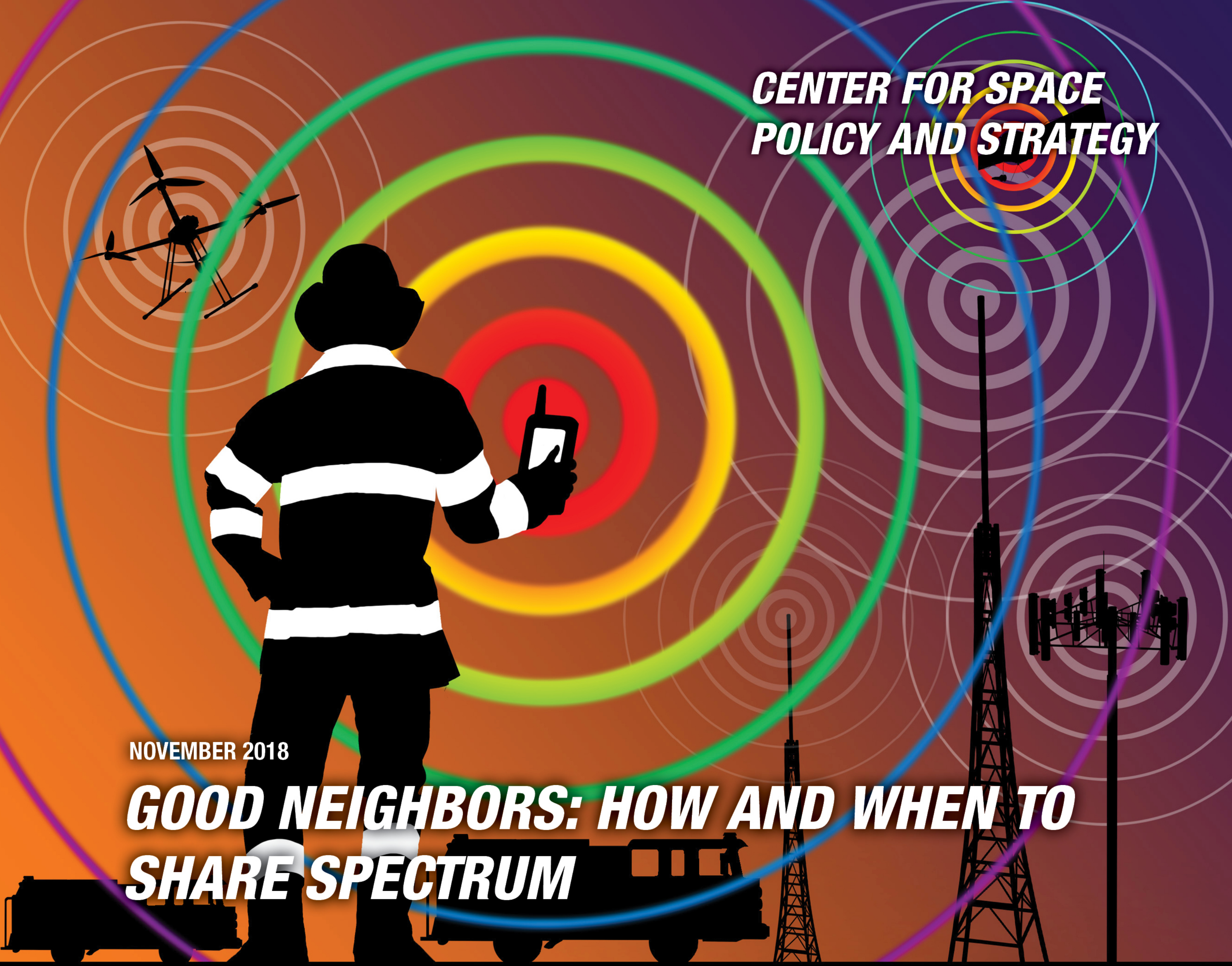


CENTER FOR SPACE POLICY AND STRATEGY

NOVEMBER 2018

GOOD NEIGHBORS: HOW AND WHEN TO SHARE SPECTRUM

MATTHEW A. CLARK
THE AEROSPACE CORPORATION

AEROSPACE

MATTHEW A. CLARK

Matthew A. Clark is an engineering specialist with The Aerospace Corporation's Communication Architectures Department, specializing in communication systems engineering, radio frequency interference analysis, and spectrum regulations and policy. He received his Ph.D. in electrical engineering from the University of Southern California, where his research and dissertation focused on optimizing performance and privacy in spectrum-sharing systems.

ABOUT THE CENTER FOR SPACE POLICY AND STRATEGY

The Center for Space Policy and Strategy is dedicated to shaping the future by providing nonpartisan research and strategic analysis to decisionmakers. The Center is part of The Aerospace Corporation, a nonprofit organization that advises the government on complex space enterprise and systems engineering problems.

Contact us at www.aerospace.org/policy or policy@aero.org

AEROSPACE

Summary

The dramatic growth of wireless technologies, including smartphones, tablets, the internet of things, smart cities, and autonomous vehicles, is undoubtedly changing our lives. Wireless technologies are estimated to have contributed $475 billion to the U.S. economy in 2016,[1] and continued development is expected to improve our quality of life and play a strong role in maintaining U.S. technological and economic leadership. Radio frequency (RF) spectrum is the lifeblood of all wireless systems. As highlighted in the 2018 "Presidential Memorandum on Developing a Sustainable Spectrum Strategy for America's Future,"[2] spectrum sharing is a critical means for providing efficient access for new wireless technologies. Stakeholders are applying and evolving a range of spectrum-sharing techniques today. The choice of spectrum-sharing methods will influence the likelihood of harmful interference, the availability of spectrum for new systems, and the degree to which potentially private user information may be exposed. Spectrum sharing can introduce complex interactions between systems that make these issues difficult to analyze. Today's policy decisions on spectrum sharing will drive investment and development, having lasting impacts on wireless infrastructure. This paper examines a range of spectrum sharing options and the issues that should be considered by both wireless system operators and spectrum regulators when contemplating spectrum policies to maximize the utility of spectrum for the public good.

