, and she has worked on several projects sponsored by NSF (ERC and MRI programs), including a DCAS Doppler Polarimetric Weather radar Network and an Off-the-Grid- (OTG) X-band weather radar network, both deployed on the western part of the island of Puerto Rico to study tropical weather on complex terrain. She worked in the NASA (TCESS) Tropical Center for Earth and Space Sciences project for several years. She was a member of National Academies' Committee on Radio Frequencies (CORF) from 2010 to 2014. Dr. Cruz-Pol is a senior member of the Institute of Electrical and Electronic Engineers, the IEEE Geoscience and Remote Sensing Society (GRSS), and the Tau Beta Pi and Phi Kappa Phi Honor Societies. She was the Associate Editor for University Affairs for the IEEE GRSS Newsletter for 5 years. She was the counselor for the student chapter of the IEEE in UPRM, the largest in IEEE Region 9. She has been a recipient of NASA, GEM, NSF-GEE and GTE Fellowships. She has also spent time as a researcher at AT&T Laboratories, Lincroft, NJ, and Middletown, NJ.

6. *Pierre de Vries*

Silicon Flatirons Center, University of Colorado
Moderator, Panel 1

Pierre de Vries is a Senior Adjunct Fellow and Co-Director of the Spectrum Policy Initiative at the Silicon Flatirons Center for Law, Technology, and Entrepreneurship at the University of Colorado, Boulder. He researches the intersection between technology, commerce and government policy. His current work focuses on ways to maximize the value of radio operation, e.g. by improving the allocation of the rights and responsibilities of wireless systems, and decentralizing spectrum management decisions.

7. *Phil Fleming*

Nokia Networks
Member, Panel 2; Keynote Speaker

Phil Fleming is CTO for Nokia Networks North America. He has broad experience in wireless communication technologies and special expertise in converting research and advanced technology concepts into business value for wireless equipment suppliers and operators. He currently holds 20 U.S. patents and he is co-author on 12 journal publications and 20+ conference papers in a variety of technology areas related to wireless communications. Dr. Fleming earned his Ph.D. in Mathematics from the University of Michigan (Ann Arbor) in 1981 and started his engineering career in 1982 at Bell Laboratories where he was named Distinguished Member of the Technical Staff in 1990. He joined Motorola in 1991 and was awarded the title Dan Noble Fellow in 2007. While at Motorola, he was Fellow of the Technical Staff and Senior Director of the Advanced Radio Technology and Engineering team from 2005 to 2011 in the Network Advanced Technologies organization and was responsible for radio access standards, algorithms and advanced RAN development of WiMAX and LTE. In 2011, he and his team joined Nokia Network's CTO office where they designed and developed advanced radio access algorithms and architectures, most recently focused on dense radio deployments such as urban centers, stadiums and other special venues. He was the lead technologist and inventor of Nokia's Centralized RAN which has won a number of industry awards including the 2014 Leading Lights Award for "Best Mobile Product." In January 2013, he was appointed Head of the Advanced Technologies group in NSN's Technology and Innovations organization responsible for acceleration of research and forward-looking concepts into products across Nokia Networks business lines.

8. *Erwin Gianchandani*

National Science Foundation
Keynote Speaker

Dr. Erwin Gianchandani is the Acting Deputy Assistant Director of the Directorate for Computer and Information Science and Engineering (CISE) at the National Science Foundation (NSF), where he contributes to all aspects of the directorate's management, including strategic planning and oversight of day-to-day operations. Most recently, Dr. Gianchandani has been the deputy division director for the CISE Division of Computer and Network Systems (CNS). Before joining NSF in 2012, Dr. Gianchandani served as the inaugural director of the Computing Community Consortium (CCC), providing leadership to the computing research community in identifying and pursuing audacious, high-impact research directions. Prior to the CCC, Dr. Gianchandani was an AAAS Science and Technology Policy Fellow at NSF and contributed to the establishment of NSF's smart health and wellbeing program. Previously, he was director of innovation networking at the University of Virginia, reporting to the university's vice president for research. Dr. Gianchandani has published extensively and presented at numerous international conferences on the subject of computational systems modeling of cellular reaction networks, with the goal of better understanding disease mechanisms and identifying therapeutic targets. Dr. Gianchandani received his Ph.D. in biomedical engineering, M.S. in biomedical engineering, and B.S. in computer science from the University of Virginia.

