Promoting Economic Efficiency in Spectrum Use: the economic and policy research agenda

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

April 23-24, 2013

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1. Executive Summary

Commercial demand for additional spectrum resources cannot be met by new allocations of spectrum. Technical innovations and the elimination of regulatory and market barriers can help expand the usable capacity of spectrum. However, as long as there are contending demands for usage rights,[1] spectrum will remain a scarce economic resource. Efficient spectrum sharing will depend on using the right approach based on the given circumstances.[2] It will require the commercialization of new wireless technologies as well as new and robust policy frameworks and business models.

The goal of this workshop was to help set the agenda for the necessary economic and policy research needed to advance the national interest in the best ways to share spectrum.

Ensuring that our radio frequency resources are used to further our national interests requires a mix of sharing solutions. These include clearing and reassigning spectrum to higher value uses (most typically, via auction), spatial sharing through increased use of smaller cell architectures, and introducing new models for spectrum sharing among existing and future users and applications. This last topic is of special relevance for Federal and non-Federal sharing. Identifying the best options and the best solutions poses a significant multidisciplinary challenge among engineers, economists, and policymakers, and involves collaborative decision-making. Fundamental research is still needed in areas such as: assessing the consequences of new interference management models; understanding the challenges and opportunities of commercializing novel dynamic spectrum access technologies; and the policy frameworks and market mechanisms needed for the diverse set of user communities.

Some key lessons:

- (L1) Spectrum scarcity is an economic reality, necessitating efficient use to best promote our national interest. Spectrum is a scarce economic resource that needs to be used efficiently by all users to best promote our national interest in sustainable growth, innovation, and global competitiveness;
- (L2) Better identification of economically viable spectrum sharing opportunities is needed to ensure efficient spectrum usage;

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[1] All wireless uses/users are expected to expand their usage – this includes communications (mobile broadband) and remote sensing (radio telemetry) uses by commercial and government users; and demand for spectrum rights includes demand for particular rights frameworks that are consistent with the business model of the party seeking spectrum usage rights. For example, there is obviously not enough spectrum to meet the demand from all parties for exclusive spectrum rights.

[2] Spectrum may be shared in many ways. Cellular operators with exclusive spectrum licenses manage the sharing on behalf of their subscribers; unlicensed WiFi users share spectrum in an uncoordinated, non-cooperative way; and mixed models such as low-power underlays (e.g., UWB) or geo-time dynamic overlays (TV white space) share spectrum via tiered usage rights providing for differing levels of prioritized access. Research is needed to see what mixes of sharing models and supporting market/policy infrastructures and frameworks best support the needs of diverse users/uses (communication/sensing, real-time/asynchronous, narrow/broadband), business models (incumbent/entrants, operator/equipment, local/wide area), and spectrum management regimes (exclusive licensed/unlicensed, cooperative/non-cooperative).

- (L3) Aligning stakeholder incentives across industry, government, and spectrum user communities is essential; and,
- (L4) Multidisciplinary research collaboration is needed to ensure that technical, economic, and policy issues are addressed holistically in order to properly evaluate options, align incentives, and effect appropriate change.

Key components of the economic and policy research agenda include:

- (R1) Data, models and empirical methods to better identify spectrum needs, usage, and interference implications
- (R2) Spectrum valuation and economic analysis tools and methods to better assess total and per stakeholder costs and benefits
- (R3) Analysis of incentives and evaluation of institutional, regulatory and market structure reform options to better align incentives to promote greater spectrum efficiency
- (R4) Commercialization challenges and opportunities for novel wireless technologies
- (R5) Special topics including addressing the spectrum needs of public safety, co-existence with government radar, and international spectrum harmonization

2. Background and Workshop Description

The Wireless Spectrum Research and Development (WSRD) Workshop IV: *Promoting Economic Efficiency in Spectrum Use – the Economic and Policy Agenda* was the fourth in a series of workshops focused on promoting spectrum efficiency, sharing, and the commercialization of wireless innovations.

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

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

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

New wireless and spectrum sharing technologies call forth a need for new policy frameworks and business models, and confront users and markets with new wireless economics that need to be better understood in order to realize the full potential of wireless innovation. Gaining user and network operator acceptance and trust in new spectrum sharing models and designing such systems to be secure and resilient is *not* just a technical challenge; it simultaneously calls for changes in spectrum management procedures and practices by network operators, users, and regulatory authorities and the evolution of new types of economic relationships among spectrum rights holders. In addition to engineering, the R&D agenda includes theoretical and empirical work on wireless technology markets, regulatory reform, and radio system design – where one takes seriously the perspective that the "system" includes the larger ecosystem of users, network operators, and regulatory authorities. Serious attention must be paid to the incentives of key stakeholders in industry, government, and among spectrum users to adopt and share the costs and benefits of new spectrum sharing solutions.

Examples of open spectrum-related R&D questions with a significant non-engineering component include:

1. What are the most important new wireless technologies that are not being commercialized sufficiently quickly, and what economic (incentive, business model, or market factors) and policy challenges explain this?
2. What is the value of spectrum? How does it vary by band, by use, over time, or by regulatory regime? What metrics are needed to facilitate valuing spectrum and usage rights?
3. What is the optimal institutional framework for managing spectrum interference? How might existing regulatory institutions best take advantage of the smart radio technologies like cognitive radio, spectrum access databases, and sensing? How should property rights for primary and secondary users be modified to align incentives for efficient spectrum use?
4. How will use of Dynamic Spectrum Access (DSA) enabled radios affect the operations of public safety professionals? What will be the operational and financial impact of transitioning to new public safety radio systems?
5. How much activity might we expect to see in active spectrum sharing markets? Over what time-scale? How might it vary by band? By spectrum-management framework?
6. What will the economic impact be from increased sharing of spectrum resources? Among government users? Among commercial users? Among government and commercial users?
7. What is the optimal economic design for small-cell mobile broadband last-mile architectures for municipalities? What are the implications for sharing spectrum and Radio Access Network (RAN) infrastructure?
8. What are viable business models for using secondary access or pre-emptible spectrum resources?
9. How will DSA impact competition in wireless infrastructure and services?

The goal of WSRD IV was to identify economic and policy research that will facilitate the commercialization of technologies, business models, wireless systems, and institutional/policy frameworks that will align incentives and ease roadblocks to promoting progress toward maximizing the economic benefit from our collective use of wireless systems and the radio frequency spectrum on which such systems depend.

WSRD IV brought together top industry, academic, and government multidisciplinary expertise on the economics and policy issues associated with the commercialization of spectrum sharing technologies, business practices, and policy frameworks. This helps inform the recommendations of the WSRD Senior Steering Group and contributes to building research capacity and focusing efforts on the R&D needed to advance spectrum sharing technologies. During the workshop, participants reviewed on-going work, research proposals, and gaps for R&D projects that would address the challenges identified by Congress, the FCC, the NTIA, and the WSRD SSG to make spectrum sharing technologies more available to all sectors of the wireless community.

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

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

This workshop was held in Cambridge, Massachusetts on April 23-24 and included two full days of presentations and discussions. It was hosted by MIT at the CSAIL Lab (32 Vassar Street) with approximately 50 participants in attendance and a large community of remote viewers via webcast.

The workshop chairs and planning committee were as follows:

Planning committee co-chairs:
William Lehr (MIT)
John Chapin (DARPA)

Planning committee members:
Wendy Wigen (NITRD)
Paul Kolodzy (Kolodzy Consulting)
Yochai Benkler (Harvard)
Greg Rosston (Stanford)
Joe Heaps (DOJ)
Rangam Subramanian (Idaho National Laboratory)
Douglas Sicker (U. of Colorado, Boulder)

3. Key Lessons

During the workshop, a number of core themes/lessons were articulated multiple times. These included:

- (L1) Spectrum scarcity is an economic reality, necessitating efficient use to best promote our national interest. Spectrum is a scarce economic resource that needs to be used efficiently by all users to best promote our national interest in sustainable growth, innovation, and global competitiveness;
- (L2) Better identification of economically viable spectrum sharing opportunities is needed to ensure efficient spectrum usage;

- (L3) Aligning stakeholder incentives across industry, government, and spectrum user communities is essential; and,
- (L4) Multidisciplinary research collaboration is needed to ensure that technical, economic, and policy issues are addressed holistically in order to properly evaluate options, align incentives, and effect appropriate change.

