Complexities of Spectrum Sharing

How to Move Forward

April 2014

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Executive Summary

The success of mobile broadband and consequent need for more spectrum has led to collaboration over the past several years on how government and industry might share spectrum, especially in the AWS-3[1] and 3.5 GHz small-cell bands. While clearing spectrum and making that spectrum available for exclusive use licensing is the preferred model, spectrum sharing in some bands may be necessary in the future. This collaborative work effort has yielded greater understanding of, although not solutions to, the issues associated with spectrum sharing.

Spectrum sharing can take many forms, ranging from simple geographic separation to sophisticated dynamic systems. Spectrum sharing will be successful to the extent that industry and government are motivated to share spectrum and can agree on a realistic path forward. Limiting the scope of sharing in initial stages will simplify what will be a multi-year development process. Unrealistic goals or mandates will slow and adversely affect the dynamic and important wireless sector.

Spectrum sharing technologies do exist. They include TV white space databases and standardization by the European Telecommunications Standards Institute of a system called Licensed Shared Access. But none of these solves the problems under discussion. The Spectrum Access System (SAS) planned for 3.5 GHz spectrum is likely to be the most complex spectrum management system ever developed, involving new architectural concepts, protocols, interfaces, stringent security, and policy-enforcement methods.

Over the last year, The Commerce Spectrum Management Advisory Committee (CSMAC), through five working groups, has researched and reported on sharing for AWS-3. Meanwhile, 3.5 GHz developments have included industry submissions and an FCC workshop held in January 2014.

Based on the work to date, key concerns include overly conservative assumptions for government systems; inappropriate or overly simplistic modeling for exclusion and protection zones; the potential of exclusion zones rendering spectrum non-useful; the disparity and multiplicity of government systems; restricted Department of Defense (DoD) information hampering industry analysis; and lack of detail about coordination requirements.

The challenges of spectrum sharing are multifold, including lack of maturity, the complexity of developing the 3.5 GHz SAS, propagation-modeling complexities, frequency management, disparate secondary users and differing use cases, unclear role and workability of spectrum sensing, database and other security concerns, and the need for new enforcement mechanisms.

This paper makes a number of recommendations to help address these challenges.

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[1] AWS-3 consists of 1695-1710 MHz and 1755-1780 MHz uplink frequencies, which will be shared, the latter to be combined with 2155 to 2180 MHz for the downlink.

With respect to sharing scenarios where most government users will be relocated but some will remain and will share the band with non-federal users (e.g., as contemplated in the AWS-3 band): The government needs to use realistic and real-world interference assumptions; industry and government need to agree upon realistic propagation models; industry and government should take advantage of the recently established trusted-agent process; and government should vacate as many systems as possible from the spectrum and adopt simple sharing and coordination approaches.

With respect to sharing scenarios that will be managed by a combination of coordination/protection zones and dynamic access technologies (e.g., as contemplated in the 3.5 GHz band): Ongoing measurements should be considered to progressively refine models and protection zones; geographic protection zones should protect incumbent users rather than new entrants; the SAS should not exercise direct control over networks; SAS rules should assume the appropriate use-case scenarios to protect against co-channel interference; rules should segment spectrum to minimize the possibility of general-access users (called Tier 3 GAA users in the case of the 3.5 GHz band) interfering with users that have priority over general-access users (called Tier 2 service providers in the 3.5 GHz context); spectrum allocations should be assigned to priority or Tier 2 service providers on a longer-term (non-varying) basis; rules should accommodate unlicensed LTE for general-access or Tier 3 operation; and use cases should include more than just extremely small coverage areas.

Unless government and industry choose appropriate use cases, propagation models, measures, and other effective approaches for spectrum sharing, little meaningful progress will occur, harming not only the economy, but causing the U.S. to cede mobile broadband leadership.

Introduction

The scarcity of spectrum, especially frequencies suitable for mobile broadband, demands multiple approaches to maximize the value of this national asset.[2] In 2011, President Obama announced his National Wireless Initiative to bring 500 MHz of unused and underused spectrum to market for wireless services, from exclusive use to sharing.[3] Since 2012, when The President's Council of Advisors on Science

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[2] Phil Weiser, "The Untapped Promise of Wireless Spectrum," July 2008, available at http://www.brookings.edu/~/media/Research/Files/Papers/2008/7/wireless%20weiser/07_wireless_weiser.PDF.

[3] National Wireless Initiative, Feb. 2011, available at http://www.whitehouse.gov/the-press-office/2011/02/10/president-obama-details-plan-win-future-through-expanded-wireless-access.

and Technology published its report on realizing the full potential of government-held spectrum[4], government and industry have increased their investigations into how they might share spectrum.

Initial reports and workshops reveal how spectrum sharing is one of the most complex radio developments ever undertaken.[5] While simple sharing scenarios exist and are in use today, sharing spectrum in real time among disparate systems is a multi-dimensional challenge, not only for technical reasons, but also for regulatory and political ones. Economic models to incentivize sharing and to value shared spectrum are only now emerging.[6]

Although the concept of spectrum sharing has developed momentum with multiple global investigatory and standardization efforts, the idea needs to be kept in perspective: It is just one approach for spectrum management, and today's key wireless technologies, such as LTE, were designed to operate in licensed, dedicated spectrum. Accordingly, the Spectrum Act of 2012 states that the Department of Commerce's National Telecommunications and Information Administration (NTIA) must prioritize clearing and reallocation, pursuing sharing only when "that relocation of a Federal entity from the band is not feasible because of technical or cost constraints."[7]

To deliver the high quality of service that consumers expect and demand, today's 3G and 4G networks need stable, predictable, and manageable spectrum resources. Therefore, spectrum sharing must be approached carefully and in well-defined steps.