9. *Pramod Khargonekar*

National Science Foundation
Keynote Speaker

Dr. Pramod P. Khargonekar was appointed by the National Science Foundation (NSF) to serve as Assistant Director for the Directorate of Engineering (ENG) in March 2013. In this position, Khargonekar leads the ENG Directorate with an annual budget of more than $800 million. The ENG Directorate invests in frontier engineering research and education, cultivates an innovation ecosystem, and develops the next-generation of engineers. He is a member of the senior leadership team at NSF and thereby involved in setting priorities and policies at NSF.

Khargonekar received B. Tech. Degree in electrical engineering from the Indian Institute of Technology, Bombay, India, in 1977, and M.S. degree in mathematics and Ph.D. degree in electrical engineering from the University of Florida in 1980 and 1981, respectively. He has held faculty positions at the University of Florida, University of Minnesota, and The University of Michigan. He was Chairman of the Department of Electrical Engineering and Computer Science from 1997 to 2001 and also held the position of Claude E. Shannon Professor of Engineering Science at The University of Michigan. From 2001 to 2009, he was Dean of the College of Engineering and is currently Eckis Professor of Electrical and Computer Engineering at the University of Florida. He also served briefly as Deputy Director of Technology at ARPA-E, U. S. Department of Energy in 2012-13.

10. *Edward Knightly*

Rice University
Leader, Breakout Session 4A

Edward Knightly is a professor and the department chair of Electrical and Computer Engineering at Rice University in Houston, Texas. He received his Ph.D. and M.S. from the University of California at Berkeley and his B.S. from Auburn University. He is an IEEE Fellow, a Sloan Fellow, and a recipient of the National Science Foundation CAREER Award. He received best paper awards from ACM MobiCom, IEEE SECON, and the IEEE Workshop on Cognitive Radio Architectures for Broadband. He has chaired ACM MobiHoc, ACM MobiSys, IEEE INFOCOM, and IEEE SECON. He serves as an editor-at-large for IEEE/ACM Transactions on Networking and serves on the IMDEA Networks Scientific Council.

Professor Knightly's research interests are in the areas of mobile and wireless networks with a focus on protocol design, performance evaluation, and at-scale field trials. He leads the Rice Networks Group. The group's current projects include deployment, operation, and management of a large-scale urban wireless network in a Houston under-resourced community. This network, Technology For All (TFA) Wireless, is serving over 4,000 users in several square kilometers and employs custom-built programmable and observable access points. The network is the first to provide residential access in frequencies spanning from unused UHF TV bands to legacy WiFi bands (500 MHz to 5 GHz). His group developed the first multi-user beam-forming WLAN system that demonstrates a key performance feature provided by IEEE 802.11ac. His group also co-developed a clean-slate-design hardware platform for high-performance wireless networks, TAPs and WARP.

11. J*. Nicholas Laneman*

University of Notre Dame
Leader, Breakout Session 3B

J. Nicholas Laneman is Founding Director of the Wireless Institute in the College of Engineering, a Professor of Electrical Engineering, and a Fellow of the John J. Reilly Center for Science, Technology, and Values at the University of Notre Dame. He joined the faculty in August 2002 shortly after earning a Ph.D. in Electrical Engineering and Computer Science from the Massachusetts Institute of Technology (MIT). His research and teaching interests are in communication systems engineering, with emphasis on wireless systems. In addition to three conference best paper awards, Laneman has received a 2006 Presidential Early-Career Award for Scientists and Engineers (PECASE), a 2006 National Science Foundation (NSF) CAREER Award, a 2003 Oak Ridge Associated Universities (ORAU) Ralph E. Powe Junior Faculty Enhancement Award, and the 2001 MIT EECS Harold L. Hazen Graduate Teaching Award. He is an IEEE Fellow and has served as an Associate Editor for IEEE Transactions on Communications, as a Guest Editor for Special Issues of IEEE Transactions on Information Theory and IEEE Journal on Selected Areas in Communications, and as the first Online Editor for the IEEE Information Theory Society. Laneman is author or co-author on over 120 publications, including 40 journal articles and 3 invited book chapters, and has been recognized by Thomson Reuters as an ISI Highly Cited Researcher (2015, 2010). He is co-inventor on 6 U.S. patents and has several patents pending.