3.1. (L1) Spectrum scarcity necessitates efficient use

Like water, our global endowment of radio frequency spectrum is fixed, and hence in economic terms, a scarce resource. Demand by all users – commercial and government, incumbents and entrants, for today's and tomorrow's uses – outstrips availability. This fundamental scarcity means that we need to use spectrum efficiently if we are to realize the greatest economic value from this critical resource.

Economic efficiency means that when uses are rival, the needs of higher-value uses are met first (allocative efficiency), and that the total value from using spectrum is maximized with the lowest possible resource cost (technical efficiency), and that this remains true over time (dynamic efficiency). The value of using spectrum is not measured solely by the profits that may be realized by commercial users, but also from such public uses as for basic research (for example, space exploration and radio astronomy) and national defense. And, ensuring both technical and dynamic efficiency requires us to continue to innovate and invest as markets evolve over time, a challenge that most economists believe is best ensured by promoting competition.

What constitutes "efficient use" is thus something that we must debate. Certainly, ensuring technical spectral efficiency (maximum bits per Hz per area per time) is part of what is needed, but adopting new technologies requires investments and the costs and benefits of changing how we use spectrum are not evenly distributed. We may all agree that wireless has been a key driver and facilitator of economic growth and that continued growth in services from mobile broadband to sensor-enabled "Internet of Things" devices, from smart grids to green energy, will require increased access to spectrum. Yet we are unlikely to agree, at least easily, on how best to meet our collective needs.

Luckily, there are a host of wireless innovations emerging from research labs and in the early stages of commercialization that can aid in our efforts to promote economic efficiency. In addition to holding the promise for significant improvements in spectral efficiency, these innovations also enable spectrum to be shared much more intensively in space, time, frequency, and indeed, any dimension over which radio waveforms may differ. Adopting, promoting, and realizing the benefits of such innovation in wireless network design and spectrum usage enables and requires compensatory adjustments in wireless markets, business models, and institutional/organizational structures. The need for change is inherent to the process of competition in commercial markets, but changes are needed also by government users. As when you change the mix of fuel in an engine, changing the spectrum fuel that powers all wireless systems will require adjustments in the mix and management of other capital and human resources. Moving to smaller cells, co-existing with disparate uses in the same bands, and smoothly transitioning to support new uses over time will require collective adjustments in spectrum management policies and wireless industry economics. Aligning incentives will require addressing the interests of both incumbents and entrants and how best to share the costs and benefits of adopting new spectrum use models.

3.2. (L2) Better identification of sharing opportunities needed

As noted above, a key to efficient spectrum use means sharing the fixed allotment of radio frequency spectrum to maximize the total value of uses at the lowest possible cost. A prerequisite to accomplishing that goal is to be able to identify sharing opportunities. This includes understanding better how we currently use spectrum so we can better understand existing demand so as to enable us to efficiently reconcile conflicting claims for usage rights when those arise. Part of this may be gleaned from better measurements and data on radio transmissions by location, time, and band; but simply measuring the energy in a band does not tell us whether the spectrum is in use. For example, radio astronomy is a passive application that listens very intently with sensitive radio telescopes, but does not transmit any energy for other users to detect. Mobile service operators need to be able to access spectrum resources sufficient to meet peak service demand which is not perfectly predictable in time or space, leading to potentially incorrect inferences about spectrum availability for other uses/users. Some uses/users co-exist better than others (e.g., Frequency Division Duplex (FDD) v. Time Division Duplex (TDD), high v. low power, mobile v. fixed, broadcast v. point-to-point, etc.).

Identifying spectrum sharing opportunities, or as some refer to them "white spaces," requires spectrum modeling – of supply and demand, both in technical (spectral) and economic (cost/benefit) terms. In today's world of static spectrum assignments with a primary focus on technical opportunities to share spectrum, too often the analysis focuses on worst-case scenario modeling. This framework looks at the incumbent receiver that is most susceptible to interference (e.g., the one at the edge of the signal-to-noise boundary) to identify the threshold for allowable third-party (non-cooperative shared) use. This overly conservative approach leaves too many useful sharing opportunities unexploited. The sharing may be cooperative and there may be economically efficient approaches to tolerate higher shared utilization of the spectrum (e.g., improvements in receiver tolerance to interference, changes in transmission power distributions, or better coordination of radio operations).

Part and parcel with the need for better technical *and* economic models of spectrum usage is the need for better, more granular, and comprehensive data on spectrum usage. This includes not just knowing what transmitters are currently doing (and not doing), but also who else wants to do what and how they might do it better. We need models and data both for experimental and real-world environments, and the models/data for real-world users and uses cannot wait until new uses and technologies are commercialized. We know from the economics of technology adoption and standardization that the best solutions do not always win and that markets may become locked into or stuck with an inferior outcome. Commercial and government users, and spectrum policymakers and wireless innovators need better ways to understand and evaluate alternative spectrum usage models earlier in the development cycle. This will enable a richer and earlier conceptualization of spectrum sharing opportunities, with a better understanding of both the costs and benefits of alternative solutions.

For markets to work and for users to make efficient bargains[3] over how best to allocate the benefits and costs of shared use, the relevant information has to be collected and shared by the

[3] In a famous paper, Nobel-laureate economist Ronald Coase explained how a clear assignment of property rights can enable market participants to efficiently allocate social costs if bargaining is costless (see Coase, R. (1960) "The Problem of Social Cost," *Journal of Law and Economics*, 3 (October 1960), 1-44.) He offered an even earlier application of these insights specifically to the challenge confronting the

market participants. Thus, in addition to the models and data (empirical measurements), we need to consider the infrastructure to collect, share, and manage the data. Since our analysis of spectrum sharing opportunities will impact how this important scarce resource is allocated, we can expect the analysis to engage strategic behavior which will raise policy concerns in its own right (e.g., confidentiality, privacy, and supporting the R&D costs of better collective decision-making).

3.3. (L3) Incentives critical for mobilizing progress

As already noted, the allocation of scarce resources in a market economy does not automatically guarantee an efficient outcome. To understand behavior and outcomes, we need to understand the incentives of market participants. For it to be economically rational for spectrum users to adopt socially optimal approaches to using scarce spectrum, there have to be appropriate incentives.

For commercial users, the profit motive provides a potent driver toward efficient decision-making. However, the legacy of sunk and shared investments, imperfect markets and competition, and the need to reconcile private and public welfare means that we cannot simply presume that commercial incentives will align so as to maximize total surplus.

For government users, the challenges are greater because the clarity of a for-profit motive and market forces are lacking. We look to the government to do those things that commercial markets are unsuited for, and public administration introduces its own organizational structures and incentive hierarchies. While radio spectrum does not change because the user is commercial or non-commercial, the regulatory management, the organizational structure, and the economics do. And, the challenges get greater when we look toward a future where commercial and non-commercial users will increasingly need to co-exist in the same spectrum. The need for such sharing and co-existence is due not only to the need to exploit spectrum sharing opportunities more fully, but also because of the need to better integrate government and commercial markets and structures. For example, military and public safety users need to co-exist with commercial uses to train and maintain preparedness for when their special services are required, and to be able to take advantage of both wireless and other infrastructures when needed. It is too costly and sub-optimal to maintain completely parallel and independent investments in infrastructure solely for defense and public safety.

Understanding incentives of spectrum users in a rich, contextual way that best makes use of available technology *and* innovations in business, administrative, and market institutions and practices is needed to appropriately evaluate and exploit spectrum sharing opportunities today and in the future. In addition to the technical research, we need to explore new administrative models for incentivizing government users to adopt more efficient spectrum usage. Reforms may include restructuring of spectrum access rights and enforcement regimes so as to influence more spectrum efficient behavior. For example, the work on receiver protection rights, equipment certification policies, enforcement regimes, and reforms to secondary markets may each play a part.

3.4. (L4) Fundamentally a multidisciplinary research challenge

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FCC in managing spectrum interference(see Coase, R. (1959) "The Federal Communications Commission." *Journal of Law and Economics*, 2 (October 1959), 1-40).

From the above it should be clear already that progress toward realizing more efficient spectrum usage models requires multidisciplinary research. As was clear at multiple times during the workshop, we need new technical solutions. Some of these are already being commercialized (e.g., the transition from 3G to 4G LTE), while others are still in the early stages of development (e.g., low cost 1 GHz wideband flexible radios).