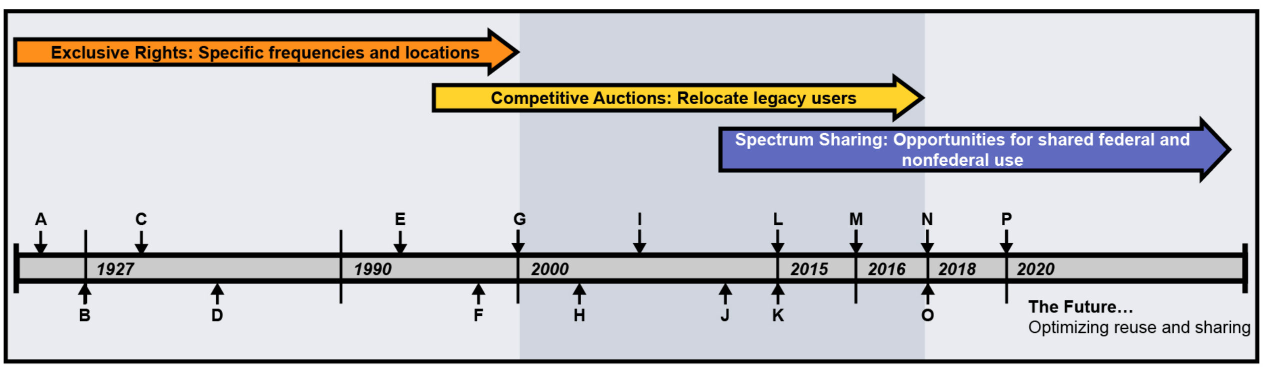
Introduction

Since the rise of Wi-Fi and the smartphone, consumers have demonstrated an insatiable demand for new mobile wireless technology. This trend shows no sign of slowing, with burgeoning industries in smart-homes, smart-grids, connected cars, satellite networks, and 5G cellular technologies.[3,4,5] Demand for connectivity anytime and anywhere comes with a corresponding demand for increased access to the radio frequency (RF) spectrum, where more bandwidth translates to more wireless connections and faster speeds.

Getting access to new RF bandwidth is no easy task. Nearly all the RF spectrum useful for mobile wireless is already occupied by a myriad of existing systems that are providing vital services, such as air traffic control, weather forecasting, GPS, remote news feeds, broadcasting, and national defense. In the past, a range of radio frequencies, also called a band, could be cleared of incumbent users and reallocated for exclusive use by new technologies. Now, much of the low-hanging fruit has been plucked, and clearing incumbents is proving increasingly difficult, as noted by the National Telecommunications and Information Administration (NTIA), the U.S. regulator of federal spectrum use.[6]

> ***"It is clear that we can't meet the challenges that arise from this increased demand by using the traditional methods of spectrum reallocation, which often take too long and cost too much money.... The answer is spectrum sharing, a flexible and evolving option that is helping to optimize this resource to the benefit of both the public and private sectors."***
>
> — Paige Atkins
> Associate Administrator of the
> NTIA Office of Spectrum Management

Spectrum sharing describes any approach enabling multiple systems to use the same RF spectrum. The challenge is that different systems may interfere with each other. If a person with a cell phone stands near a sensitive receiver intended to detect signals from satellites, the cell phone signal will be strong at the satellite receiver due to proximity, while the satellite signals, which are traveling a much greater distance, will be relatively weak. If the cell phone and satellite signals are operating in very different RF bands, frequency filters may prevent the stronger cell phone signal from affecting the satellite receiver. However, if cell phone and satellite signals are in the same or adjacent frequency bands, filters may be ineffective, and the relatively strong cell phone signals may prevent the detection of the satellite signals. This is analogous to someone talking into your ear while you are attempting to listen to someone speak from across the room.



Milestone Legend

A – **Radio Act of 1912:** First U.S. spectrum legislation, gives Secretary of Commerce responsibility to regulate spectrum (1912)

B – **Radio Act of 1927:** Federal radio commission established to regulate nonfederal spectrum use in response to broadcasting interference (1927)

C – **Communications Act of 1934:** Federal Communications Commission formed (1934)

D – **National Telecommunications and Information Administration:** Formed in 1978 to combine responsibilities for regulation of federal spectrum use (1978)

E – **Omnibus Reconciliation Act of 1993:** Included reallocation of 135 MHz of spectrum. Gave FCC authority to auction spectrum, leading to the first auction in 1994 (1993)

F – **Strom Thurmond National Defense Authorization Act of 1998:** Federal agencies that relocate or make modifications to accommodate spectrum reallocation are to be compensated for costs incurred (1998)

G – **National Defense Authorization Act of 2000:** Federal spectrum may be reallocated only if full capability of federal systems can be retained (2000)

H – **Spectrum Relocation Fund (SRF):** Created by Commercial Spectrum Enhancement Act of 2004 to streamline relocation of federal systems in anticipation of auctions supporting 3G (2004)

I – **AWS-1 Auction of 2006:** Reallocates 90 MHz of spectrum to support 3G cellular (2006)

J – **PCAST Report of 2012:** Assesses reallocation of spectrum for exclusive use as unsustainable; new access to spectrum will require spectrum sharing (2012)

K – **Spectrum Pipeline Act of 2015:** Identifies 130 MHz of spectrum for reallocation and makes the SRF more flexible (2015)

L – **AWS-3 Auction of 2015:** Reallocates 65 MHz of spectrum to support 4G cellular (2015)

M – **Spectrum Frontiers:** FCC proceeding targeting spectrum above 24 GHz for reallocation to support 5G (2016)

N – **Spectrum Now:** Would make SRF more flexible to support R&D (2018)

O – **Mobile Now:** Largely included in FY 2018 omnibus, identifies 255 MHz of spectrum for reallocation (2018)

P – **5G:** Initial deployments expected (2020)

Figure 1: One hundred ten years of U.S. spectrum policy development. Initially starting with command control (exclusive rights), progressing to market-based management (auctions and secondary markets) and, more recently, to innovative options for spectrum sharing.