The U.S. spectrum bands receiving the greatest emphasis for sharing are 1695-1710 MHz uplink, and 1755-1780 MHz uplink (referred to as Advanced Wireless Service-3 when combined with 2155-2180 MHz downlink), and the 3550-3650 MHz "small-cell" band (which could be combined with 3650-3700 MHz). This paper summarizes the results of recent investigations into spectrum sharing, details the

[4] Executive Office of the President, President's Council of Advisors on Science and Technology, *Realizing the Full Potential of Government-Held Spectrum to Spur Economic Growth*, Washington, DC, July 2012.

[5] For example, Rysavy Research, "Spectrum Sharing – The Promise and the Reality," *Mobile Future*, Jul 2012, http://www.rysavy.com/Articles/2012_07_Spectrum_Sharing.pdf

[6] For example, The Brattle Group, "Spectrum Sharing – Taxonomy and Economics," Feb 2014, http://www.brattle.com/system/publications/pdfs/000/004/983/original/Spectrum_Sharing_-_Taxonomy_and_Economics_Bazelon_McHenry_020614.pdf?1391797552.

[7] Spectrum Act 6701(a)(1)(B) (amending section 113(j) of the National Telecommunications and Information Administration Organization Act (47 U.S.C. 923)); *see also id.* (entitling such subsection "Relocation Prioritized Over Sharing"); Spectrum Act 6401(a) (entitled "Clearing Certain Federal Spectrum").

complexities and pitfalls involved, and makes recommendations on how to optimally move forward to harness the potential of spectrum sharing.

Spectrum-Sharing Progress and Status

The science of dynamic spectrum access (DSA) and cognitive radio (CR) has existed since the 1990s.[8] Cognitive radio systems that exploit underused spectrum do exist, but much of the development has emphasized military systems operating under assumptions far different from the sharing scenarios being contemplated for domestic use.

One commercial instance of sharing is TV white spaces, for which the Institute of Electrical and Electronic Engineers (IEEE) has developed two standards: IEEE 802.11af[9], "Amendment 5: TV White Spaces Operation," (TVWS), and IEEE 802.22-2011[10], "Cognitive Wireless RAN Medium Access Control (MAC) and Physical Layer (PHY) specifications: Policies and procedures for operation in the TV Bands." These technologies rely on databases to inform wireless systems of what spectrum is available.[11]

TVWS database methods, however, rely on openness and active, manual coordination among willing cooperative entities. They also assume higher-power incumbents and non-mobile users. Further, they do not address the end-to-end requirements for sharing between commercial and government systems. These requirements include: automated interfaces, standardized protocols to different systems, security of these protocols, database secrecy and security, and policy enforcement mechanisms among possibly non-cooperating or non-trusted entities.

For cellular mobile broadband (e.g., 4G networks), no "off-the-shelf" technology exists to implement spectrum sharing other than geographic-sharing instances. Industry and government are largely working with a blank slate—an opportunity for creative solutions but with much to learn and develop given the significant challenges articulated below.

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[8] For example, see J. Mitola III and G. Q. Maguire, Jr., "Cognitive radio: making software radios more personal," *IEEE Personal Communications Magazine*, vol. 6, nr. 4, pp. 13–18, Aug. 1999.

[9] IEEE 802.11af project details available at http://standards.ieee.org/develop/project/802.11af.html.

[10] IEEE 802.22 specification available at http://standards.ieee.org/findstds/standard/802.22-2011.html.

[11] See also IEEE, *IEEE 1900.5 - Standard for Policy Language Requirements and System Architectures for Dynamic Spectrum Access Systems*, 2012.

In June 2013, a White House presidential memorandum accelerated spectrum-sharing efforts when it set the goal that within one year, a spectrum policy team "shall publish a report describing how NTIA and FCC are incorporating spectrum sharing into their spectrum management practices."[12]

The FCC issued a Notice of Proposed Rulemaking (NPRM) to license AWS-3 spectrum, and recently adopted rules in a Report and Order that requires coordination of non-Federal operations with Federal incumbents, although details of such coordination are not yet specified.[13] The resulting auction, expected in late 2014, with spectrum auctioned and licensed by February 2015, will significantly expand the capacity of the Advanced Wireless Services (AWS) bands.

The institution tasked with research and recommendations for AWS-3 sharing was CSMAC, which created five working groups to pursue specific areas and which in 2013 issued multiple reports detailing the results of its investigations.[14]

Some representative statements regarding working group efforts include the following:

> **CSMAC.** The work of the groups was purposeful and productive, although it was characterized by some public characterizations that military and other Federal government users are relying on "worst case" technical analyses for harmful interference, and are unwilling or slow to share classified or sensitive information in an open forum with commercial wireless stakeholders. In the end there was agreement that relocation of some Federal systems will be required (e.g., law enforcement video surveillance operations). The WG (Working Group) reports could not make across the board recommendations that sharing within 1755-1780 MHz is possible. There was continual pressure by industry for Federal operations to be compressed into the upper 70 MHz (1780-1850 MHz) so that the lower 25 MHz sought by carriers for auction can be cleared for exclusive use.[15]

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[12] The White House Office of the Press Secretary, "Presidential Memorandum -- Expanding America's Leadership in Wireless Innovation," June 14, 2013.