12. *William Lehr*

Massachusetts Institute of Technology
Member, Steering Committee; Moderator, Breakout Summary Panel 1; Member, Panel 3

Dr. William Lehr is a telecommunications/Internet industry economist and policy analyst with over 20 years as an academic researcher and industry consultant. He is a research scientist in the Computer Science and Artificial Intelligence Laboratory (CSAIL) at the Massachusetts Institute of Technology engaged in multidisciplinary research on the economic and policy challenges confronting the evolving Internet ecosystem. Dr. Lehr is engaged in a range of industry-academic research projects focusing on the economic and policy implications of key Internet trends such as the rise of mobile broadband and wireless innovation, the implications of Big Data for evidence-based decision-making, and the security and identity management challenges of transitioning to future Internet architectures. In addition to his academic research, Dr. Lehr provides business strategy and policy advice to public and private sector clients in the U.S. and abroad. Dr. Lehr holds a Ph.D. in Economics from Stanford, an M.B.A. from the Wharton Graduate School, and M.S.E., B.S. and B.A. (1979) degrees from the University of Pennsylvania.

13. *John Leibovitz*

Federal Communications Commission
Member, Panel 1

John Leibovitz has played an integral role in driving spectrum and wireless policy for the Federal Communications Commission. He helped formulate a comprehensive spectrum strategy for the United States, first as spectrum team lead for the National Broadband Plan and more recently as Special Advisor to the Chairman for Spectrum Policy. As Deputy Chief of the Wireless Bureau, he has supervised implementation of this strategy and other wireless policies.

14. *Bruce Mueller*

Motorola Solutions
Leader, Breakout Session 3B

Bruce Mueller leads Wireless Research for the CTO office in Motorola Solutions. While at Motorola, he has been instrumental in inventing, prototyping and realizing the key technologies behind 2G, 3G and 4G cellular systems, cable data and telephony solutions, and numerous other wireless platforms. An inventor with 22 issued patents, he is active in developing the next generation of mission critical connectivity for first responders and public networks. When wearing his futurist hat, Bruce also collaborates with technology startups, university research and external agencies to connect them with MSI to enable the future of critical communications.

Bruce Mueller joined Motorola Solutions 26 years ago after graduating with a BSEE from Rose Hulman Institute of Technology and a MSEE from the University of Michigan. Bruce is a proud 'maker' with a wide spectrum of interests in electronics, robotics and education. He is active with FIRST Robotics, the Boy Scouts of America, and numerous other educational activities in the Chicago area.

15. *James Neel*

Federated Wireless
Leader, Breakout Session 4B

Dr. James (Jody) Neel is the Principal Investigator for Federated Wireless's research programs. Federated Wireless is developing a dynamic Spectrum Access System (SAS) platform that will provide cost-effective spectrum to extend wireless carrier network access and scale where coverage is needed most. Dr. Neel earned his PhD. in Electrical Engineering from Virginia Tech and has fifteen years experience leading the research, design, and prototyping of cognitive radio systems spanning his time at Virginia Tech, Cognitive Radio Technologies, and Federated Wireless. He has received three paper awards on the design of cognitive radio algorithms and systems, is the Chair of the Cognitive Radio Work Group in the Wireless Innovation Forum, and help organize and contributes to the Wireless Innovation Forum's (WINNF) committee for standardizing radar / communications coexistence at 3550 MHz.