Spectrum Policy—From Ease of Use and Exclusive Rights to Efficient Use and Sharing

President Trump issued a presidential memorandum to the heads of executive departments and agencies in October 2018, directing the creation of a National Spectrum Strategy[2]. Through sharing and flexible spectrum management, the memo calls for efficient and effective spectrum use to achieve "economic, national security, science, safety, and other federal mission goals." To better understand where policy can enable increasingly effective spectrum use, it is helpful to review the issues that motivated our existing spectrum policies. A timeline of U.S. spectrum policy development is illustrated in Figure 1.

Foundation of National Spectrum Regulations—The Radio and Communications Acts

Spectrum policy has its roots in maritime safety. After a shore station radio operator famously refused to accept a message from Prince Henry of Prussia during his visit to the U.S. in 1902, the German government organized a preliminary radio conference in 1903 to discuss the prospect of international radio regulation.[10] The first International Radiotelegraph Conference followed in 1906, proposing regulations for ship-to-ship and ship-to-shore radio interoperability and establishing the foundation of today's international regulatory structure. Passed in part due to the sinking of the RMS Titanic earlier that year, the Radio Act of 1912 adopted the International Radiotelegraph Conference proposal for radio interoperability and assigned regulatory authority to the Secretary of Commerce.

RF spectrum was lightly used, and interference between RF systems wasn't addressed until the Radio Act of 1927, which initiated regulation of nonfederal use of RF spectrum to curb interference caused by the emergence of unlicensed radio broadcasting. This responsibility to regulate nonfederal spectrum use was brought under the Federal Communications Commission (FCC) with its formation by the Communications Act of 1934.

Spectrum Sharing Between Satellite and Mobile Wireless Services

The FCC Advanced Wireless Service 3 (AWS-3) auction in 2015 made available 65 MHz of spectrum to cellular operators, raising over $41 billion.[7], New cellular operators will share the spectrum with incumbent federal systems indefinitely. These federal systems include meteorological satellites downlinking weather data to fixed receive sites and Department of Defense earth stations commanding satellites. By analyzing the likelihood of interference, joint federal and industry working groups defined geographic areas around these fixed sites where interference is most likely to impact either the cellular systems or federal satellite Earth station receivers.[8],[9] Cellular operators could account for these restrictions in their business plans, leading to the auction's success.

Cellular systems are now being implemented in this band, but several challenges remain. Perhaps chief among them is that, the geographic boundaries are only estimates. The strength of the interfering signals cannot be predicted precisely due in part to the effects of terrain and obstacles on RF signals. Similarly, the aggregate effect of many cell phones operating simultaneously introduces uncertainty due to continually varying numbers of users and their behavior. For federal Earth station receivers, this uncertainty results in conservative protection zones spanning tens of kilometers in radius. A protection zone around a meteorological site in Florida, for example, overlaps most of Miami, an important commercial market. What interference mechanisms will be effective in allowing cellular operators to access these areas remains an open question.

Regulation of federal use of spectrum remained the responsibility of the White House with support from the Department of Commerce, eventually transferring to the NTIA with its formation by executive order in 1978.

Spectrum Allocations and Exclusive Rights

After 1927, both U.S. and international spectrum regulations came to rely heavily on spectrum allocations and exclusive licensing. Spectrum allocations designate a band of radio frequencies to one or more services that describe a general type of RF use. For example, a band allocated to the "Mobile" service may be suitable for a cellular network, while a band allocated to the "Fixed Satellite Service" might be suitable for use by a commercial communications satellite network. Bands were allocated based on the needs of the radios at the time and also on the potential for a radio in one service to interfere with radios of other services already allocated in the same or adjacent bands. Regulators then licensed individual operators on a first-come, first-served basis, typically granting them exclusive rights to use the spectrum in a portion of an allocated band over a well-defined geographical area. This approach enabled regulators and operators to minimize interference without much ongoing effort.

Congested Spectrum, Efficiency Considerations, and Auctions

By the 1970s, some desirable spectrum bands became congested, with all licenses having been awarded. Considering that some licenses were lightly or never used, prospective users pressured regulators to modify their processes and make this underutilized spectrum available to other users. The FCC and international community experimented with methods to award spectrum to operators that would make the most use of it and to encourage efficient use by licensees already holding spectrum. The Omnibus Reconciliation Act of 1993 included legislation requiring that the FCC reallocate 135 MHz of spectrum and granted the FCC authority to award that spectrum by way of an auction. This enabled the FCC to oversee, in 1994, the first auction for spectrum, which appeared to be a promising way to reallocate spectrum for efficient use. After several subsequent auctions affected federal access to spectrum, the National Defense Authorization Acts of 1998 and 2000 placed restrictions on FCC reallocation of spectrum. These restrictions required the following: that federal agencies be funded for costs incurred to relocate or modify their systems to support the reallocation, and that reallocation should be pursued only if the full capability of federal systems could be sustained, e.g., through access to other spectrum bands. In 2004, the Commercial Spectrum Enhancement Act (CSEA) established the Spectrum Reallocation Fund (SRF) to streamline funding for relocation of federal systems by leveraging proceeds from auctions.