As an example, consider the design of enforcement of interference protection rights. For access rights to be valuable they have to have some expectation of interference protection and that implies some expectation of enforcement. The enforcement regime is embodied both in the technology and in the business practices (contracting) and policy regimes (regulation) that structure the marketplace. The optimal mix of database, sensing, and other radio or network technologies that are part of a sharing scenario will help determine and influence the sorts of contracts and external monitoring and enforcement that is appropriate. This requires research on industry/market economics, government regulation

The needed multidisciplinary research will engage lots of niche ideas -- new radio design (e.g,. inexpensive wideband radios), new enforcement models (e.g., spectrum sensing regimes, spectrum access system), new contracting/licensing mechanisms (e.g., ASA/LSA[4] v. real-time markets), new usage cases (public safety use of cognitive radios, intelligent transportation systems), etc. -- in all cases, there is a plethora of technical and economic/policy ideas (fees, liability rules, auction redesign, property rights) that can NOT be looked at in isolation but require integration (auction design/theory that is technology-aware and radio technology design that is policy/economics aware).

For spectrum sharing and wireless innovations to impact society and the economy they have to be commercialized. Ensuring that the economic/policy research is relevant will require that it be well-informed about the technology. And, good economic/policy research can help insure that the technical research is appropriately aware of economic and policy considerations. This will require cross-disciplinary, academic/industry, and commercial/government collaborations. Building the capacity and capabilities to undertake such research requires time and resources. This means supporting research collaborations which include specialists with a mix of technical

[4] Authorized Shared Access (ASA) and Licensed Shared Access (LSA) are slightly different terms for referring to a new model for enabling licensed sharing in which a new class of user is granted protected access rights to share with an incumbent user. For further discussion of the ASA model, see Parcu, Pier Luigi, Nicita, Antonio, Corda, Giorgio, Rossi, Maria Alessandra and Bravo, Laura Ferrari, Authorised Shared Access (ASA): An Innovative Model of Pro-Competitive Spectrum Management (May 1, 2011). Available at SSRN: http://ssrn.com/abstract=2174518 or http://dx.doi.org/10.2139/ssrn.2174518; and for discussion of the LSA model, see http://www.gsma.com/spectrum/wp-content/uploads/2013/04/GSMA-Policy-Position-on-LSA-ASA.pdf. Both LSA/ASA, which posit a two-tiered access regime, are closely related to a three-tiered regime proposed by the President's Council of Advisors on Science and Technology (PCAST) in its July 2012 report on government spectrum sharing (see, http://www.whitehouse.gov/sites/default/files/microsites/ostp/pcast_spectrum_report_final_july_20_2012.pdf) and which is under consideration by the FCC in its proposal for enabling commercial access to the 3.5GHz band (see, http://hraunfoss.fcc.gov/edocs_public/attachmatch/FCC-12-148A1.pdf).

and economic/policy expertise and fostering cross-disciplinary opportunities to share research results (e.g., workshops, publications, shared test bed research efforts).

4. The Economic and Policy Research Agenda

During the workshop, participants sought to identify research opportunities, challenges, and priorities in multiple ways: there were focused sessions on specific usage contexts (e.g., Public Safety), on differing stakeholder perspectives (e.g., industry and investor views on challenges to spectrum sharing), and on core economic and policy considerations (e.g., spectrum valuation and regulatory institutional reform options); there were a mix of overview talks summarizing current progress on sharing initiatives and offering assessments of the current-state-of-the-art in economic/policy research, lightning-talk proposals for specific research initiatives, and breakout sessions to allow for real-time collaboration to further flesh out and synthesize emerging themes.

Key research focus areas include:

- (R1) Data, models and empirical methods to better identify spectrum needs, usage, and interference implications
- (R2) Spectrum valuation and economic analysis tools and methods to better assess total and per stakeholder costs and benefits
- (R3) Analysis of incentives, institutional, and market structure reform options to better align incentives to promote greater spectrum efficiency
- (R4) Commercialization challenges and opportunities for novel wireless technologies
- (R5) Special topics including addressing the spectrum needs of public safety, co-existence with government radar, and international spectrum harmonization

These are discussed further in the following sub-sections.

4.1. (R1) Data, models and empirical methods

Identification of sharing opportunities requires new data, models, and empirical methods to support evidence-based evaluation of sharing options. Research requirements and priorities here include:

4.1.1. More granular technical & socio-economic data on usage

More granular technical data on spectrum usage, capable of being matched to granular socio-economic data on costs and usage impacts (value and other) is needed.

More data is needed on spectrum utilization and interference impacts. Ideally, this includes more granular data on transmission activity (by frequency, location, time, and with details about the waveforms). A sufficient justification for requiring more technical data on radio spectrum usage (actual and planned) is to support dynamic spectrum access and sharing, but this data must be matched with appropriate socio-economic data to evaluate sharing options. The socio-economic data needs to include system capital and operating cost data, including data to support estimation of risk-adjusted, economic opportunity costs.[5] It also needs to include data to estimate the dollar

[5] The economic opportunity cost of an action is the cost of the next-best alternative that must be foregone in order to pursue the chosen action. In spectrum valuation, it is the cost of using the spectrum in the next-

and social impacts of alternative demand/usage scenarios (e.g., application usage). Research is needed to cross-validate data from different measurement platforms and to integrate new and legacy data sources. For example, the FCC is in the process of extending its measurement efforts to consider mobile broadband measurements[6] and Google's M-Lab[7] is expanding to offer access to a global measurement platform. It would be useful to consider how such network level measurement data might be combined with application performance and/or spectrum utilization data. And, researchers in academia, the OECD[8] and national statistical agencies are evaluating how to better measure the social and economic impacts of the Internet and wireless services on the economy using national accounts, business, and consumer survey data. Innovative research methods are needed to link and exploit these disparate but more granular data.

4.1.2. Continuum of data sources from simulations to real-world testing

Continuum of data sources should be pursued in parallel, from simulations to increasingly realistic test bed data.

This is a tall order, but we have so little data available today to characterize radio usage technically, and especially, to support economic evaluation of usage scenarios, that progress on any front would be helpful. A continuum of sources will prove useful, ranging from simulation results to testbed data. The latter comprises a continuum from lab bench testing to increasingly realistic real-world testing environments.[9] To assess economic and social impacts, the real-world testing needs to consider usage environments and user responses. Although it has been common to proceed sequentially from theory to simulation to increasingly real-world testing environments in the evaluation of spectrum usage models, the strict adherence to this sequential approach is no longer appropriate to the faster-pace of wireless innovation and global markets. All of the approaches ought to proceed more in parallel and with conscious attention to interactive feedback across approaches.[10] Of special note, efforts must be made to increase our empirical understanding of real-world/end-user socio-economic impacts to incorporate such perspectives sooner in the design phase for wireless innovations.

4.1.3. More realistic models to go beyond worst-case analysis

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best alternative use. In evaluating spectrum options, ideally, the total costs (and benefits) should be considered (i.e., including infrastructure, customer switching, and other costs associated with adopting a new option), not just the value of the radio frequency resources used.

[6] See http://www.fcc.gov/document/mobile-broadband-measurement.

[7] See http://www.measurementlab.net/.

[8] See http://www.oecd-ilibrary.org/docserver/download/5k43gjg6r8jf.pdf?expires=1375631206&id=id&accname=guest&checksum=A95B27722D9D44AACC01FD57D1846EB1.

[9] Earlier WSRD collected and created a searchable inventory of wireless testbeds (see, http://www.nitrd.gov/apps/wsrdmap/index.php?title=WSRD_Testbeds).

[10] Obviously, the sequential model of simulating before prototyping before full commercial release will still prevail; however, it is no longer necessary nor desirable to adhere to this model too rigidly. For example, market research with live consumers is feasible even at the simulation stage; and commercial releases may be phased with significant redesign occurring even after an active service market is underway.

More realistic models of spectrum usage to replace worst-case scenarios

The status quo approach to analyzing interference impacts has relied on worst-case modeling. This is due in part to data limitations, and the inherent simplicity of adopting such an approach. Unfortunately, worst-case modeling is too conservative and tends to exclude too many valuable sharing opportunities. Better technical propagation models that better capture realistic system performance are needed to ensure that valuable sharing opportunities are not missed. Additionally, more case studies/business modeling of real-world deployments are needed to inform a better understanding of both aggregate and stake-holder specific impacts. We do not yet have agreement on how to define, measure, or adjudicate economic harm from interference and the costs of mitigation.