[13] Amendment of the Commission's Rules with Regard to Commercial Operations in the 1695-1710 MHz, 1755-1780 MHz, and 2155-2180 MHz Bands, *Notice of Proposed Rulemaking and Order on Reconsideration*, 28 FCC Rcd 11479 (2013); Amendment of the Commission's Rules with Regard to Commercial Operations in the 1695-1710 MHz, 1755-1780 MHz, and 2155-2180 MHz Bands, *Report and Order*, FCC Rcd, FCC 14-31 (rel. Mar. 31, 2014).

[14] CSCMAC reports are available at http://www.ntia.doc.gov/category/csmac.

[15] Janice Obuchowski, Commerce Spectrum Management Advisory Committee, "Lessons Learned,"13 Dec. 2013, http://www.ntia.doc.gov/files/ntia/publications/csmac_obuchowski_talking_points_13dec2013c.pdf.

CSMAC. Information needed for effective sharing and how to handle it will be more difficult in some cases then others. There is no one size fits all solution for what information needs to be shared. In fact for some systems, it will be difficult to share at all due to nature of systems (see 1755 MHz WG 2 Video Surveillance). We should focus on the most solvable scenarios first. Such solvable scenarios could include ship borne radar and fixed satellite Rx.[16]

T-Mobile. Studies submitted by Working Group 4 [1755-1850 MHz, Point-to-Point Microwave, Tactical Radio Relay (TRR), Joint Tactical Radio System / Software Defined Radio] and 5 [1755-1850 MHz Airborne Operations] in particular remain incomplete and the processes they employed merit further review in order to provide more useful guidance. In particular, the interference analyses produced by these groups are overly conservative, and there was inadequate time to refine the results based on recommendations contained in the Working Group reports. In addition, there was no consideration of operation, frequency planning, or alternative bands that would have laid the foundation for comprehensive recommendations . . . Federal Advisory Committee Act ("FACA") Structure. CSMAC was created under FACA. While the FACA structure and requirements are intended to ensure transparency in the decision-making process, they proved to be an impediment to sharing necessary technical and operational information, based on concerns by the Department of Defense ("DoD") and other Federal agencies that potentially sensitive information would be broadly released. This limited the ability to have fully informed discussions. As a result, NTIA should consider whether there are other structures that might be available that would facilitate more complete access to the relevant data.[17]

The statements above echo current technical, engineering, and related operational concerns about spectrum sharing, including the difficulty of defining and measuring what may constitute harmful interference to either primary or secondary systems, overly conservative assumptions being applied by government systems, either inappropriate or overly simplistic propagation modeling, the potential of exclusion zones being so large as to render spectrum non-useful, and the disparity of the systems under investigation.

[16] Commerce Spectrum Management Advisory Committee, *Spectrum Management via Databases Working Group Interim Report, Version 1.0,* 13 Dec. 2013, 4, http://www.ntia.doc.gov/files/ntia/publications/sswdb_wg_update_ver1.pdf.

[17] T-Mobile, "In the Matter of Meeting to Discuss Lessons Learned from Commerce Spectrum Management Advisory Committee Working Group Process, Comments of T-Mobile USA, Inc.", 6 Dec., 2013, http://www.ntia.doc.gov/files/ntia/publications/comments_of_t-mobile_usa_inc.pdf

Key concerns:

- **Overly conservative assumptions for government systems**
- **Inappropriate or overly simplistic modeling for exclusion zones**
- **Potential of exclusion zones rendering spectrum non-useful**
- **Disparity and multiplicity of government systems**
- **Restricted DoD information hampering industry analysis**
- **Lack of detail about coordination requirements**

Lack of detail at this time about the coordination requirements, particularly for AWS-3, and the possibility that such details may not be resolved until after the auction, could dampen operator enthusiasm for AWS-3 spectrum and undermine auction proceeds.[18]

Confidentiality of government systems has also complicated the modeling process, since it has denied non-governmental stakeholders sufficient information to refine sharing and modeling parameters. A "Trusted Agent" process created through confidentiality agreements among DoD and 12 twelve industry members will potentially help information flow.

The FCC also issued an NPRM for the 3.5 GHz band that anticipates spectrum sharing based on a three-tier model consisting of incumbents, licensed secondary users, and opportunistic users.[19] In January 2014, the FCC conducted a workshop for this band.[20]

As an example of overseas developments, Ofcom in the United Kingdom issued a consultation request in 2013 that focuses on "the role greater spectrum sharing could play in the mobile broadband and M2M

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[18] For a discussion of the effects of spectrum uncertainty, see Rysavy Research, "Uncertain Government Spectrum Policies Have Far-Reaching Consequences ", Nov 2013. http://www.rysavy.com/Articles/2013-11-Uncertainty-Consequences.pdf.

[19] Federal Communications Commission, *FCC 12-148 Amendment of the Commission's Rules with Regard to Commercial Operations in the 3550-3650 MHz Band, Notice of Proposed Rulemaking and Order,* GN Docket No. 12-354, Dec 2012.

[20] FCC, *3.5 GHz Spectrum Access System Workshop*, Jan 2014. https://www.fcc.gov/events/35-ghz-spectrum-access-system-workshop.

sectors."[21] The UK study illustrates that other countries are no further along than the U.S. in implementing sharing.