Spectrum Reallocation and Sharing

In 2009, faced with an explosion in consumer demand for commercial mobile wireless services driven largely by the emergence of the smartphone, the FCC published a National Broadband Plan.[11] This publication warned of an impending "spectrum crunch" where the demand would exceed the supply that could be supported by existing spectrum and technologies and therefore called for reallocation of 500 MHz of spectrum. In 2010, the Obama administration issued an executive memorandum, directing the NTIA and the federal agencies to work with the FCC to find this 500 MHz of spectrum and make it available for broadband mobile wireless use.[12] Initial investigations assumed that the bands should be cleared of incumbent use and auctioned to mobile wireless operators for exclusive use, but NTIA-led studies concluded that such efforts would be costly, time consuming, and would require the reallocation of additional spectrum to federal users for the relocation of affected systems. The cost to federal incumbent operators for reallocation of one band of interest was estimated to be $18 billion. Reallocation would also require 10 years to relocate most of the systems and would require new federal access to two spectrum bands.[13] In a 2012 report, the President's Council of Advisors on Science and Technology (PCAST) described clearing and reallocating spectrum bands for auction, the approach of the prior two decades, as unsustainable, where reallocation should be expected to grow increasingly difficult.[14] Instead, PCAST advocated for increased spectrum sharing, leveraging enhanced sharing technologies and systems to maximize spectrum efficiency and provide sustainable access to spectrum for present and future services.

Ever since the PCAST report was issued, sharing has played an increasing role in spectrum policy. The Obama administration issued another memorandum directing federal agencies to support reallocation and sharing[15]. The CSEA was amended in 2015 to allow the reimbursement of Federal agencies from the SRF for costs associated with sharing. The FCC auction of AWS-3 bands in 2015 relied on expectations of successful sharing between incumbent federal systems and new mobile wireless operations. Subsequent legislation and FCC proceedings have also leveraged spectrum sharing to open spectrum bands and, in some cases, call for new sophisticated spectrum-sharing technologies. The implementation of these policies is underway, and it will be years before the full effects are realized due to the long timelines involved with spectrum reallocation, spectrum assignment, hardware development, infrastructure deployment, and consumer adoption of new devices.

The recent Trump administration memo rescinds the two previous memos from the Obama administration, removing the specific reallocation targets. It states the policy of the United States is to use spectrum as efficiently and effectively as possible, calling for "a balanced, forward-looking, flexible, and sustainable approach to spectrum management," and highlights spectrum sharing as a key enabler of efficient and effective spectrum use. It calls for the creation of a National Spectrum Strategy, which will need to account for both the potential enhancements and practical limitations of spectrum sharing.

Spectrum Sharing Methods

Two or more RF systems may effectively share spectrum by separating operations in frequency, time or space. Before examining the potential advantages and challenges involved with any given spectrum-sharing solution, we loosely organize spectrum-sharing methods into one of three categories: geographic separation, cognitive radios, and centralized sharing.

Geographic Separation

Pre-established boundaries may ensure that systems are geographically separated enough to avoid interference. In the satellite and cell phone sharing example, if cell phones maintain a sufficient distance from the satellite receiver, the interference will be weak enough that the satellite signals can still be successfully detected.

Policy for sharing via geographic separation is well established with many precedents over several decades. Federal agencies have long relied on geographic separation, where agencies register the use of their systems and coordinate new uses with one another. Geographic separation is typically accompanied by technical constraints on the systems; e.g., limits on maximum transmission power to ensure separation distances are sufficient to avoid interference. Other techniques may be employed to reduce the geographic separation required, such as antenna beamforming and spread spectrum.

Static geographic separation may be relatively inefficient if systems use spectrum intermittently, and it may not be effective at all if the location of interference victims cannot be known in advance. For example, if satellite receivers are mobile and may operate anywhere in the country, it will be impossible to predefine geographic separation, but other sharing methods may be viable.

Cognitive Radios

Flexible and efficient use of RF spectrum may be achieved by cognitive radios that can sense the RF environment, detect the operation of other systems nearby, and adjust their own operation to avoid interference. The word "cognitive" also implies an ability to learn from the history of the sensed RF environment and make more effective decisions and predictions[16]; e.g., via artificial intelligence. Simpler variations have been put into practice, such as dynamic frequency selection employed by some Wi-Fi devices, where systems apply predefined detection thresholds to determine occupancy of an RF channel and switch to an available one.

While dynamic frequency selection has seen limited success, exploiting the full potential of cognitive radios is challenging under the existing regulatory command and control structure. This is in large part due to the manual process used to deconflict wireless systems. Incumbent operators may have experience determining whether a specific system with fixed technical parameters is compatible with their own system, but they typically will not be prepared to assess a wide range of operating modes that may be possible with a cognitive radio. Similarly, spectrum regulators may lack the tools to effectively certify a cognitive radio's ability to avoid interference across a full scope of real-world operating conditions. As a result, spectrum policies and regulations often treat cognitive radios no differently than they treat classical radios, and getting access to enough spectrum to make a cognitive radio viable may be prohibitively cumbersome.

In some spectrum-sharing cases, cognitive radios may still be ineffective, particularly in cases where receivers are not reliably detectable.[17] In the satellite receiver example, if the receiver does not also transmit back to the satellite (e.g., because it is receiving a weak broadcast signal from the satellite), it may be completely impractical to detect that receiver from a cellular device or base station.

Centralized Sharing

Wireless devices may interface directly with a centralized sharing system that leverages a variety of information sources to identify available spectrum on the fly.[14] Centralized RF sensing and user data collected via direct interfaces can theoretically enable very efficient use of the spectrum while also mitigating the detection reliability challenges associated with device-centric cognitive radio approaches to sharing.

Recent efforts have established a baseline of spectrum policies and regulations supporting centralized sharing techniques based on simple databases. Stakeholders are continuing to develop these policies to support increasingly dynamic and capable centralized systems. New cloud-based architectures may provide access to RF spectrum with an unprecedented level of efficiency, robustness, and flexibility. However, developing sufficient requirements and certifying the effectiveness of the systems may present substantial challenges and an arduous process for implementing centralized sharing systems in any given spectrum band.