4.1.4. Data collection and management economic and policy impacts

Attention to the economic and policy impacts of data collection and management

The more granular and detailed the data, the more costly its collection and management, and the greater the potential for impinging policy concerns such as national security and privacy. For example, national security concerns will limit access to detailed characterizations of military radar waveforms and usage; while granular data on consumer usage (by application, by location, by time) that includes personally identifiable information will raise privacy concerns. In an age of Big Data enabled by ubiquitously deployed wireless devices and sensors, it becomes increasingly possible to measure almost everything. In this environment, choosing what to measure, what data to retain, and how to manage access to the data becomes a strategic decision. Economic and policy research on the design of our data management infrastructure and its implications for regulatory policy and markets is needed to help guide decision-making in this area.

4.1.5. Spectrum Access System (SAS) design and implementation research

Spectrum Access System (SAS) design and implementation

Of special note, is the need to design and implement a Spectrum Access System, or more appropriately, ecosystem, that will support the identification of sharing opportunities and their management. Efforts are underway to implement distributed database and sensor-enabled frameworks to manage spectrum access more dynamically (in time, space, and frequency-space) in multiple bands.[11] The design of such systems and the market/regulatory structures to support their usage is a technical and economic/policy research challenge. We need research that addresses the potential impacts for regulatory policy, competition, and innovation of alternative architectures for the SAS.

4.2. (R2) Spectrum valuation and economic analysis

[11] The FCC has approved multiple operators of components of the Spectrum Access System to support access to TV whitespaces, and the design of analogous systems are in discussion for use in managing spectrum in the 3.5GHz band.

In addition to needing better data on spectrum needs, uses, and co-existence (interference) implications, we need better economic analysis tools to value spectrum and assess the private (stakeholder) and social (total) costs and benefits of alternative spectrum usage models.

Better tools are needed for evaluating policy alternatives and for participants to frame business strategies. These can contribute to better decision-making in a range of areas, including:

- Spectrum valuation
- Radio system business and cost modeling
- System adjustment costs (relocation,
- Auction rules
- Spectrum fees

These are discussed further below in the following sub-sections.

4.2.1. Spectrum valuation

What is spectrum worth? The answer depends on the context and who is asking. Furthermore, we do not value the spectrum directly, but the rights for its use. Different rights regimes imply different spectrum valuations. For example, the frequency of the spectrum may impact its suitability for different uses/applications and hence will impact its value. If the spectrum rights are for exclusive or shared spectrum, for paired or unpaired frequencies, and for which geographic areas will all impact valuation. Whether the spectrum is cleared or encumbered will also impact valuation. Finally, it is reasonable to expect that private and social values may differ, and the time horizon for valuation will also impact valuation.

Traditional techniques for valuing spectrum rights include analysis of comparable transactions (auctions, licensing deals, M&A activity), econometric analysis, and cost-modeling. All of these approaches are of interest and relevant to estimating the dollar and social impacts of spectrum usage under different scenarios.

4.2.2. Radio system business and cost modeling

Realizing the economic value of spectrum requires radio networks. It is possible to substitute spectrum resources for network infrastructure. For example, building more (smaller) cells or more intelligent (capable) radios may provide increased communications capacity with less spectrum resources, but may involve incurring additional costs. Or, using spectrum more intensively may result in increased incidence of harmful interference events, resulting in increased interference management costs.

To identify the optimal mix of investment in infrastructure/radio technology and spectrum, we need better economic modeling tools for alternative radio system designs. How much should we invest in radio flexibility to ensure that long-lived assets remain optimal over time? What are the costs of investing in more infrastructure/better radios that tolerate or limit interference better, and who should bear those costs? What are the cost/benefit trade-offs of alternative radio architectures? Empirical and theoretical engineering cost modeling can help inform these questions, but such models need to consider market/industry structure and policy frameworks as well.

4.2.3. System adjustment costs (relocation)

Adopting new technical, business, or policy approaches for spectrum usage will almost always incur adjustment costs. A significant source of such costs are associated with relocating legacy users from spectrum that is to be reallocated to a new use or users. These adjustment costs contribute to the total cost-benefit calculus and cannot be ignored, although they may be borne asymmetrically. Figuring out how to minimize and allocate adjustment costs will require significant analyses. The best Coasian solution for managing adjustment costs may not be readily discernible.

4.2.4. Auction rules

Spectrum auctions have played an important role in facilitating the transition of spectrum to new uses. Auctions have a rich and valuable history as an economic mechanism/institutional framework for assigning resources and managing buy/sell transactions. In addition to their use in assigning spectrum licenses, auctions have been employed in real-time markets (e.g., stock markets) and in procurement contracts (e.g., reverse auctions). The FCC is currently engaged in designing a novel two-part auction to reallocate television band spectrum at 600MHz for new commercial uses, including broadband as part of the FCC's Incentive Auction.[12]

The design of spectrum auctions and the potential use of auctions in other aspects of spectrum management (e.g., to manage secondary markets) has focused on the rules for participation and bidding strategies, but has only scratched the surface of considering how the goods that are auctioned are defined, including licensing terms[13] and band/frequency plans.

4.2.5. Spectrum fees

There are many other economic mechanisms that might be considered for assigning spectrum usage rights and capturing the benefits/allocating the costs of spectrum usage. One example includes charging spectrum fees (or royalty auctions) where payments depend on the level of usage or value capture based on ex post measurements. Spectrum fee mechanisms may offer advantages over traditional auction frameworks. Understanding the contexts where this might be true and how best to design a spectrum fee mechanism would be helpful.

4.3. (R3) Analysis of incentives, institutional, and market structure reform options

The success of adopting new technologies and spectrum usage models will depend on the extent to which we are successful in aligning stakeholder incentives. There are a range of issues and topics where a better understanding of key stakeholders incentives and the private/social cost-benefit implications of alternative approaches is needed.
Some of the key stakeholders whose incentives and perspectives need to be better understood include:

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[12] See Notice of Proposed Rulemaking, In the Matter of Expanding the Economic and Innovation Opportunities of Spectrum Through Incentive Auctions, Before the Federal Communications Commission, Docket No. 12-268, released October 2, 2012, available at: http://www.fcc.gov/document/broadcast-television-spectrum-incentive-auction-nprm.

[13] For example, how might auction outcomes be impacted by changing license durations, varying whether the licenses are exclusive or shared, or by institutional guarantees of protection?

4.3.1. Cellular Operators deploying 4G LTE

It is widely expected that cellular operators will continue to play a leading role in the provisioning of mobile broadband services, accounting for a significant share of the economic value and activity (employment, investment, and usage) associated with wireless services. Understanding how their incentives to invest in or adopt novel technologies or embrace alternative sharing regimes will help in the design of new management frameworks.

4.3.2. New Entrants and Innovation

While incumbent operators will continue to be an important source of innovation, the interests of entrants and the potential for promising innovations that challenge incumbent models needs to be considered. Ensuring adequate access to spectrum resources for new users/uses is important for preserving competition and promoting innovation.

4.3.3. Equipment Markets and Adoption

The success of novel radio technologies will depend, in part, on how equipment costs evolve over time. Equipment markets are global, and achieving global scale economies can influence which technologies are most cost-effective over time, and the market adoption process. Radio system design and regulatory policy can impact the timing and extent to which global scale economies may be realized.

4.3.4. Government Users and Economic Incentives

Government spectrum users are not for-profit enterprises and inducing them to respond to market forces is non-trivial. One potentially promising way to introduce economic incentives for more efficient government spectrum usage is to introduce the concept of "spectrum bucks" – or budgetary dollar-equivalents that provide an indirect mechanism for mapping from government budgets to spectrum efficiency decision-making. Introducing an artificial "currency" in this context provides flexibility to address the challenges of introducing efficient economic behavior incentives in a non-profit decision making environment.

4.3.5. Secondary Markets and Efficiency

To ensure spectrum is continually assigned to its most efficient uses over time, it is important that it be feasible to dynamically re-assign access rights. Active and efficient secondary markets will provide useful data on spectrum opportunity costs and will highlight bands/markets where additional reform is needed. Efficient secondary markets provide a complementary mechanism for auctions, enabling pre- and post-auction transactions that may allow rights seekers to better optimize their spectrum rights portfolios over time.

4.3.6. Investors and Regulatory Uncertainty

Legacy regulatory processes for spectrum management introduce uncertainty and lengthy delays that may pose a deterrent for investors and users contemplating adoption of a novel technology.