The European Telecommunications Standards Institute (ETSI) is the leading organization standardizing cognitive radios. The most relevant effort is called Licensed Shared Access (LSA), a two-tier spectrum sharing system that includes incumbents and licensed secondary users that access shared spectrum via a database, as depicted in Figure 1.[22] Although the frequencies currently differ from the ones of interest in the U.S., some of the LSA database mechanisms could potentially be applied to database approaches for spectrum sharing in the U.S. Fully standardizing such an approach for LTE would require additional specification work by 3GPP.

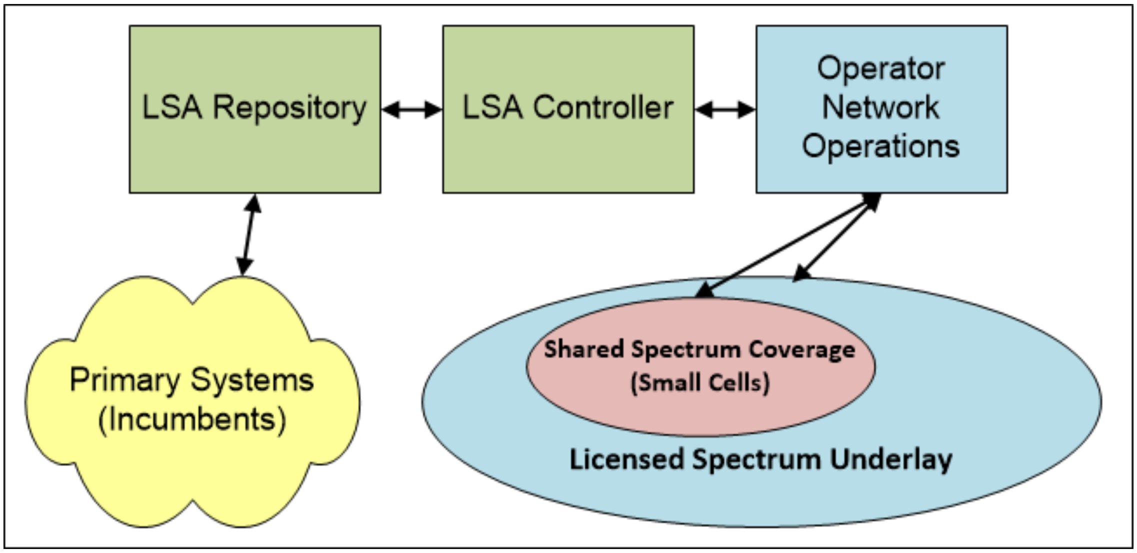

Figure 1: Licensed Shared Access Architecture

The LSA work mirrors the Authorized Shared Access (ASA) architecture developed by Qualcomm, which also uses two tiers.[23]

[21] Ofcom, *The future role of spectrum sharing for mobile and wireless data services - Licensed sharing, Wi-Fi, and dynamic spectrum access*, Aug 2013, http://stakeholders.ofcom.org.uk/consultations/spectrum-sharing/

[22] European Telecommunications Standards Institute, *TR 103 113 v1.1.1 (2013 07) Electromagnetic compatibility and Radio spectrum Matters (ERM); System Reference document; Mobile broadband services in the 2300-2400 MHz frequency band under Licensed Shared Access regime*, Jul 2013, http://www.etsi.org/deliver/etsi_tr/103100_103199/103113/01.01.01_60/tr_103113v010101p.pdf

[23] Qualcomm, *The 1000x Wireless Data Challenge & Small Cells*, http://www.qualcomm.com/1000x (accessed 8 Jan. 2014).

Architecture and Approaches

Government can allocate spectrum for exclusive licensed use, unlicensed use (e.g., Wi-Fi), or shared use, as shown in Figure 2. The current sharing architectures being discussed include opportunistic access (e.g., TV white space), two-tier shared access, or three-tier shared access. PCAST espouses a three-tier model, as does the FCC 3.5 GHz NPRM, while LSA (and ASA) define a two-tier model. The FCC NPRM refers to Tier 2 users as Priority Access and Tier 3 users as General Authorized Access (GAA). AWS-3 sharing will use two tiers. There have also been discussions in the past of opportunistic sharing, in which a device senses when airwaves are not in use and transmits or receives at this time. Opportunistic sharing based on sensing alone has seen limited success and has not been shown to work in a low-power, mobile environment.