Depending on the systems involved, implementing effective sharing will vary in cost and complexity. In some cases, the implementation cost may outweigh the benefit of the sharing. For example, a centralized sharing system may make it theoretically feasible to share with a band heavily used by non-transmitting receivers. However, the heavy use by the legacy receivers may still limit how much and how often the new systems can access the shared band. The cost of building an interface and tracking the receivers may be far greater than the value of the spectrum to the operators of these new systems.

Evaluating Spectrum-Sharing Systems

For any spectrum-sharing scenario, the best approach will depend on the needs and functions of all systems involved. Centralized sharing systems, cognitive radios, sensing components, geographic

Device Centric Example: Spectrum Sensing and Dynamic Frequency Selection

Spectrum may be shared by devices that sense the local RF environment and dynamically select a frequency channel that does not appear to be in use. Wi-Fi devices effectively share spectrum this way, listening to the RF channel before transmitting and backing off if another transmitting signal is detected.

Regulators have applied this approach with the intent of allowing access for Wi-Fi-like devices in bands where spectrum must be shared with legacy users susceptible to interference. The FAA has tolerated many interference incidents in recent years as a result.[18] In principle, the new devices should be able to detect the presence of FAA Terminal Doppler Weather Radars (TDWRs), which provide measurements of weather hazards around airports, and select a different frequency to avoid interference. In practice, operator error, insufficient certification testing, and relocation of devices have all resulted in devices not behaving as intended and causing harmful interference to the TDWR. Since TDWRs were not designed for this kind of an environment, they cannot recover from the interference, and the radar measurements are therefore either degraded or lost. Resolving these interference incidents remains an ongoing enforcement problem, which highlights a policy challenge for spectrum-sharing scenarios that rely on individual operators and devices to share effectively.

boundaries, technical constraints, and direct communication between systems may all prove to be effective mechanisms for sharing different spectrum bands. A system operator should seek a cost-effective sharing method that satisfies their needs. A spectrum regulator will need to both identify which kinds of systems are well suited to share spectrum and which sharing method will be most effective for those systems.

Designing a sharing system can be a daunting task. Details of the sharing system will affect how often users suffer from harmful interference, how much spectrum is made available, the security and privacy of users, whether the rules of the sharing system are enforceable, and the overall cost and complexity of implementing the sharing mechanisms. Complex interactions between multiple systems make rigorous analysis of these issues challenging and can introduce unintended consequences if not handled carefully. Many factors introduce uncertainty that complicate this problem for both wireless system operators and spectrum regulators.

Harmful Interference to Incumbent Systems

When considering spectrum sharing, the incumbent spectrum user's primary concern is typically whether system performance will be acceptable or if the spectrum-sharing system will result in harmful interference. Harmful interference is inherently subjective. All systems receive some interference all the time. Many system operators will also tolerate occasional instances of high interference if those instances are negligible relative to other factors limiting their system's availability. How much interference is harmful may ultimately require detailed studies of user experiences under varying interference conditions. Complex analysis, simulation, and procurement of expensive testbeds may be necessary.

Conducting these kinds of studies for all possible sharing scenarios would be impossible. Instead, establishing conservative interference thresholds may be more practical. If a new user can meet these thresholds, the incumbent user can be assured that the resulting interference will not be harmful. In this case, further analysis required to implement sharing may be minimal. Other complications, however, may need to be considered, such as apportionment of interference, where multiple users may comply with the threshold individually but produce harmful interference in aggregate. Both new and incumbent operators should view conservative thresholds as useful starting points to keep analysis tractable. If sharing does not appear to be feasible under these thresholds, operators may need to refine their assumptions and analyses.

Determination of harmful interference thresholds should account for performance of critical receiver components, including antenna gain patterns, RF filtering, and susceptibility of the receiver to overload and damage. Harmful interference will also depend on the received strength of the desired signal. Strong reception of the desired signal may mean the system has significant margin to tolerate additional interference. However, margin is typically built in to RF systems to maintain performance through other time-varying effects that will reduce the signal strength, such as weather or normal movement of user devices. The resulting time-varying nature can make susceptibility to interference difficult to predict. The lowest-anticipated strength of the desired received signal may be used to compute a conservative threshold. If this conservative approach is overly restrictive, then more complex, probabilistic definitions of harmful interference may be adopted. For example, masks describing the percentage of time that interference may exceed certain power levels are applied to account for the time-varying nature of both the desired signal and the interference levels. A probabilistic approach is often necessary in practical spectrum-sharing scenarios, where a suitably low probability of harmful interference may be negligible relative to other sources of outages, such as weather and maintenance. The services enabled by the spectrum will also factor in to determination of an appropriate threshold. For example, air traffic control, public safety, military, and other safety-of-life services typically require more conservative thresholds due to the severe potential consequences of an outage caused by harmful interference.

Centralized Server Example: Television White-Space Sharing

An alternative to a device-centric approach to spectrum sharing is to employ a centralized server that enables dynamic sharing. Television White Space (TVWS) sharing is accomplished with a centralized database of TV transmitters. A simple location lookup allows a secondary device to determine which channels are not in use in the area and thus are available for use by the device. Devices are designed to operate only with confirmation from the central server that spectrum is available, which alleviates the problem of resolving unexpected interference.

TVWS faces a practical challenge in that spectrum sharing is needed most in urban areas where existing bands are heavily congested. Unfortunately, television channels are also heavily used in urban areas, limiting the opportunity for access by secondary users. Given this limitation, the extent to which operators will adopt TVWS devices remains to be seen. Even if TVWS does not prove to be a practical success, it broke regulatory, policy, and technical ground regarding how to enable centralized, automated approaches to spectrum-sharing systems.[19] Of course, TV stations are stationary and rarely change. Applying this sharing method to other bands may involve additional complexity and cost if more frequent updates to the database are necessary.