The economics and policy literature on administrative processes and efficient regulatory institutional design suggest a wide range of process reforms that may prove useful in reducing regulatory uncertainty and expediting efficient decision-making. These need to be investigated for their applicability to spectrum management challenges. Examples of potential administrative reforms that might be worth analyzing further include:

4.3.6.1. *Process time-clocks*

Time-clocks for decision-making that would commit the FCC or other regulatory review to making decisions faster and according to a finite schedule may both expedite and render more predictable policy-based decision-making;

4.3.6.2. *Agenda Controls*

Agenda controls that provide a clear mapping of applicants to different policy-tracks are often adopted in conjunction with time-clock commitments to allow sorting of action items into those that qualify for expedited processing and those that may require exception processing

4.3.6.3. *Evidence rules*

Evidence rules that clearly identify what sorts of information must be provided and how it will be applied in decision-making can also contribute to reducing uncertainty and expediting decision-making, while providing a potentially clearer audit trail for *ex post* reviews and appeal processing.

4.3.6.4. *Liability assignment*

Liability assignment for responsibility for adverse outcomes can also help applicants and other stakeholders clarify who bears the burden of ensuring that bad outcomes are avoided. (e.g., whether self-certification is sufficient)

4.3.7. Enforcement reform

Credible enforcement mechanisms help frame incentives and influence behavior throughout the decision-making process. For example, clarity regarding how interference claims will be adjudicated and collective trust that violations will be detected and enforced will help remove impediments to more intensive spectrum sharing. However, the mode of enforcement will depend critically on the context in which sharing takes place (e.g., macro or small cell, cooperative or non-cooperative, etc.).

4.3.8. Spectrum management authority reform

Responsibility for regulating spectrum access in the U.S. is split between the FCC (for non-Federal users) and the NTIA (for Federal users). This joint control poses a challenge for managing government/commercial sharing, and may be less effective in other contexts as well. A number of researchers have suggested that the multiplicity of regulatory authorities increases regulatory uncertainty and delays. For example, having both the NTIA and FCC manage overlapping portions of the spectrum for different classes of users raises questions about jurisdiction that might be better addressed with a reassignment of authority. Analysis of possible options for institutional reform of spectrum management agencies could help address these challenges.

4.3.9. International harmonization:

An additional process challenge confronting spectrum management is the need to coordinate sovereign national policies to help sustain a healthy global market in wireless equipment and services, and to manage interference issues that arise when wireless systems span national borders. In light of new technologies like cognitive radios and changing global market conditions, a reexamination of international spectrum management practices is warranted. Additionally, cross-national research of spectrum management policies and socio-economic outcomes provides a wealth of natural experiments (in process/institutional design, market conditions, etc.) that is difficult to undertake otherwise.

4.3.10. Property rights, Interference Protection, and License Rights

All spectrum access rights regimes, whether for exclusive or unlicensed spectrum usage, are property rights regimes that offer different interference protection and other terms. A richer and more nuanced understanding of property rights frameworks enable enhancements.

Examples of refinements include:

4.3.10.1. Receiver standards

Graduated permissions/protections based on compliance with receiver standards may offer a useful way to induce voluntary compliance.[14]

4.3.10.2. Secondary access rights expanded

A range of novel approaches for expanding secondary access to spectrum are under consideration, including Licensed Shared Access (LSA) or Authorized Shared Access (ASA) and General Authorized Access (GAA), in current standards work and regulatory proceedings at the FCC.[15]

4.3.10.3. Auction design reforms

As noted above, there are a range of auction design refinements that are worthy of further investigation. A subset of the range of issues are touched upon in the FCC's Incentive Auction NPRM.[16]

4.4. (R4) Commercialization of novel wireless technologies

[14] See de Vries, J. Pierre (2012), "Optimizing Receiver Performance Using Interference Limits," November 1, 2012, TRPC, available at http://ssrn.com/abstract=2018080.

[15] See for example, *Notice of Proposed Rulemaking and Order*, In the Matter of Amendment of the Commission's Rules with Regard to Commercial Operations in the 3550-3650 MHz Band, Before the Federal Communications Commission, GN Docket No. 12-354, released December 12, 2012, available at: http://apps.fcc.gov/ecfs/document/view?id=7022080889.

[16] See FCC Incentive Auction NPRM, note 12 supra.

Commercializing novel wireless technologies poses a significant challenge that would benefit from additional economic and policy focused research. A number of specific focus areas for research were identified, including.

4.4.1. Case studies of spectrum sharing experiences

There have been a number of spectrum sharing initiatives in the past, and many more are on-going currently. Some have been significantly more successful than others. Additional detailed case studies of such earlier efforts can provide a wealth of information which may prove useful in promoting more efficient spectrum sharing.

4.4.2. Radio system design and economics

As intelligence is distributed more widely throughout networks and radio systems, including cognitive radios, it is becoming increasingly necessary to embed economic mechanisms in radio systems, and modify spectrum management mechanisms in the larger ecosystem to take account of new radio technologies. We need to better understand what wide-spread deployment of new capabilities may mean in terms of socio-economic impacts and the evolution of industry value chains and market structures. Some of these technologies have the potential to radically disrupt/re-engineer the way we build radio networks. Some of the topics worthy of further study include:

4.4.2.1. *Wideband GHz Radio/Cognitive Radios*

A difficult challenge for DSA system is the cost of wideband spectrum sensing on inexpensive platforms. If radios could more cost-effectively scan larger spectrum bands, sharing opportunities would be greatly expanded. Until recently, it has been prohibitively expensive to design inexpensive sensors capable of scanning GHz-wide chunks of spectrum. Recent research suggests this is no longer the case.[17] We need to better understand what large-scale deployment of such radios might mean for spectrum management.

4.4.2.2. HetNets

A number of operators are investigating architectures that mix small and large cell base stations in the same frequencies, so-called "HetNet" architectures. This poses interesting challenges for managing shared use and provides a potentially cost-effective strategy for operators to more granularly address coverage and capacity issues in licensed spectrum. A better understanding of the cost-benefit economics of such architectures would be valuable.

4.4.2.3. *Time-limited leases*

Time-limited spectrum access leases offer a potentially useful mechanism for managing access to shared spectrum. Recourse to such methods provides a useful mechanism for controlling radio access while mitigating potential harm from radios.[18]

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[17] See Hassanieh, et al. (2013), "GHz-wide sensing and decoding on commodity radios," available at: http://apps.fcc.gov/ecfs/document/view.action;jsessionid=KhSSR2pBQfH5DpHWpKjxTRMZx9GP2FhqLLLrSLQbvLWvKmvysYy1!-1705390101!956499833?id=7022123547.

[18] See Chapin, J. and W. Lehr (2007) "Time-limited Leases for Innovative Radios," with John Chapin, IEEE Communications Magazine, June 2007.

4.4.2.4. *Small cell economics and design*

It is widely recognized that the future of radio system design includes increased use of smaller cell architectures. The motivations for this are several: to enable spatial reuse, to reduce power requirements, and to localize access. The transition to a greater number of small cells for cellular operators may pose a challenge for competition, and it is worthwhile considering how such smaller cell infrastructure might be shared and the benefits that might accrue from such sharing.[19]

4.4.2.5. *Distributed Antenna Systems*

Another promising technology that can expand spectrum capacity is Distributed Antenna Systems. Such systems have the potential to expand capacity and coverage, and like the small cell architectures, raise interesting issues for how such architectures might be deployed and shared.

4.4.2.6. *End-user deployed infrastructures*

Unlike wired architectures, the potential for wireless to support carrier-less and end-user deployed infrastructure as a complement or substitute for carrier-deployed infrastructure raises the specter of new models for competition, ad hoc networking, and end-user control. The opportunity to off-load cellular traffic to WiFi demonstrates the significant potential for user-deployed infrastructure to augment wireless options.

4.5. (R5) Special topics

Special Topics

- Public Safety
- Internet/Wireless Integration
- International Harmonization
- Handset scale/scope economies and impacts
- Wireless Patents and Innovation
- Financial market and investor responses

4.5.1. Public Safety

Public safety has a compelling need for expanded mobile broadband applications, including better support for mesh/ad hoc networking, for dynamic resource (spectrum) reconfiguration, for mobility, and for real-time communications (video) and latency tolerant (dbase access) applications. But, public safety also confronts significant challenges such as: rigorous quality standards, tight budget constraints, the need for training personnel, and for optimizing public safety processes to make use of new wireless technologies.

There are a range of technologies and capabilities that need to be studied, including:

[19] See Chapin, J. and W. Lehr (2011) "Mobile Broadband Growth, Spectrum Scarcity, and Sustainable Competition," 39th Research Conference on Communications, Information and Internet Policy (www.tprcweb.com), Alexandria, VA, September 2011, available at: http://people.csail.mit.edu/wlehr/Lehr-Papers_files/chapin_lehr_tprc2011%20mobile%20broadband.pdf.