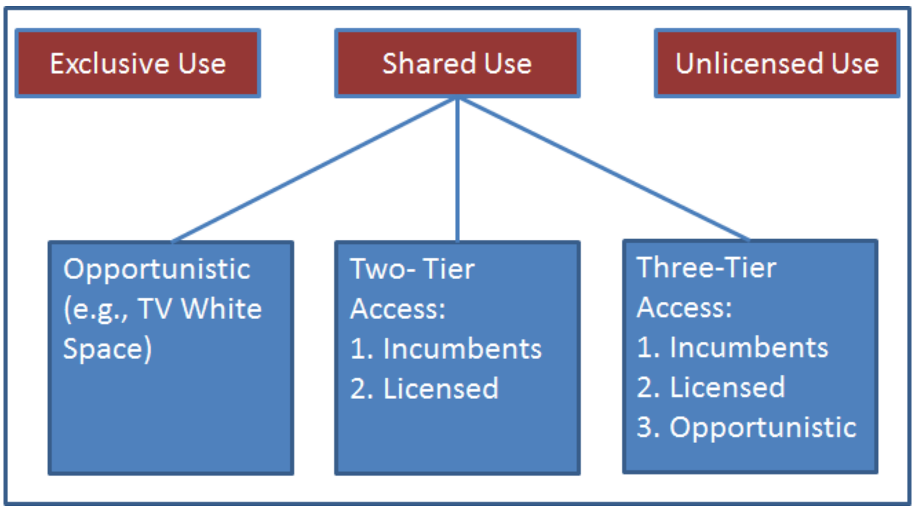

Figure 2: Forms of Spectrum Licensing and Types of Shared Use

Spectrum-sharing schemes range from relatively simple to extremely complex. In the simplest approach, geographic sharing, primary and secondary users are separated by geography. Even this approach, however, is complicated by the need to define exclusion zones and protection zones, which requires signal propagation models, measurements, and determination of signal levels that actually interfere.

Another simple form of sharing is time-based, in which primary and secondary systems agree to use the spectrum at different predetermined times. Dynamic sharing in time, however, introduces significant complexity since it requires a database in which the primary system posts spectrum availability and which the secondary system queries to determine spectrum availability. For 3.5 GHz, the database is an integral component of what the FCC refers to as the "Spectrum Access System." The SAS will be the most complex spectrum management system ever developed in human history. Its complications are detailed in the section below on spectrum-sharing challenges.

Not all military systems have the potential for automation, so interaction with an SAS might, for example, require that flight data be entered to define an exclusion zone around an airborne radar, telemetry, or communications use case and the craft's flight path.

Another potential approach is spectrum sensing, in which a user device radio or network radio senses the environment, or looks for beacons, to determine if spectrum is available for use. Sensing can also be combined with databases. Sensing difficulties include radio receivers attempting to receive dissimilar waveforms and bandwidths, lack of any synchronization, and the problem of identifying nearby receive-only systems that one's own future transmissions may interfere with. No pure sensing approaches are under consideration for current bands, although sensing could be combined with databases to refine propagation models and exclusion zones.

Another potential solution is "out-of-band" beaconing. Under this approach, an incumbent system (for example, a high-power ship-borne air traffic control radar) would use a separate ship-to-shore radio link to self-report its mode of operation, channel use, power level, angle of coverage, and current position back to a secure land network to inform the SAS of spectrum occupancy and region of interference. This approach would allow the exclusion zone to be narrowed down to the current occupancy and avoid the use of non-secured spectrum sensing and the reporting of military operations.

To integrate shared spectrum into a network, a (likely commercial) radio-access network architecture uses licensed spectrum to provide a coverage underlay and shared spectrum as an overlay in a subset of the operator's coverage area to augment coverage. The carrier-aggregation capability in LTE assists with this approach. A further advantage of this approach is that it is independent of whether or not the network interfaces with a spectrum-sharing database. LTE's self-optimizing and self-organizing capabilities may also assist in dynamically aggregating spectrum.

Small cells, already an important element for capacity augmentation, are good candidates for spectrum sharing because their limited coverage areas and low-power transmissions are less likely to receive or transmit interference from/to incumbent systems, thus reducing the size of exclusion zones. In areas less encumbered by incumbent operations, higher power levels and antenna gains may be feasible.

An alternate architecture to the one discussed above is using shared spectrum for backhaul, an approach contemplated for TV white space spectrum, with local access provided by Wi-Fi or LTE.

AWS-3-band spectrum-sharing participants in government and industry are working on the following items:

1. **Protection zones.** Within protected zone areas, sharing will occur through some coordination process that has not yet been defined. The size of a protection zone depends on assumptions

regarding operating parameters. For the 1695-1710 MHz band, the protection zones are based on mobile uplink Effective Isotropic Radiated Power (EIRP). For the 1755-1780 MHz band, the coordination zone currently is nationwide, as NTIA, FCC and industry collaborative efforts have not yet enabled the identification of more discrete coordination areas. Needed interference analysis methodologies are still under development to determine at what locations and at what frequencies multiple operations can co-exist at the same or different times.[24] Protection zones are usually employed to protect variable usage areas, such as flight paths for training missions using a specific airborne system.

2. **Exclusion zones.** Within coverage areas referred to as "exclusion zones," no commercial entity will be able to operate a network. The size of an exclusion zone depends on assumptions, such as mobile uplink transmit power levels. Exclusion zones are usually employed to protect local static incumbent operations, for example, a military training base or fixed government facility. In the recent AWS-3 Report and Order, the FCC does not employ exclusion zones, but work has not been completed regarding the coordination process in the 1755-1780 MHz band.

3. **Transitional sharing.** Within AWS-3 bands, some government systems will vacate the band immediately, while some systems will reside permanently. The rest will be present for an interim period before relocating to other bands, and hence sharing will occur during the transitional phase. One implication is that sharing mechanisms will likely be simpler than for permanent sharing arrangements, which can justify greater investment in sharing methodology.[25]

4. **Occupancy measurements.** Spectrum-sharing participants conducted studies in 2013 to determine to what extent spectrum assigned to different agencies is in use across geographical areas. This information will potentially assist in defining how sharing could occur.[26]

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[24] CSMAC, *Proposed Future CSMAC Work*, Aug 2013, 2, http://www.ntia.doc.gov/files/ntia/publications/new_csmac_work_and_volunteers_130821.pdf.