Harmful interference thresholds must be compared against the anticipated interference resulting from other systems sharing the spectrum band. Estimating these interference levels is often complicated by the time-varying and unpredictable nature of system operations, as well as uncertainty in aspects of the interference analysis. Estimating aggregate interference is complicated in many cases where the number of systems operating in the environment, and the parameters of their transmissions will change in response to user

Centralized Dynamic Example: Citizens Broadband Radio Service

Building on the recommendations of the PCAST, the FCC is currently developing rules for the Citizens Broadband Radio Service (CBRS) band that would take a step towards efficient, dynamic spectrum sharing enabled by spectrum-sharing servers, known as spectrum access systems (SAS). These SAS will provide access to the band for new secondary and tertiary operators, protecting incumbent primary access to the spectrum based on information exchanged directly with operator systems and measurements by an Environmental Sensing Capability (ESC).[21]

This centralized, dynamic approach has unprecedented potential for spectrum-sharing efficiency while also enabling reliability and effective enforcement. However, achieving the full potential will require significant effort and cost to overcome the complexity. Detailed user and system information will be required, driving cost and raising security and privacy concerns.

While the general nature of the system suggests it may be applicable to a wide variety of spectrum bands, the value of the new spectrum access will need to outweigh the implementation costs. In some bands, SAS will not be effective, such as cases where locations of receive-only systems are not predictable and a direct interface between those systems and an access system is impractical.

demand and environmental conditions. Current cellular network technology, for example, automatically admits new users to the network and adjusts transmit power levels to account for distance of users from the nearest base station including compensation for signal obstruction by buildings and obstacles. These two features complicate the task of estimating aggregate interference from a cellular network since the number of devices on the network and their position cannot be precisely predicted. This is especially true in scenarios where new spectrum sharing is being contemplated and the cellular network has not yet been fully designed, let alone deployed. Other factors, such as propagation effects, also introduce uncertainty in the estimation of interference. While there are many models to predict the effects of propagation, the most general models are statistical in nature and often not very precise. Further, many models have been designed conservatively to overestimate losses. While overestimating losses is suitable for ensuring that the minimum desired signal level is maintained, to understand the interference environment, received power levels at victim receivers should be considered when losses are at a minimum, not maximum.[20] Uncertainty in traffic load, user positioning, and propagation, among other effects, often makes spectrum sharing based on strict guarantees untenable, further justifying the use of more complex, probabilistic approaches for estimating interference and its impact.

New entrants and spectrum regulators may use the results of initial, conservative analyses to focus more detailed effort on spectrum bands where sharing is likely to be most effective, recognizing that it is impractical to analyze all options in detail given limitations on regulator and incumbent resources. To improve overall spectrum use efficiency, incumbent users may need to work to refine their assumptions and analyses where appropriate.

The Value of Shared Spectrum for New Services

Spectrum-sharing systems cannot be designed with the singular goal of minimizing interference. That approach will yield excessively restrictive conditions for new users, precluding them from offering any kind of practical service in the band. An incumbent user should help regulators to identify sharing alternatives that maximize the availability of the spectrum for new users while still satisfying their interference constraints. Failing to consider such alternatives may result in pressure on the incumbent user to make concessions on interference or spectrum access, especially if the spectrum holds high economic value for the prospective user. For example, in the lead-up to the 2015 AWS-3 auction, regulators initially sought incumbent meteorological satellite user support in making the 1675–1710 MHz band available for new cellular services. However, shared use of this entire band would be very challenging due to the distribution of users that receive broadcast weather data below 1695 MHz. Recognizing the economic value to the prospective commercial users, incumbents successfully advocated for a simpler geographic sharing approach in the upper 1695–1710 MHz band where downlinks requiring protection could be limited to several fixed sites.

Quantifying the amount and economic valuation of the spectrum made available through any given sharing technique is complex, time consuming and, ultimately, an inexact science. A variety of metrics have been proposed for measuring spectrum efficiency, accounting for bandwidth, affected area, and population served, but these are typically valid only for relative comparisons between similar systems.[22] Regulators are notably lacking more general metrics that could be applied to help guide policy decisions on effective spectrum sharing.[14] As a result, optimization of spectrum sharing will typically require complex models for the user and sharing systems to refine value estimates of spectrum based on predicted levels of service and reliability. Development of these complex models is resource intensive. Regulators may currently lack the tools to efficiently and rigorously identify which user and sharing systems are the most well suited to co-exist in a spectrum band. For instance, there are many nonprofit stakeholders that depend upon spectrum for weather modeling and prediction, water monitoring, emergency response, and national defense. There are clear public benefits from these spectrum-dependent services, though the economic benefit is not always direct or straightforward to quantify.[23] Ensuring that an economic valuation of spectrum includes societal benefits is important—and challenging.

Security

Spectrum sharing requires the exchange of information among spectrum users. Sharing systems may also enable systems to affect the behavior of other systems and could potentially allow a nefarious operator to dramatically alter the RF environment. Effective cyber security mechanisms need to be employed in a sharing system to restrict user access to information, and to ensure that the system cannot be exploited to maliciously influence users or other systems.[24] In simple sharing cases—e.g., geographic sharing—security may present a logistical challenge, as users must expend additional time and resources to determine what information they can provide during negotiations and to the public record. In more sophisticated, automated systems, accounting for security may require more detailed analysis of user authentication and encryption protocols, as well as assessment of vulnerability to denial-of-service, spoofing, and other cyber attacks.[25]

Privacy

Even if cyber security mechanisms are effective, users should anticipate some loss of privacy, or impact to operational security (OPSEC), by participating in a sharing system. Even if all users follow the rules and the system is robust to malicious attacks, the normal exchange of required information and operation of the sharing system may allow an adversary to infer sensitive information about user systems and behaviors. In a centralized, automated sharing system, for example, an adversary may participate in the sharing system as a legitimate spectrum user. By tracking when and where they receive access to the spectrum, the adversary may be able to infer the location, time of use, frequencies, and sensitivity to interference of incumbent systems. Any of these details may be considered sensitive by the incumbent operator. Spectrum users should evaluate sharing systems to ensure that their privacy and OPSEC are adequately protected, but this may be a challenging task. Mechanisms to measure and protect privacy have been the subject of ongoing work.[26] The best method to protect privacy is not always intuitive. For example, a sharing system that relies on sensor measurements may seem likely to better preserve privacy than one where operators report their locations directly to a centralized entity. However, obfuscation schemes may be applied to systems with a direct interface between the sharing and user systems which can outperform sensing-based systems in terms of both spectrum-sharing efficiency and user privacy.[27]