- Inexpensive Air-to-ground real-time video (e.g., on-site helicopter sends situation-relevant video to command center).
- Dynamic frequency assignable radios/spectrum (e.g., to enable real-time resource management)
- Penetration of buildings and structures (e.g., access in tunnels, underground).
- Ubiquitous coverage (i.e., need advanced communication capabilities wherever the emergency happens to occur which is potentially anywhere, not only where folks are most often).
- Interoperability to integrate commercial and public safety capabilities and resources.
- Keeping up with the bleeding edge of technology. Public safety will always offer a compelling case for the latest wireless technologies while posing special challenges for rapid commercialization.

4.5.2. Wireless Security and Reliability Policy

A number of wireless applications (e.g., smart grids, vehicle-to-vehicle critical systems) require extremely high reliability. These reliability requirements may be more important and worth sacrificing capacity and capabilities (e.g., spectral efficiency, broadband) to achieve. Research on how to optimize spectrum management for different critical uses poses a special challenge.

4.5.3. Financing Novel Wireless Technologies

A paradigm shift in spectrum management that results in expanded access and reduced scarcity ought to lower the overall cost of spectrum access, but will have implications for financing of wireless businesses. One the one hand, a traditional source of investment return has been associated with the control of exclusive licenses and proprietary technologies. For widespread sharing and new open access models that reduce spectrum scarcity rents, we need to substitute new models of sustaining investment returns. This could be long-term customer contracts, proprietary technology (innovation), equipment tie-ins, etc.

Additional research is needed into how spectrum access and sharing impacts the ability of wireless innovators to attract investment capital both for large-scale (e.g., cellular) deployments and new entrants (e.g., WISPs, novel wireless services).

Research is also needed on how equipment and device cost economics impact and are impacted by sharing regimes. How can radios be designed to be more spectrum-agile while retaining cost-economies? What components need global scale? How might we balance trade-offs of global scale in component costs v. per-device costs (due to radio complexity/agility/cognitive functionality)?

The role of standards and interfaces in moderating costs of proprietary technology and promoting interoperability are also worth studying.

Alternative ownership models for key elements of infrastructure, including shared and/or end-user owned infrastructure offers another approach for financing and lowering the costs of deploying spectrum sharing technology. For example, might the costs of DAS be integrated with building ownership? How might MegaMIMO antennas be shared if owned by different parties? What might the role be for tower companies as new players in facilitating more open small-cell ecosystem?

5. Appendix A: Workshop Agenda

The Networking and Information Technology Research and Development (NITRD) Program

WSRD Workshop IV
Efficient spectrum utilization: the economic and policy R&D Agenda

When: April 23-24, 2013
Where: MIT (32-G449 Patil Conference Room/Kiva, 32 Vassar Street, Cambridge, MA 02139)

Day 1: Tuesday, April 23

Time	Description
8:30-9:00	Coffee & Registration
9:00-9:30	Greeting, Logistics, Introductions (Bill Lehr, MIT; Byron Barker, NTIA; Andy Clegg, NSF; John Chapin, DARPA)
9:30-10:00	Keynote: Tom Power (OSTP)
10:00-10:15	• Break
10:15-11:30	*Panel 1.1 Recent Experiences with Spectrum Sharing* Moderator: Byron Barker (NTIA) 1. Mark Gibson - ComSearch (on 1755-1850 band) 2. Steve Sharkey - T-Mobile (on 1695-1710 and 1755-1850 bands) 3. Peter Ecclesine - Cisco (on 5 GHz bands) 4. Jeff Schmidt - SpectrumBridge (TV White Space)
11:30-12:15	*Panel 1.2 Public Safety and New Spectrum Use Models* Moderator: Fred Frantz (NLECTC) moderator 1. Don Denning, CIO for Public Safety, City of Boston 2. P. A. (Al) Sadowski, North Carolina Department of Public Safety 3. Scott Wilder, Director of Technology, Brookline Police Department
12:15-13:15	Lunch w/ Peter Rysavy (Rysavy Research) (speaker, 12:40-1:05)
13:15-14:45	• *Panel 1.3 Impediments to Commercialization of Sharing* • Moderator: John Chapin (DARPA). 5 min each, max 2 slides 1. Dean Brenner - Qualcomm (Small cell in 3.5 GHz) 2. Steve Sharkey - T-Mobile 3. Chris Guttman-McCabe - CTIA 4. Stacey Black, AT&T 5. Brett Kilbourne, Utilities Telecom Council 6. Jake MacLeod, TIA 7. Mark Cooper, CFA
14:45-15:00	• Break
15:00-16:00	• *Panel 1.4 Jumpstarting investment - Investor and Legal Perspectives* • Moderator: Peter Tenhula (NTIA) 1. Barlow Keener/Armand Musey 2. Mark Lowenstein (Mobile Ecosystem) 3. Mitchell Lazarus (FHH)
16:00-16:45	• Breakouts: Small group breakouts to prioritize list of barriers/problems/issues and identify list of research questions (10-12 per group)
16:45-17:20	• Moderator: John Chapin (DARPA) • Group discussion to coalesce break-out group discussion
17:20-17:30	• Closing remarks Tom Power (OSTP)
17:30-18:30	• Free time/return to hotel/etc.
18:30-21:00	• Dinner (Kendall Square, TBD)

WSRD Workshop IV
Efficient spectrum utilization: the economic and policy R&D Agenda

When: April 23-24, 2013
Where: MIT (32-G449 Patil Conference Room/Kiva, 32 Vassar Street, Cambridge, MA 02139)

Day 2: Wednesday, April 24

Time	Description
9:00-9:15	• Greeting, Introductions -- Bill Lehr (MIT)
9:15-9:35	John Leibovitz (FCC) Research a policymaker would like to see
9:35-10:45	• *Panel 2.1 Lightning Talks I* • Moderator: Andrew Clegg (Moderator) • 5-7 minute talks "here's valuable research that needs to be done " 1. Martin Weiss (UPitt) Enforcement in cooperative sharing 2. Anant Sahai (UC, Berkeley) Building trust against political risk 3. Michael Marcus (Marcus) FCC delays and impact on investment & innovation 4. Barlow Keener (Keener) Economic loss from fallow spectrum 5. Mark Cooper (CFA) Evolving regulatory rules for innovation and social benefit 6. Michael Honig et al. (Northwestern) Spectrum valuation & regulatory regime
10:45-11:00	• Break
11:00-12:15	*Panel 2.2 Economics Research Challenges & Opportunities* Moderator: Tom Hazlett (George Mason) 1. Gerry Faulhaber (UPenn) 2. Michael Katz (UC, Berkeley) 3. Scott Wallsten (TPI) 4. Guilia McHenry (Brattle Group)
12:15-13:15	Lunch w/ International Research Perspectives from Vanu Bose (Vanu) & Xavier Fernando (Ryerson) (12:30-13:00)
13:15-14:15	• *Panel 2.3 Spectrum Management Reform* • Moderator: Yochai Benkler (Harvard) 1. Pierre de Vries (UColo, Boulder) Receiver management 2. John Quinlan (OMB) Spectrum Incentives in the Federal Budgetary Framework 3. Preston Marshall (ISI) Implementing new spectrum utilization metrics
14:15-15:25	• *Panel 2.4 Lightning Talks II* • Moderator: Andrew Clegg (Moderator) 1. Tom Hazlett (George Mason) Overlays and Efficient Spectrum Relocation 2. Michael Marcus (Marcus) Efficient Co-design of military radar and comm systems 3. Martin Weiss (UPitt) Moving spectrum markets up the stack 4. Doug Sicker (UColo) Metrics, methods and measurement of spectrum 5. Dina Katabi (MIT) GHz-wide sensing and decoding using cheap radios 6. Allan Sadowski (NC Pub Safety) Spectrum Efficient Antenna Revolution
15:25-15:40	• Break
15:40-16:30	• Breakouts: Small group breakouts to prioritize list of barriers/problems/issues and identify list of research questions (6-8 per group)
16:30-17:15	• Moderator: Doug Sicker (UColo, Boulder) • Group discussion to coalesce break-out group discussions
17:15-17:30	• Wrap-up and Closing – Bill Lehr (MIT)

6. Appendix B: Instructions for Breakout Sessions

WSRD Workshop IV
Efficient spectrum utilization: the economic and policy R&D Agenda

BREAKOUT SESSIONS – Goals and Instructions

Time: Day 1 (April 23 -- 16:00-17:20), Day 2 (April 24 -- 15:40-17:15)

Following the workshop, we will be producing a report that summarizes key findings and includes a list of *multidisciplinary* research topics that can promote more efficient spectrum use (in the economic sense).