16. *Jerry Park*

Virginia Tech
Member, Steering Committee

Dr. Jerry Park received his Ph.D. degree in Electrical and Computer Engineering from Purdue University, West Lafayette, IN, USA in 2003. He is currently a Professor in the Department of Electrical and Computer Engineering at Virginia Tech, and the Site Director of an NSF Industry-University Cooperative Research Center (I-UCRC) called Broadband Wireless Access & Applications Center (BWAC). As the Site Director of BWAC at Virginia Tech, Park is leading several sponsored research projects on wireless networks and network security. He is widely recognized for his pioneering work on enforcement and security problems in cognitive radio networks and spectrum sharing. His research interests include cognitive radio networks, spectrum sharing technologies, wireless security and privacy, applied cryptography, and wireless communications and networking. Current or recent research sponsors include the NSF, National Institutes of Health (NIH), Defense Advanced Research Projects Agency (DARPA), Army Research Office (ARO), Office of Naval Research (ONR), and a number of industry sponsors. Recently, Park has been elected to serve as an Executive Committee Member of the National Spectrum Consortium (NSC) starting in Jan. 2016. The primary mission of the NSC is to improve collaboration between the industry, government, and academia to advance research and development of technologies to enhance the utilization of the electromagnetic spectrum. The Executive Committee is the NSC leadership and governance body authorized to oversee the activities of the Consortium. Park is a recipient of a 2014 Virginia Tech College of Engineering Faculty Fellow Award, a 2008 NSF Faculty Early Career Development (CAREER) Award, a 2008 Hoeber Excellence in Research Award, and a 1998 AT&T Leadership Award. He is currently serving on the editorial boards of the IEEE Transactions on Wireless Communications and the IEEE/KICS Journal of Communications and Networks.

17. *Peter Tenhula*

National Telecommunications and Information Administration
Leader, Breakout Session 4B

Peter Tenhula is the Deputy Associate Administrator for Spectrum Management in the Office of Spectrum Management (OSM) at the National Telecommunications and Information Administration (NTIA). As the Deputy Associate Administrator for Spectrum Management, Mr. Tenhula develops and implements initiatives in the highly complex technical area of radiocommunications and management of the Federal Government's use of the radio frequency spectrum. Prior to joining OSM in October 2014, he was a Senior Advisor in NTIA's Office of the Assistant Secretary where he advised the Assistant Secretary of Commerce for Communications and Information, OSM, and the Institute for Telecommunication Sciences on spectrum policy matters. Before joining NTIA in 2012, Mr. Tenhula worked at Shared Spectrum Company in Vienna, Virginia, for six years, serving as the company's Vice President and General Counsel. He was also was a member of the Board of Directors of the Wireless Innovation Forum (formerly the SDR Forum) and chaired the forum's Regulatory Committee. From 1990 to 2006, Mr. Tenhula served at the Federal Communications Commission, where he held several positions including Acting Deputy Chief of the Wireless Telecommunications Bureau, Director of the Spectrum Policy Task Force, Senior Legal Advisor to Chairman Michael Powell, Special Counsel to General Counsel William Kennard, and staff attorney in the Office of General Counsel and the Mass Media Bureau. Mr. Tenhula received his undergraduate degree in telecommunications from Indiana University, Bloomington, and earned a law degree from Washington University in St. Louis, Missouri. Peter Tenhula is the Deputy Associate Administrator for Spectrum Management in the Office of Spectrum Management (OSM) at the National Telecommunications and Information Administration (NTIA). As the Deputy Associate Administrator for Spectrum Management, Mr. Tenhula develops and implements initiatives in the highly complex technical area of radiocommunications and management of the Federal Government's use of the radio frequency spectrum. Prior to joining OSM in October 2014, he was a Senior Advisor in NTIA's Office of the Assistant Secretary where he advised the Assistant Secretary of Commerce for Communications and Information, OSM, and the Institute for Telecommunication Sciences on spectrum policy matters. Before joining NTIA in 2012, Mr. Tenhula worked at Shared Spectrum Company in Vienna, Virginia, for six years, serving as the company's Vice President and General Counsel. He was also was a member of the Board of Directors of the Wireless Innovation Forum (formerly the SDR Forum) and chaired the forum's Regulatory Committee. From 1990 to 2006, Mr. Tenhula served at the Federal Communications Commission, where he held several positions including Acting Deputy Chief of the Wireless Telecommunications Bureau, Director of the Spectrum Policy Task Force, Senior Legal Advisor to Chairman Michael Powell, Special Counsel to General Counsel William Kennard, and staff attorney in the Office of General Counsel and the Mass Media Bureau. Mr. Tenhula received his undergraduate degree in telecommunications from Indiana University, Bloomington, and earned a law degree from Washington University in St. Louis, Missouri.

