



## **Outcomes Report**

### **A Spectrum Policy Initiative Conference "Frontiers in Spectrum Sharing"**

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## Executive Summary

Dynamic spectrum sharing has gained rapid popularity as one potential solution to the problem of radio spectrum scarcity. The Silicon Flatirons Center for Law, Technology, and Entrepreneurship at University of Colorado Law School held a conference on September 9th and 10th, 2021, to explore the expanding frontiers of spectrum sharing. This conference provided experts from government, academia, and various industries the opportunity to analyze ways to expand spectrum sharing. This report identifies the key themes and issues they addressed.

Participants presented a variety of paths to creating an efficient and sustainable spectrum ecosystem. They largely agreed that increased use of and reliance on dynamic spectrum sharing (at least in some form) is inevitable. However, there was disagreement on what precisely that use would be. While some expressed that sharing was the best—if not the only—way forward, others felt that overreliance on sharing (versus more exclusive licensing) could destabilize the spectrum governance regime.

Informative keynote speeches by Ambassador Grace Koh and Commissioner Nathan Simington kicked off each conference day. The first panel discussed the present opportunities and challenges for spectrum sharing in space. The second panel took a deep dive into the frontiers of “coexistence” engineering. Finally, the third panel centered on governance and incentives in sharing. The conference wrapped up with a panel discussion reflecting on the earlier sessions, synthesizing critical thoughts into overarching themes, challenges, and recommendations.

Overall, cautious optimism pervaded the conference at every turn. Speakers and panelists almost universally recognized the growing importance and viability of dynamic spectrum sharing even as they acknowledged the hurdles that still must be overcome for the successful adoption of more advanced sharing regimes. Many also agreed that two of the biggest challenges—trust and incentives—could be conquered by a more widespread commitment to transparency and cooperation from various stakeholder communities.

## Speaker Lineup

**Jonathan Ashdown**, Senior Electronics Engineer, Air Force Research Laboratory

**Coleman Bazelon**, Principal, The Brattle Group

**Nomi Bergman**, Senior Executive, Advance

**Leonard Cali**, Senior Vice President, Global Public Policy, AT&T

**John Chapin**, Special Advisor for Spectrum, National Science Foundation

**Andrew Clegg**, Spectrum Engineering Lead, Google

**Ari Q. Fitzgerald**, Partner and Leader, Communications, Hogan Lovells

**David Goldman**, Director of Satellite Policy, SpaceX

**Keith Gremban**, Senior Fellow, Silicon Flatirons Center

**Vernita Harris**, Director, Spectrum Policy and Programs, Department of Defense Chief Information Officer, U.S. Department of Defense

**Grace Koh**, U.S. Ambassador to the World Radio Conference 2019; Vice President, Legislative Affairs, Nokia

**Petri Mähönen**, Professor, Head of Institute, Institute for Networked Systems, RWTH Aachen University

**Scott Palo**, Associate Director, SpectrumX; Endowed Professor in the Smead Aerospace Engineering Sciences at the University of Colorado Boulder

**David Redl**, former Assistant Secretary for Communications and Information, U.S. Department of Commerce; Founder and CEO, Salt Point Strategies

**The Hon. Nathan Simington**, Commissioner, U.S. Federal Communications Commission

**Mariam Sorond**, Senior Vice President and Chief Research and Development Officer, CableLabs

**Peter Tenhula**, former Deputy Associate Administrator, Office of Spectrum Management, National Telecommunications and Information Association; Senior Fellow, Silicon Flatirons Center

**Alexandre Vallet**, Chief, Space Services Department, Radiocommunication Bureau, International Telecommunication Union

**Ashley VanderLey**, Senior Advisor for Facilities, National Science Foundation

## Introduction

In the words of Commissioner Nathan Simington of the Federal Communications Commission (FCC), “within living memory . . . [radio] spectrum was so abundant that the easiest way to connect spectrum to services was just to give every service its own band.” Over time, however, technological and societal developments have vastly increased the utility of spectrum and, as a result, demand for the resource skyrocketed. Recently, a record eighty-one billion dollars were bid on less than one gigahertz of spectrum—almost double the amount bid in the previous record spectrum auction. The skyrocketing value of this resource raises many questions and concerns about the future of spectrum governance.

One potential emerging solution is dynamic spectrum sharing.<sup>1</sup> While spectrum sharing itself is not new, dynamic sharing promises to allow the near-simultaneous utilization of the same band by independent systems. At its best, dynamic sharing permits multiple users or operators to use the same spectrum at the same time without cumbersome restrictions and

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<sup>1</sup> For this report, we define “spectrum sharing” to be any method of allowing multiple entities to use the same range (“band”) of spectrum across at least one of the two non-frequency “dimensions” of radio spectrum: time and geography. A simple geographic-sharing example would be two FM radio stations operating far apart on the same band or channel at the same time; a simple time-sharing example would be two radio stations operating at different times on the same band in the same geographic area.