[25] *CSMAC, Transitional Sharing Working Group – Status Report,* Dec 2013, http://www.ntia.doc.gov/files/ntia/publications/csmac_-_transitional_sharing_working_group_121313.pdf.

[26] CSMAC, *Proposed Future CSMAC Work*, Aug 2013, 3.

The following table shows how different spectrum-sharing attributes apply to AWS-3 and 3.5 GHz.

Table 1: Spectrum-Sharing Attributes

Attributes	**AWS-3**	**3.5 GHz**
Extent of Sharing	Limited, with many government systems on transitional basis	Extensive and permanent. (Incumbents are mostly government radar systems.)
Tiers	Two: Incumbent and licensed secondary	Three: Tier 1 Incumbent, Tier 2 licensed (Priority Access), and Tier 3 opportunistic (General Authorized Access)
Exclusion and protection zones	Protection Zones Adopted	Both anticipated
Databases	Unlikely, with other coordination methods likely	Planned (Spectrum Access System)
Types of Tier 2 users	Cellular operators	Multiple, including cellular operators, wireless ISPs, high-priority users (hospitals, etc.), others
Types of Tier 3 users	None	To be determined, but examples include sharing-enabled Wi-Fi and unlicensed LTE
Uplink and/or downlink in shared bands by non-incumbents	FDD: Uplink only (1755-1780 MHz UL paired with 2155 -2180 MHz DL)	TDD: Uplink and downlink, dissimilar air interfaces, unsynchronized
Sensing	Pure cognitive sensing for access not required by recent FCC Report and Order. Ongoing measurements could refine models but not being actively considered.	Pure cognitive sensing for access not planned. Ongoing measurements could refine models.
Transitional sharing	Expected	Unlikely. Possible phased approach. Possible hybrid band plan.

Spectrum Sharing Challenges

The spectrum-sharing challenges identified by recent investigations and academic research are material and significant—in fact, they are insurmountable in the near term. The only possible way to move forward is to first clear spectrum for exclusive use whenever possible and then limit the number of variables involved in spectrum sharing. Specifically, concentrate on only a small number of bands, limit the number of systems co-existing, develop a framework that can begin simply and expand in complexity over time, and develop roadmaps and timeframes that allow for further development as the science evolves.

Challenges span maturity, modeling, frequency management, disparate secondary users, unclear use of cognitive sensing, database development, cost of dynamic radios and front-end filters, and security.

Lack of Maturity

Being so new and unproven, spectrum sharing makes both primary users and secondary users cautious, and both have to make sure their interests are fully represented. For the types of systems under evaluation for sharing, efforts currently are at the simulation and thought-experiment stage, to be followed by testing and ultimately deployment. Anticipating the actual problems that may materialize is difficult, if not impossible.

Confidence over the forthcoming decade will slowly increase, with evaluations and trials of new types of spectrum management systems involving different primary and secondary users. Currently, academia, government, and industry are still assessing the various forms of architecture that could be employed, including the best balance of sensing and databases, as well as unsupervised versus centrally supervised versus decentralized supervisory systems. One architecture may ultimately prevail, or multiple architectures might exist based on scenario requirements.

Until spectrum sharing matures, industry will be reluctant to invest heavily in unproven approaches that may change or be abandoned. The situation argues for incremental developments with well-defined constraints and objectives.

Multiplicity of Government Systems

Determining the ability of a government system to share spectrum requires an analysis of multiple factors, including the susceptibility of the government system to interference and the propagation of its radio signals. Of concern to industry is the number of different government systems to analyze.

For example, four separate working groups within CSMAC began the initial evaluation of the 1775-1780 MHz band in 2013 to analyze the following systems: law enforcement, explosive disposal, short-distance links, satellite control, electronic warfare, point-to-point microwave, tactical radio relay, joint tactical radio systems, software-defined radio, airborne operations, small unmanned aircraft systems, precision-guided munitions, and aeronautical mobile telemetry.[27]

SAS Definition and Complexities (3.5 GHz)

Architectures, concepts, and implementation details for performing the SAS management function need a great deal of definition and work to address:

- algorithms and methods
- methods of nesting hierarchical SAS entities (federal secure SAS versus commercial SASs)
- coordination among multiple, competing commercial SAS managing entities
- interface definitions
- communication protocol definitions
- database and protocol security
- policy enforcement
- speed of channel allocation/reallocation
- time intervals for spectrum allocation
- effectively managing large numbers of Tier 3 GAA users
- data ownership, fees, rules, fairness, and conflict resolutions, all of which have policy, regulatory, and business implications

TVWS databases available today address only a tiny subset of these requirements.

Propagation Modeling Complexities

Radio propagation models play a crucial role by determining spectral reuse factors and interference maps. Industry and government are using multiple models and have not yet agreed on what type of model is appropriate for each sharing scenario. For example, differences exist between Longley-Rice models that assume line-of-sight propagation and Hata models that better account for near-the-ground clutter. Appropriate models have not yet been developed for small cells that operate at lower power with low antenna heights.

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[27] [6] Commerce Spectrum Management Advisory Committee, Working Group 2, *1755-1850 MHz Law Enforcement Surveillance, Explosive Ordnance Disposal, and other short distance links*, 2013. Working Group 3, *Report on 1755-1850 MHz Satellite Control and Electronic Warfare*, 2013. Working Group 4, *1755-1850 MHz Point-to-Point Microwave Tactical Radio Relay (TRR) Joint Tactical Radio System / Software Defined Radio (JTRS/SDR)*, 2013. Working Group 5, *1755-1850 MHz Airborne Operations (Air Combat Training System, Small Unmanned Aircraft Systems, Precision-Guided Munitions, Aeronautical Mobile Telemetry)*, 2013.