Toward this end, at the end of each day, we will have a 90 minute session during which we will organize into smaller breakout groups, which will be followed by a plenary session to coalesce results. These sessions are intended to foster focused discussion and contributions from all workshop participants.

We will finalize the topics for the breakout sessions and participation in real-time based on what we hear and learn over the course of the workshop and will need all participants to actively contribute.

At the start of each day's breakout session, participants will vote on which areas should be discussed in the groups. Participants will self-select which group to join based on research interests, but should avoid being with the same people both days.

We will be collecting topic areas for the breakout groups based on what we hear throughout the workshop proceedings, but are offering these candidates to seed the list.

Type I: "Greater adoption/use of X would promote more (economically) efficient spectrum use"

- more/better enforcement
- small cell architectures (potentially shared)
- evidence based policy making
- commercial/federal shared spectrum
- dynamic spectrum access
- private commons / band managers
- secondary markets
- spectrum usage rights / receiver standards
- expansion of unlicensed spectrum

If your group focuses on a Type I area, please answer the following questions:

1. What are the key sticking points preventing or slowing forward progress in this area?
2. What are worthwhile projects for interdisciplinary research that would help get past those sticking points? Identify specific research projects, ideally with reference to methods/approach, data sources, and desired research outcomes.
3. What are tangible next steps that should be taken to launch those projects - by federal agencies, by academia, by industry? Who would be the right collaborators to pursue the work?

Type II: "Appropriate research on Y would promote more (economically) efficient spectrum use"

- policy/rules/business cases for spectrum sharing
- cost/incentives for adopting more efficient approaches
- process/drivers/economic policy tools for evolution
- measuring the value/use of spectrum
- techniques to improve technical efficiency
- new standards that facilitate sharing

If your group focuses on a Type II area, please answer the following questions:

1. What are the most likely pathways for research results in this area to promote more efficient spectrum use? Try and identify with as much specificity as possible what entities (audience) would exploit research results in this area, and how would they exploit them.
2. What are worthwhile projects for interdisciplinary research within this area? Again, identify specific research projects, ideally with reference to methods/approach, data sources, and desired research outcomes.
3. What are tangible next steps that should be taken to launch those projects - by federal agencies, by academia, by industry? Who would be the right collaborators to pursue the work?

To repeat: We will be adjusting/expanding the above lists of areas throughout the workshop proceedings.

After 45 minutes of breakout discussion, we will reconvene in plenary session and each group will report on their discussions and we will have an opportunity for feedback between the groups.

Group results and discussion notes will feed into the workshop report preparation process. And, we request that participants with further thoughts and notes share those with the organizing committee in real-time or after the workshop to supplement those discussions.

7. Appendix C: Participant List

Barker, Byron, NTIA -DC
Benjamin, Stuart, Duke Law
Benkler, Yochai, Harvard
Berry, Randall, Northwestern (EE)
Black, Stacey, AT&T
Bose, Vanu, Vanu, Inc.
Brenner, Dean, Qualcomm
Calabrese, Michael, New America
Chapin, John, DARPA
Clegg, Andrew, NSF
Cooper, Mark, CFA
de Vries, Pierre, UColorado
Denning, Don, City of Boston
DeVito, Don, NTIA
Ecclesine, Peter, Cisco
Emery, Gil, Portsmouth NH Police Dept
Faulhaber, Gerald, UPenn
Fernando, Xavier, Ryerson Communications Lab
Frantz, Fred, Engility (National Inst of Justice support contractor)
Gibson, Mark, ComSearch
Gillett, Sharon, MIT -former FCC
Guttman-McCabe, Chris , CTIA
Harris, Phillip, DoJ
Hazlett, Thomas, George Mason
Honig, Michael, NWestern (EE)
Kahn, Carolyn, MITRE
Katabi, MIT, MIT
Katz, Michael, Berkeley
Keener, Barlow, Keener Law Group
Kilbourne, Brett, Utilities Telecom Council
Kolodzy, Paul, DARPA
Laneman, Nick, Notre Dame
Lazarus, Mitchell, Fletcher, Heald & Hildreth, PLC
Lehr, William, MIT
Leibovitz, John, FCC
Lowenstein, Mark, Mobile Ecosystem
Luker, Mark, NCO NITRD
MacLeod, Jake, TIA Board Member
Marcus, Mike, Marcus Spectrum
Marshall, Preston, Google
Mayo , John, Georgetown
McHenry, Giulia, Brattle Group
Musey, Armand, Summit Ridge Partners
Nelson, Eric, NTIA-ITS
Peha, Jon, CMU
Power, Tom, OSTP
Reed, David,
Rosston, Greg, Stanford
Rysavy, Peter, Rysavy Research
Sadowski, Paul (Allan), North Carolina Department of Public Safety
Sahai, Anant, Berkeley
Sandvig, Christian, U of Michigan
Schmidt, Jeff, Spectrumbridge
Sharkey, Steve, T-Mobile
Sicker, Doug, UColorado
Song, Min, NSF (WSRD SSG)
Stine, John, MITRE
Tenhula, Peter, NTIA
Vohra, Rakesh, Northwestern (Kellogg)
Wallsten, Scott, Tech Policy Institute
Weiss, Martin, Upitt
Wigen, Wendy, NCO NITRD
Wilder, Scott, Brookline, MA

8. Appendix D: Lightning Presentation Submissions

In advance of the workshop, participants were invited to suggest topics for short "lightning talks" that would present a research topic they would like to undertake or see someone else undertake, with the following email:

> "The principal goal for this workshop is to help set the agenda for spectrum sharing-related economic/policy research, and we would like to surface as many ideas as possible of high-impact research projects that might be undertaken both in the near term (next 12-24 months) and longer term. Consequently, we have two 'Lightning Talk' Sessions where we will give selected participants a 5-7 minute slot to propose a research project: explaining what needs to be done, thoughts about how to proceed/implement the research, challenges to be confronted in undertaking the research, and thoughts about the benefits/uses of the research. The talk should be able to be delivered in 3-5 slides. If you have a topic you would like to suggest during one of the available slots, please send it to us ASAP. At this point, all you need to do is provide enough of a description so we can figure out what it is you would like to present."

We received the following 25 proposals in response (edited to render them more consistent):

1. Practical aspects of enforcement in cooperative sharing (Martin Weiss, University of Pittsburgh)

Cooperative sharing requires mechanisms by which the parties and manage potential interference events. There are a suite of available options, each with different technical and social costs. Technical costs include sensing and data analysis and social costs include opportunity costs associated with ex ante enforcement. Effective balance between ex ante and ex post mechanisms requires cost efficient detection and adjudication techniques.

2. Moving spectrum markets "up the stack" (Martin Weiss, University of Pittsburgh)

Spectrum markets have largely focused on what Hazlett has called "naked spectrum". While this may make sense as an input to a wireless market, it is problematic for many reasons (spectrum opportunities are not necessarily fungible). Instead, Doyle and others have proposed connectivity markets over heterogeneously owned infrastructure. This requires resource planning on the part of service providers and provisioning on the part of the network owners. Despite the complexity this poses, moving to trading of virtual connectivity could result in liquid markets

3. Exploring and Preserving the Socio-Technical Underpinnings of the Success of the Unlicensed Revolution (Mark Cooper, Consumer Federation of America)

The Internet and unlicensed spectrum models have complemented each other and supported a successful digital communications resource ecosystem, but also result in new challenges like exaflood traffic growth. This research project would being by articulating the fit between the underlying technologies and the institutional structures that led to success, and would seek to identify rule changes and policy principles that are necessary to accommodate new technologies and what effect such changes would have on the core functioning of the resource system.

4. Empirical work to understand the trends in noise floor (Doug Sicker, University of Colorado, Boulder)

To assess through measurement of interference and the noise floor how (of if) the interference environment is changing, where, and why; and then, examine mitigation costs under alternative options.

5. Assessing the tradeoffs between policy-based interference protection and technology solutions (Doug Sicker, University of Colorado, Boulder)

Interference protection requires a balance of technical and policy-based mechanisms. Evaluation of the appropriate mix requires understanding how these may be composited and the trade-offs of different approaches.