18. *Dipankar Raychadhuri*

Rutgers University
Leader, Breakout Session 1B

Dipankar Raychaudhuri is Distinguished Professor, Electrical & Computer Engineering and Director, WINLAB (Wireless Information Network Lab) at Rutgers University. As WINLAB's Director, he is responsible for an internationally recognized industry-university research center specializing in wireless technology. He is also PI for several large U.S. National Science Foundation funded grants including the "ORBIT" wireless testbed and the "MobilityFirst" future Internet architecture project. Dr. Raychaudhuri has previously held corporate R&D positions including: Chief Scientist, Iospan Wireless (2000-01), AGM & Dept Head, NEC Laboratories (1993-99) and Head, Broadband Communications, Sarnoff Corp (1990-92). He obtained the B.Tech (Hons) from the Indian Institute of Technology, Kharagpur in 1976 and the M.S. and Ph.D degrees from SUNY, Stony Brook in 1978, 79. He is a Fellow of the IEEE.

19. *Jeffrey Reed*

Virginia Tech
Member, Steering Committee; Moderator, Panel 3

Dr. Jeffrey H. Reed is the Willis G. Worcester Professor in the Bradley Department of Electrical and Computer Engineering at Virginia Tech. He currently serves as Founding Director of Wireless@Virginia Tech, one of the largest and most comprehensive university wireless research groups in the US which he founding in 2006 and served as its first director. In 2010, he founded the Ted and Karyn Hume Center for National Security and Technology and served as its Interim Director. Dr. Reed is co-founder of Cognitive Radio Technologies (CRT), a company that is commercializing of the cognitive radio technologies produced for military applications, Federated Wireless, a company that is developing spectrum sharing technologies; and for PFP Cybersecurity, a company that specializes in security for embedded systems, including Android platforms. He has also served as a consultant for approximately thirty organizations, covering topics such as merger evaluation, network neutrality, and band planning. Dr. Reed served on the President's Council of Advisor in Science and Technology (PCAST) Advisory Group on how to transition federal spectrum for commercial economic benefits. In 2014, Dr. Reed was selected to be a member of CSMAC, the advisory group on spectrum issues for the US Department of Commerce. In 2014, Dr. Reed served as co-general chair for the IEEE Dynamic Spectrum Access Networks (DySPAN) conference. In the fall of 2015, Dr. Reed testified before Congress on the importance of research for transitioning federal spectrum for commercial use.

20. *Dennis Roberson*

Illinois Institute of Technology
Member, Panel 2

Dennis Roberson has been Vice Provost and Research Professor with the Illinois Institute of Technology (IIT) since June 2003. At IIT he established a new undergraduate business school, a wireless research center (WiNCom), IIT's corporate relations initiative, and is currently responsible the latter two efforts. He is also responsible for IIT's Research efforts, strategic plan assessment, its externally focused entrepreneurial efforts and the technology commercialization office. Professor Roberson is also President, CEO and Member of Roberson and Associates, LLC, a technology and management consulting firm serving a variety of government and commercial customers since 2008.

Prior to IIT, Professor Roberson was Executive Vice President and Chief Technical Officer of Motorola, Inc. Through his career he has held senior executive positions with NCR Corporation, AT&T, Digital Equipment Corp. (now part of Hewlett Packard) and IBM. Professor Roberson is a Director of Advanced Diamond Technologies, Cleversafe, Caerus Institute, OnKol and SonSet Solutions, and serves on the Technical Advisory Committees of several other firms. He chairs the U.S. Federal Communication Commission's Technological Advisory Council and serves on the U.S. Commerce Department's Commerce Spectrum Management Advisory Committee (CSMAC). He has served as an invited expert for the development of the PCAST Spectrum Policy Report, the Board of Directors of FIRST Robotics, the National Advisory Council for the Boy Scouts of America, the Board of Singapore's Agency for Science, Technology and Research, and as an International Advisory Panel member for the Prime Minister of Malaysia. He holds Bachelor of Science Degrees in Physics and Electrical Engineering from Washington State University and a Master of Science in Electrical Engineering from Stanford University.