Furthermore, models incorporate multiple parameters and assumptions, which have not yet been fully defined or agreed upon.

Initial government assumptions that are overly conservative have produced extremely large exclusion zones. For example, the suggested value of I/N of -6 to -10 dB assumes that incumbent systems have no tolerance for interference.

In addition, industry and government do not currently agree on appropriate measures, such as I/N versus alternate approaches. For example, CSMAC states in a report:

> Consideration of different interference threshold based on the desired signal to noise plus interference level desired rather than defining interference as a rise in the noise floor. . . While there is no desire to modify the internationally accepted criterion, the wireless industry believes that the study of interference relative to a desired carrier taking into account actual system operations would be beneficial to understand how government and LTE systems would interact in a shared environment with close coordination between users, and believe that could significantly reduce required separation distances.[28]

Frequency Management

The FCC has expressed a desire in its NRPM to freely allocate all channels across the whole band without sub-block specific channel sets per user or user type.[29] This requirement will require all radios to tune to the whole band. Because there are no front-end filters to eliminate cross-user or cross-user-type interference, this approach relies on a database system, as yet undefined, for channel use security and interference protection.

This wideband approach also raises concerns about front-end overload, consequent damage, as well as small-signal-blocking effects (from adjacent and other channel interference), thus limiting performance. In sharing scenarios with disparate power levels and lack of synchronization, these concerns place the entire coordination burden on the SAS manager.

Disparate Secondary Users and Differing Use Cases

The technical and commercial communities are concerned about the different types of secondary users of spectrum that may emerge. For example, both LTE and wireless Internet service providers might wish to be secondary spectrum users, each with different antenna gains, power levels, and types of channels. Other Tier 2 use cases include sectorized cells, point-to-point communications,

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[28] Working Group 5, *1755-1850 MHz Airborne Operations (Air Combat Training System, Small Unmanned Aircraft Systems, Precision-Guided Munitions, Aeronautical Mobile Telemetry)*, 2013, 8.

[29] Federal Communications Commission, *FCC 12-148 Amendment of the Commission's Rules with Regard to Commercial Operations in the 3550-3650 MHz Band, Notice of Proposed Rulemaking and Order,* GN Docket No. 12-354, Dec 2012. Paragraph 76.

and non-line-of-sight backhaul. Commercial entities will not only have to learn how to share spectrum with government systems, but with one another.

Two-tier sharing approaches (e.g., Licensed Shared Access) limits the number of potential scenarios, but three-tier sharing (e.g., PCAST) expands sharing to unlicensed systems, which could interfere with licensed secondary systems in unpredictable ways, expanding development time for centralized control mechanisms and security measures. Use of a third tier requires the SAS manager to play a much more active role when no intermediate radio network controller systems are present.

Unclear Role of Spectrum Sensing

Traditionally, cognitive sensing has referred to networks dynamically measuring the spectrum environment and choosing clear frequency bands, sometimes called dynamic spectrum access (DSA). While pure sensing approaches have been dismissed as insufficiently reliable to protect incumbent systems, sensing combined with databases can provide closed-loop feedback to propagation models, resulting in more efficient systems with tighter frequency reuse. For example, if an LTE network informed the database of its measurements of incumbent systems, the database could adjust its parameters and modify the size of exclusion zones.

A closed-loop approach, however, is inherently more complex, requiring more upfront planning and additional requirements for both second- and third-tier hardware devices. In contrast, open-loop approaches without sensing are simpler but result in less efficient, rigid frameworks that will be difficult to modify in the future.

Industry and government are far from knowing or agreeing on how best to employ sensing.

Database Security

Database attacks include malicious corruption of the database, intrusion to obtain sensitive information about primary users, or even threats to the privacy of primary users by queries to the database that can reveal the types and locations of incumbent systems. Database vulnerabilities further include systems masquerading as others, impersonation of the database, and modification or jamming of either queries to the database or responses from the database.

Sharing Security

Potential threats to systems employing spectrum sharing are numerous and perhaps not sufficiently appreciated.[30] Malicious attacks, or even broken systems, can threaten both spectrum-sensing mechanisms and databases.

In the past, front-end filtering restricted operation to commercial bands, preventing devices or networks from operating in government radio bands. With spectrum sharing, compromised devices,

[30] For example, see Rysavy Research, "Spectrum Sharing Opens a Potential Attack Route," *GigaOM*, Oct. 2013, http://gigaom.com/2012/10/13/spectrum-sharing-opens-a-potential-attack-route/

compromised secondary networks, or compromised databases can breach privacy or deny service to both primary and secondary systems.

Spectrum sensing relies on valid information about who is using the spectrum, especially if this information is distributed among nodes. The system is therefore vulnerable to data falsification. Attacks can include rogue devices that emulate a primary user to hijack spectrum, corrupt control channels, falsified beacons used to coordinate channels or that do not comply with defined back-off windows.

Three-tier systems further complicate security since they enable more independent devices, which are "less-controlled," to operate opportunistically. Attacks on third-tier systems could threaten both licensed secondary users and primary users.

New Enforcement Mechanisms

Previously, use of specific-band pass filters in hardware effectively implemented spectrum rules, but spectrum-sharing networks and devices will access more spectrum in more flexible ways than ever before. Monitoring mechanisms and enforcement of rules and policies will require methods that are largely unknown at this time.