6. Implications of adopting new propagation models (Doug Sicker, University of Colorado, Boulder)

Legacy propagation models (e.g., ITM) that when combined with the classic "we will add 3dB to whatever we get" overstates interference protection needs. Demonstrate the value and the need to adopt one of the more modern modeling approaches.

7. Co-existence modeling and its effects of band planning and spectrum allocation (Doug Sicker, University of Colorado, Boulder)

Consider how coexistence modeling at the application layer might change how we view guard bands, allocations/assignments and sharing.

8. Impact of small cell, low power communication services on RADAR (Doug Sicker, University of Colorado, Boulder).

Evaluate potential co-existence implications of small cell/low power communications on Radar. These issues are being considered in the FCC's 3.5GHz proceeding and elsewhere.

9. Disclosure of Government Spectrum Use (Doug Sicker, University of Colorado, Boulder)

Better disclosure of U.S. government spectrum use (receiver and transmitter characteristics, interference impacts, location of services, duty cycles, user profiles,, etc.) would enable better identification and management of sharing opportunities, but poses a difficult challenge for security and strategic incentives. Today, we rely on a "leajy box" approach. Research is needed to evaluate better alternatives for disclosing government usage, potentially including a role for an honest third party broker. This research would explore options in this space.

10. Estimating economic losses from under-utilized spectrum (Barlow Keener, Keener Law Group)

There are large market areas with poor or no cell phone coverage, but where spectrum has been allocated. In order to better evaluate spectrum options, we need models and data to estimate the economic cost of under-utilizing spectrum in such areas. Micro geo data is available and can be used for a more accurate measurement of geographies and roads without mobile service and of the numbers of users who could be more productive and, thus, measurable in these fallow areas. An economic study could use micro mapping data to determine the precise fallow spectrum areas across the country lacking mobile coverage, and could be matched with socio-economic data on population, households, and traffic to estimate foregone productivity and other effects due to under-utilized spectrum.

11. Technical-Business model of deploying nationwide mobile broadband network in TV band spectrum (Barlow Keener, Keener Law Group)

A new nationwide mobile broadband network might be deployable using a mix of unlicensed TV white space and newly licensed TV band spectrum (from the incentive auctions). Such a network, if successful could enhance options for competition and contribute to meeting the needs of public safety. To better understand and evaluate this opportunity, it would be worthwhile to design a technical and business model plan for how such a network might be deployed.

12. Impact of FCC delay with spectrum policy decisions (Michael Marcus, Marcus Spectrum)

Delays in FCC decision making have plagued a number of proceedings such as TV Whitespace, UWB, and AWS-3. Regulatory uncertainty and delays pose impediments to investors in new technologies and business models for spectrum usage. A study assessing the impact of decision-making delays on wireless investment and innovation, and identifying policy reforms to reduce such delays could help alleviate an important impediment to progress.

13. Joint design of military radar and commercial systems to foster co-existence (Michael Marcus, Marcus Spectrum)

It is worthwhile considering how military radar and commercial communication systems might be jointly designed to foster co-existence opportunities. Commercial users might compensate military radar system designers to induce them to over-design their systems to facilitate easier sharing. Sharing the costs of redesigning new phased-array, commercial-friendly radars may offer a superior approach to trying to co-existing with legacy radar systems.

14. Overlays as Efficient Spectrum Reallocation Devices (Thomas Hazlett, George Mason University)

A useful regulatory strategy for transitioning spectrum to new usage models is to overlay new rights on legacy rights assignments. Analysis of the challenges and opportunities afforded by such an approach would enhance our understanding of the role of regulatory process and institutional reforms might accelerate the transition to more efficient spectrum usage models.

15. TV White Spaces in India (Vanu Bose, Vanu, Inc.)

Vanu Inc. is working with an Indian carrier and IIT on deploying infrastructure in spectrum white spaces. The Indian experience and context is very different from the situation in the U.S., but offers valuable insights on how such spectrum might be shared more intensively. Mining this example for lessons learned provides a valuable research topic.

16. GHz-Wide Sensing and Decoding Using Low-Power Cheap Radios (Dina Katabi, MIT)

Recent advances on the sparse Fourier Transform enable GHz-wide sensing and decoding using cheap and low-power devices. This talk shows how we can build a technology that captures GHz of spectrum in real-time using three only 50 MHz analog to digital convertors (ADC) and a front-end radio. Such a technology has the right cost and power budget to enable truly dynamic spectrum access, where secondary users can detect short spectrum vacancies in realtime and leverage them. The result contributes towards the PCAST's vision of spectrum highways, where radios can dynamically share GHz of spectrum, identifying unoccupied bands and using them, just like cars share a superhighway by moving from one lane to another.

17. Spectrum valuation under comparative regulatory regimes (Michael Honig, Randall Berry, Rakesh Vohra, Northwestern University)

While there have been attempts to compare the value of open access vs liberal licenses, more careful studies are needed in order to make informed policy decisions about future spectrum allocations. Such studies should take into account the regulatory assumptions (e.g., unlicensed, licensed, along with sharing constraints), potential uses (depending on the band), potential for innovation, engineering issues such as interference management, possible market inefficiencies, and robustness with respect to changes in technologies and associated services. We would mention some of the deficiencies with previous studies and outline the challenges involved in carrying out such a study for a particular band.

18. Spectrum management reform: status and progress in Canada (Xavier Fernando, Ryerson University)

Assessing the status of spectrum policy reform in Canada and other countries is valuable to share lessons learned, highlight international coordination challenges, and to focus and mobilize both national and international discussions.

19. **SP**ectrum **E**fficient **A**ntenna **R**evolution ("SPEAR") (Allan Sadowski, North Carolina Dept of Public Safety)

Today, antennas are largely passive components of the radio system architecture in many designs. Active management of antenna designs offers important benefits for radio system efficiency, in power management, safety, and system capacity. A better understanding of how antenna designs might be controlled and used to enhance spectrum efficiency offers important benefits.

20. Addressing political risk in spectrum management (Anant Sahai, University of California, Berkeley)

Political reform efforts must often confront the challenge of regulatory capture by vested interests. Certification rules that are too light-handed may allow mass market devices to assert ex post spectrum rights (as some argued happened in the case of Lightsquared and its challenge to GPS receivers or in the case of garage door openers operating in DoD spectrum); while rules that are too heavy-handed might be abused to slow or block the progress of worthwhile innovations. It should be possible to design an architecture that avoids both of these problems.

21. New reference model for utility benefits of automated trading (Anant Sahai, University of California, Berkeley)

We need a clean reference model of what can be accomplished (in terms of economic efficiency) with purely simulated spectrum trading using coarse models of utility. A better understanding of the performance of such a model will highlight the benefits to be expected from fuller development of a real-world trading market with all that entails. It is conceivable that overall efficiency is not sufficiently sensitive to more nuanced modeling of user preferences, rendering excess consideration of such nuanced preferences unnecessary.

22. Federal and non-Federal Sharing Incentives (Carolyn Kahn, MITRE)

Additional research should be undertaken to advance sharing between Federal and non-Federal users by investigating market forces influencing commercial companies compared to those forces impacting DoD. Opportunities for common ground among

Federal and non-Federal spectrum users should be identified. Potential new areas and technological advancements that could expand the common ground should also be examined.

23. National security and the economics of spectrum sharing (Carolyn Kahn, MITRE)

Research is needed that applies economic theory to help improve the management of spectrum resources and balance both national security and economic interests. The application of public sector economics to the spectrum domain can help determine what role the government should play to provide efficient, desirable outcomes. This should encompass developing a framework for assessing the benefit of public sector spectrum usage. It can also include looking at the impact of marginal changes, such as the impact on national security and economic interests due to spectrum reallocation.

24. Optimization model of Federal and Non-Federal Spectrum Sharing (Carolyn Kahn, MITRE)

Further research is needed to develop incentives for Federal and non-Federal users to use spectrum more efficiently. This research should build an optimization model of infrastructure and spectrum resources. The trade-space between additional build-out of infrastructure or other alternatives and added spectrum needs to be better understood and balanced in today's spectrum-constrained environment.

25. Analysis of financial and non-financial spectrum value considerations (Carolyn Kahn, MITRE)

Additional research on both the financial and non-financial value of spectrum would be beneficial. As indicated in the WSRD small group breakout discussion, there are many different valuations and utility models for spectrum. This research could compare and contrast different valuation and utility models. It could also evaluate spectrum valuation metrics that could be used across commercial, Federal, and/or non-Federal spectrum for economic comparison.