21. *Anant Sahai*

University of California, Berkeley
Leader, Breakout Session 2B

Anant did his undergraduate work in EECS at UC Berkeley from 1990-1994. From 1994-2000 he was a graduate student at MIT studying Electrical Engineering and Computer Science (Course 6 in MIT-speak) and was based in the Laboratory for Information and Decision Systems. In 2001 he was on the theoretical/algorithmic side of a team at the startup Enuvis, Inc. developing new adaptive software radio techniques for GPS in very low SNR environments (such as those encountered indoors in urban areas). He joined the Berkeley faculty in 2002.

He currently serves also as faculty adviser to UC Berkeley's chapter of Eta Kappa Nu. He has previously served as the Treasurer for the IEEE Information Theory Society. ('07-'09 inclusive) His research interests span information theory, decentralized control, and wireless communication --- with a particular interest at the intersections of these fields. Within wireless communication, he is particularly interested in Spectrum Sharing and Cognitive Radio.

22. *Akbar Sayeed*

University of Wisconsin-Madison
Member, Steering Committee; Moderator, Breakout Session 1A; Member, Panel 3

Akbar M. Sayeed is a Professor of Electrical and Computer Engineering at the University of Wisconsin-Madison, and heads the Wireless Communications and Sensing Laboratory. He received the B.S. degree from the University of Wisconsin-Madison in 1991, and the M.S. and Ph.D. degrees from the University of Illinois at Urbana-Champaign in 1993 and 1996, all in Electrical and Computer Engineering. He was a postdoctoral fellow at Rice University from 1996 to 1997. He is a Fellow of the IEEE, and has served the IEEE in a number of capacities, including as a member of Technical Committees, Guest Editor for special issues, Associate Editor, and as a Technical Program Co-chair for workshops and conferences. His research interests include wireless communications, channel modeling, statistical signal processing, communication and information theory, time-frequency analysis, machine learning, and applications in wireless communication and sensor networks. A focus of current research is the development of basic theory and system architectures for emerging 5G wireless technologies, including millimeter-wave and high-dimensional multi-antenna systems. This effort also involves prototype development, channel measurements, and technology transfer.

23. *Martin Weiss*

University of Pittsburgh
Leader, Breakout Session 3A

Martin B.H. Weiss is Professor of Telecommunications and Associate Dean for Academic Affairs and Research at the School of Information Sciences at the University of Pittsburgh, where he also holds a faculty appointment in telecommunications. He earned his PhD. in Engineering and Public Policy from Carnegie Mellon University where he studied the standards development process under Professor Marvin A. Sirbu. He also earned an MSE in Computer, Control, and Information Engineering from the University of Michigan and a BSE in Electrical Engineering from Northeastern University. His overall research theme is the analysis of situations where competing firms must cooperate technically; this has expressed itself in studying the standardization process, internet interconnection, and, most recently, radio spectrum sharing

His industrial experience includes technical and professional work at several R&D and consulting firms in the United States. From 1978 to 1981, he was a Member of the Technical Staff at Bell Laboratories; from 1983 to 1985, he was a Member of the Technical Staff at the MITRE Corp; and from 1985 to 1987 he was a Senior Consultant with Deloitte, Haskins, and Sells. He continues to consult with national and international firms, serving as an advisor, analyst and expert witness.

He is the co-author of two books and has written numerous book chapters, major conference papers and refereed journal papers in the area of standards setting, internet interconnection, and dynamic spectrum access. He has been invited to serve on numerous expert panels for industry, government and academia.

24. *Charlie Zhang*

Samsung
Member, Panel 2

Charlie Zhang is a VP and head of Standards and Research Lab with Samsung Research America at Dallas, where he leads research and standards for 5G cellular systems and next generation multimedia networks. From Aug 2009 to Aug 2013, he served as the Vice Chairman of the 3GPP RAN1 working group and led development of LTE and LTE-Advanced technologies such as 3D channel modeling, UL-MIMO and CoMP, Carrier Aggregation for TD-LTE, etc. Before joining Samsung, he was with Motorola from 2006 to 2007 working on 3GPP HSPA standards, and with Nokia Research Center from 2001 to 2006 working on IEEE 802.16e (WiMAX) standard and EDGE/CDMA receiver algorithms. He received his Ph.D. degree from the University of Wisconsin-Madison.

C. *Accessing Slides from Selected Presentations*

Presentation materials are available online in the agenda section of the workshop's website. Please see:

https://earsworkshop.wireless.vt.edu/agenda.html