Recommendations

This paper makes the following recommendations.

With respect to sharing scenarios where most government users will be relocated but some will remain and share the band with non-federal users (e.g., in the AWS-3 band):

1. Government needs to use reasonable interference assumptions. Overly conservative DoD planning could result in so little available coverage that the spectrum has little commercial value, threatening the success of this year's auction.
2. Industry and government need to agree on realistic propagation models.
3. Industry and government should take advantage of the trusted-agent process to increase information flow from DoD to industry so industry can better innovate on sharing solutions.
4. Government should vacate as many systems as possible from AWS-3 bands and should adopt simple sharing and coordination approaches, particularly in the AWS-3 context, since so little time exists between now and the auction and so many sharing questions still exist.

With respect to sharing scenarios that will be managed by a combination of coordination/protection zones and dynamic access technologies (e.g., as contemplated in the 3.5 GHz band):

1. Ongoing measurements should be considered to progressively refine models and protection zones.

2. Geographic protection zones should protect incumbent users rather than new entrants. Industry is in the best position to design networks to withstand interference from incumbent systems.
3. The network cells of priority users (called Tier 2 in the case of the 3.5 GHz band), who have priority over general-access users, should inform the managing SAS of their spectrum parameters, but the SAS itself should not exercise direct control over the networks, such as controlling transmit power levels.
4. To minimize the size of protection zones, the SAS rules base should assume the appropriate use case scenarios to protect against co-channel interference. Small-cell deployment scenarios can be used near incumbent systems where interference is an ongoing threat, for example in coastal areas.
5. For spectrum bands that will allow both priority-access and general-access use, the service rules should segment spectrum to minimize the possibility of general-access users (called Tier 3 GAA users in the case of the 3.5 GHz band) interfering with users that have priority (called Tier 2 PAL service providers in the 3.5 GHz context). A hybrid approach could have one segment with tiers 1 and 2, a second segment with tiers 1-3, and a third tier with just tiers 1 and 3.[31] The hybrid band plan can allow for migration over time in a phased approach.
6. Because LTE networks require complex frequency-specific tuning, spectrum allocations should be assigned to priority (or Tier 2) service providers on a longer-term (non-varying) basis. The precise channel assignment can vary, but actual access to spectrum should not be on a fast, dynamic basis as might be the case for general access, or Tier 3 GAA, systems.
7. 3GPP is considering specifying a version of LTE for unlicensed operation. Rules should accommodate this version of LTE.
8. Specifically with respect to the 3.5 GHz band, alternative uses cases should have allowances for Tier 2 uses above +24 dBm power levels, above + 6 dBi antenna gains, and above +30 dBm EIRP net power levels to accommodate other outdoor uses. These criteria will unnecessarily restrict all use cases to very small coverage areas.
9. Also specifically with respect to the 3.5 GHz band, uses should not be restricted to interference levels as high as 40 dB IoT (interference over thermal noise levels), as this criteria will unnecessarily restrict all use cases to very small coverage areas.

Spectrum sharing will be successful only to the extent that all stakeholders—including government, commercial providers, and the technical community—are motivated and have appropriate incentives to

[31] For example, Verizon, *Hybrid Band Plan*, Jan 2014. http://wireless.fcc.gov/workshops/sas_01-14-2014/panel-2/Shamsunder-Verizon.pdf.

share spectrum. Success will also depend on whether these stakeholders can agree on a realistic path forward. Limiting the scope of sharing while establishing achievable and definable milestones in these initial stages will both simplify what inevitably will be a multi-year development process and increase the likelihood of its ultimate success. Contrarily, establishing unrealistic goals or imposing overreaching mandates at these early stages of the development process risks slowing and adversely affecting our progress towards sustainable and industrially scalable sharing solutions, which all agree is an important component of our overall multi-part strategy of addressing the nation's spectrum challenges.

About Rysavy Research

Peter Rysavy is the president of Rysavy Research LLC, a consulting firm that has specialized in wireless technology since 1993. Projects include analysis of spectrum requirements for mobile broadband, reports on the evolution of wireless technology, evaluation of wireless technology capabilities, strategic consultations, system design, articles, courses and webcasts, network performance measurement, test reports, and acting as expert in patent-litigation cases. Clients include more than 75 organizations.

Peter is a broadly published expert on the capabilities and evolution of wireless technology. He has written more than 150 articles, reports, and white papers, and has taught more than 40 public wireless courses and webcasts. He has also performed technical evaluations of many wireless technologies including cellular-data services, municipal/mesh Wi-Fi networks, Wi-Fi hotspot networks, mobile browser technologies, wireless e-mail systems, and social networking applications.

From 1988 to 1993, Peter was vice-president of engineering and technology at Traveling Software (later renamed LapLink) where projects included LapLink, LapLink Wireless, and connectivity solutions for a wide variety of mobile platforms. Prior to Traveling Software, he spent seven years at Fluke Corporation where he worked on data-acquisition products and touch-screen technology.

Peter is also the executive director of the Portable Computer and Communications Association (PCCA, http://www.pcca.org), an industry organization that evaluates wireless technologies, investigates mobile communications architectures, and promotes wireless-data interoperability. Peter Rysavy graduated with BSEE and MSEE degrees from Stanford University in 1979. More information is available at http://www.rysavy.com.

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