Enforcement

Murphy's Law tells us that anything that can go wrong will go wrong, making no exceptions for spectrum sharing. Indeed, case studies of spectrum sharing demonstrate harmful interference resulting from malfunctioning systems, misconfigured systems, illegally imported systems, and failures to reliably predict the strength of interfering signals.[18,28] Any effective sharing system will need to include enforcement mechanisms, enabling users to detect and recover from harmful interference.

Depending on the sharing scenario, enforcement may be difficult. Sharing systems relying on geographic separation may be easy to enforce depending on the number of spectrum users involved and how deployment of systems is controlled. For example, if a single cellular network operates around a large fixed radar, both the cellular operator and the radar operator may readily attribute any interference to one another and quickly make contact to resolve the issue. On the other hand, actions of smart devices that share spectrum autonomously by detecting and avoiding other users may be difficult to enforce effectively. The complexity of the device makes exhaustive testing and certification challenging. If something does go wrong, correcting the issue may involve manually searching out the misbehaving device through direction-finding and geolocation systems. This approach to enforcement may be unacceptably costly and may result in extended periods of time where the incumbent user suffers harmful interference while the issue is being resolved. Centralized spectrum access systems offer potential for effective and efficient enforcement mechanisms since users will be tracked by the access system and misbehaving devices can theoretically have their access to the spectrum revoked immediately. However, identification of misbehaving user devices and validation of parameters reported by the spectrum users present open and potentially challenging technical problems.[29]

A spectrum user could operate a device illegally in a band independent of any spectrum sharing regulations or system. Naturally, this scenario could lead to harmful interference for incumbent users that would also require enforcement. We might be tempted to conclude that the enforcement problem is the same with and without sharing; however, the flaw in that logic lies in the rate at which incidents occur. The vast majority of interference occurs not from intentional misuse, but from legitimate users with misconfigured or damaged equipment.[30] Spectrum users and regulators should be prepared for interference events to increase with spectrum sharing, ensuring that enforcement mechanisms are effective and timely.

Spectrum-Sharing Policy and Long-Term Implications

Policy and regulations established by spectrum regulators and the administration will create the framework under which stakeholders will implement effective spectrum-sharing solutions. Effective policy will provide protections for incumbent operators and confidence for prospective operators that access to the shared spectrum will justify their investment in deploying infrastructure in the band. Overly restrictive policy may prevent technologies from continuing to develop and mature, highlighting a need for care in crafting policy that provides operator assurances while also providing flexibility to encourage innovation.

In some cases, policy-makers will face challenges requiring them to choose between near-term versus long-term benefits. Existing equipment may be available for one type of use; e.g., because the band is used for that purpose in other countries, highlighting a potential near-term benefit if the band can be reallocated domestically for use by that equipment. Other types of services, however, may be better suited to share with incumbent users and have better long-term prospects for effective use of the band once equipment is developed. Decisions on policy and implementation made today can have long-term impacts on incumbent systems and opportunities for future systems. Sustained, long-term efforts may be necessary to achieve effective sharing, requiring a balancing of longer-term national interests to encourage innovation and technology advancements with short-term advantages offered to public and private sector stakeholders.

Efficient spectrum sharing will enable the development and introduction of new wireless technologies. Clearing bands for new uses has proven increasingly impractical. While sharing is clearly necessary, selecting which systems will be sharing in which band must be carefully considered. The systems involved will determine which of many methods of sharing—e.g., geographic, dynamic frequency selection, or centralized access systems—may be most effective. Effectiveness itself is a complex consideration, where performance can be measured with respect to protection of priority users from interference, the availability of spectrum for new users, security, privacy, and cost of implementation. In some cases, two systems may be unsuitable for sharing the same band if a cost-effective sharing method does not exist.

Regulators, spectrum operators, and other organizations influencing policy must weigh these considerations when deciding on spectrum-sharing policies for a spectrum band. Forcing two incompatible systems to share may incur substantial cost, delays, and eventually ongoing impairment on the performance of one or both systems. In some cases, regulators might consider implementing a sharing method that meets the needs of the incumbent(s) while also creating flexibility for future use, even if there is no existing equipment that can leverage the new flexibility. Establishing bands with clear operational, security, and performance requirements for new users will guide technology developers, drive innovative designs and solutions, and clear a path for spectrum access. Introduction of such systems will take time but ultimately can lead to broad, efficient use of the spectrum that will make spectrum available for a wide range of prospective users, not just those that can bring billions of dollars to a spectrum auction, and not at the expense of incumbent systems that already provide great value to the nation, sometimes in ways not easy to quantify.

References

[1] "How the Wireless Industry Powers the U.S. Economy," Accenture Strategy, Apr. 2018, https://www.accenture.com/us-en/insight-smart-cities?c=strat_accenturestratemediarelations_10245982&n=mrl_0418&#block-how-the-wireless-industry-powers-the-us-economy

[2] "Presidential Memorandum on Developing a Sustainable Spectrum Strategy for America's Future," Oct. 2018, https://www.whitehouse.gov/presidential-actions/presidential-memorandum-developing-sustainable-spectrum-strategy-americas-future/

[3] "Cisco Visual Networking Index: Global Mobile Data Traffic Forecast Update, 2016-2021," Cisco Systems, Feb. 2017.

[4] Louis Columbus, "2017 Roundup of Internet of Things Forecasts," Forbes, Dec. 2017, www.forbes.com/sites/louiscolumbus/2017/12/10/2017-roundup-of-internet-of-things-forecasts/, accessed Jun. 2018.

[5] "State of the Satellite Industry Report," Bryce Space and Technology, Satellite Industry Association, Jun. 2017.

[6] Paige Atkins, "Why Sharing is the Answer to Rising Demand for Spectrum," National Telecommunications and Information Administration, 12 Feb. 2016, https://www.ntia.doc.gov/blog/2016/why-sharing-answer-rising-demand-spectrum.

[7] "Auction of Advanced Wireless Services (AWS-3) Licenses Closes," Federal Communications Commission, Public Notice DA 15-131, Jan. 2015

[8] "Commerce Spectrum Management Advisory Committee Final Report Working Group 1 – 1695-1710 MHz Meteorilogical-Satellite Rev. 1," National Telecommunications and Information Administration, Jul. 2013

[9] "Commerce Spectrum Management Advisory Committee (CSMAC) Working Group 3 (WG 3) Report on 1755-1780 MHz Satellite Control and Electronic Warfare," Jul. 2013

[10] "Overview of ITU's History," p. 2, https://www.itu.int/en/history/Pages/ITUsHistory.aspx, accessed Nov. 2018.

[11] "Connecting America: The National Broadband Plan," Federal Communications Commission, Mar. 2010, https://www.fcc.gov/general/national-broadband-plan.

[12] "Unleashing the Wireless Broadband Revolution," Memorandum for the Heads of Executive Departments and Agencies, Jun. 2010, https://www.gpo.gov/fdsys/pkg/CFR-2011-title3-vol1/pdf/CFR-2011-title3-vol1-other-id236.pdf.

[13] "An Assessment of the Viability of Accommodating Wireless Broadband in the 1755-1850 MHz Band," U.S. Department of Commerce, Mar. 2012, https://www.ntia.doc.gov/report/2012/assessment-viability-accommodating-wireless-broadband-1755-1850-mhz-band.

[14] J. Holdren et al., "Realizing the Full Potential of Government Held Spectrum to Spur Economic Growth," President's Council of Advisors on Science and Technology, Report to the President, Jul. 2012.

[15] "Expanding America's Leadership in Wireless Innovation," Memorandum for the Heads of Executive Departments and Agencies, Jun. 2013, https://www.gpo.gov/fdsys/pkg/CFR-2014-title3-vol1/pdf/CFR-2014-title3-vol1-other-id213.pdf.

[16] J. Mitola III and G. Q. Maguire Jr., "Cognitive Radio: Making Software Radios More Personal," *IEEE Personal Communications Magazine,* vol. 6, no. 4, pp. 13–18, Aug. 1999.

[17] Y. Han, E. Ekici, H. Kremo, and O. Altintas, "Spectrum sharing methods for the coexistence of multiple RF systems: A survey," Ad Hoc Networks, Dec. 2016.

[18] J. Carroll, G. Sanders, F. Sanders, and R. Sole, "Case Study: Investigation of Interference into 5 GHz Weather Radars from Unlicensed National Information Infrastructure Devices, Part III," NTIA Report TR-12-486, U.S. Department of Commerce, June 2012.

[19] "Third Memorandum Opinion and Order in the Matter of Unlicensed Operation in the TV Broadcast Bands," Federal Communications Commission, ET Docket No. 04-186, April 2012.

[20] A. Molisch, Z. Hijaz, W. Nunan, and L. Zapanta, "On Pathloss Models for Adjacent-Channel Interference in Cognitive Whitespace Systems," IEEE International Conference on Communications Workshops, May 2016.

[21] "Report and Order and Second Further Notice of Proposed Rulemaking," Federal Communications Commission, GN Docket No. 12-354, Apr. 2015.

[22] F. Sanders, K. Davis, and K. Gremban, "A 53-Year History of Spectrum Efficiency Studies and Recommended Future Directions," National Telecommunications and Information Administration, Report 18-530, Feb. 2018.

[23] Thomas D. Powell, David G. Lubar, and Karen L. Jones, “Bracing for Impact: Terrestrial Radio Interference to Satellite-Based Services,” The Aerospace Corporation, Jan. 2018 https://aerospace.org/paper/radio-interference-satellite-based-services.

[24] J.-M. Park, J. H. Reed, A. A. Beex, T. C. Clancy, V. Kumar, and B. Bahrak, “Security and Enforcement in Spectrum Sharing,” *Proceedings of the IEEE,* vol. 102, no. 3, pp. 270–281, Mar. 2014.

[25] J. Park, J. H. Reed, A. A. Beex, T. C. Clancy, V. Kumar, and B. Bahrak, “Security and Enforcement in Spectrum Sharing,” in *Proceedings of the IEEE,* vol. 102, no. 3, pp. 270–281, March 2014.

[26] M. A. Clark and K. Psounis, “Trading Utility for Privacy in Shared Spectrum Access Systems,” *IEEE/ACM Transactions on Networking,* Dec. 2017.

[27] M. A. Clark and K. Psounis, “Achievable Privacy-Performance Tradeoffs for Spectrum Sharing with a Sensing Infrastructure,” IEEE Wireless On-Demand Network Systems and Services Conference, Feb. 2018.

[28] A. Witze, “Mobile-phone expansion could disrupt key weather satellites,” *Nature* 535, 208–209, July 2016.

[29] R. K. Sharma and D. B. Rawat, “Advances on Security Threats and Countermeasures for Cognitive Radio Networks: A Survey,” in *IEEE Communications Surveys & Tutorials,* vol. 17, no. 2, pp. 1023–1043, 2015.

[30] Itzik Wulkan, “SatBroadcasting: RF Interference is No Longer a Titanic Disaster for Satellite Broadcasters,” SatMagazine, Sep. 2016, http://www.satmagazine.com/story.php?number=249287775.