“Dynamic spectrum sharing”—the primary topic of the conference and this report—is rapidly evolving and more difficult to define; in fact, a prominent theme of the conference was a lack of common understanding of dynamic sharing. Broadly speaking, however, panelist John Chapin of the National Science Foundation offered a straightforward definition: “an operation of independent systems close enough together that dynamic mechanisms are required to prevent interference.”

thus may have the potential to alleviate scarcity. At the frontiers of dynamic spectrum sharing, however, various technical, economic, and institutional challenges still stand in the way of full realization of its potential.

In recognition of the growing importance of spectrum sharing, the Silicon Flatirons Center for Law, Technology, and Entrepreneurship at University of Colorado Law School held a conference on September 9th and 10th, 2021, to explore the expanding frontiers of spectrum sharing and invite discussion on how to tackle the technical, economic, and institutional challenges to the field's continued growth. The conference featured a series of remote speakers and panelists with a live viewing opportunity at Colorado Law. Over the two-day conference, speakers and panelists shared their thoughts on where spectrum sharing will go next and the best ways to overcome those challenges along the way. Participants represented national and international entities and brought various perspectives from government, academia, and industry. And these participants had no shortage of sharing topics to discuss; in the past few years, the frontiers of spectrum sharing has exploded with new interest from the Biden administration and a proliferation of new technology with the potential to enable dynamic sharing on a much grander scale.

The panels featured at the conference included (in order): Sharing at the Final Frontier - Spectrum in Space, Frontiers in Coexistence Engineering, Frontier Justice - Governance and Incentives for Spectrum Sharing, and the Moderators' Wrap Up. The first panel focused on new opportunities for spectrum sharing, particularly in space, and the challenges of balancing public and private interests. The second panel brought in a technical perspective: what new developments are pushing out the frontiers of spectrum sharing, and what new uses might they enable? The third panel examined the policy issues surrounding the governance of spectrum and what incentives are needed to make sharing a viable alternative to exclusive use licensing. Finally, the moderators' panel provided an opportunity to identify and analyze critical themes that emerged from the earlier discussions and contemplate recommendations for the future frontiers of spectrum sharing.

Throughout the conference, several key themes emerged. Many panelists and speakers stressed the current lack of trust among spectrum users. They addressed the importance of streamlining interference resolution and enforcement to build trust and reduce the reluctance of incumbents<sup>2</sup> to allow change. Participants frequently disagreed about the definitions of efficiency, highest and best use, and even sharing itself, highlighting the importance of common vocabularies to make progress in sharing. Finally, the participants agreed that expansion of sharing is inevitable even with these barriers, and parties must shift their attitudes toward optimism to ensure that the growth proceeds in a way that keeps all spectrum uses viable into the future.

This report first summarizes the contents of the conference in chronological order. The final sections on the Moderators' Wrap-Up and the Conclusion and Recommendations provide

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<sup>2</sup> For this report, "incumbent" refers to a party with existing rights to use a specific co-frequency or adjacent "band" of spectrum and whose rights may be impacted by new users.

key takeaways and recommendations proposed during the conference. Additionally, appendices are included at the end of the report. Appendix A provides the conference agenda and Appendix B contains a list of references for further reading on topics discussed during the conference. Finally, a link to additional information, video, and transcript of the event can be found on the Silicon Flatirons website.<sup>3</sup>

Several articles were published about the event in several industry publications and newsletters. These include *TR Daily*, *Communications Daily*, *World Radiocommunication Week*, and *Multichannel News*.

### Day One Keynote: Ambassador Grace Koh

Day one of the conference began with a keynote address from Grace Koh, Vice President of Legislative Affairs at Nokia and former United States Ambassador to the International Telecommunication Union's World Radiocommunications Conference 2019, where she led the 125-member United States delegation. She opened her address with a brief retrospective on the impacts of the pandemic on the telecommunications field and the broader technological ecosystem. She stated that our technological development has focused on maximizing efficiency, which has led in part to our unpreparedness to tackle the new obstacles that have appeared during the ongoing pandemic. Ambassador Koh stated that "resiliency and preparedness are ultimately at odds with efficiency," driving home her belief that efficiency cannot be the single focus of technological innovation if longevity and adaptability are our goals.

Ambassador Koh also turned her attention to the ever-present spectrum policy topic of determining the "highest and best use" of spectrum and how that framing impacts the prioritization of technological development and spectrum policy. She asserted that the notion of a single "highest and best use" is too simplistic. In light of this, she emphasized the need for effective spectrum sharing and a forward-looking approach to designing services for coexistence with one another. She argued that there is no better time than now to meet this challenge head-on, stating that "It seems to be the perfect time to understand the characteristics of the [new and existing] services that coexist within the same radio frequency, and actually try to design for coexistence."

"It seems to be the perfect time to understand the characteristics of the [new and existing] services that coexist within the same radio frequency, and actually try to design for coexistence."

-Grace Koh

Another topic of Ambassador Koh's remark was the tension between new services and seasoned incumbents. She framed the relationship between these two interests as one in which both need to be protected, saying that "new and innovative services are absolutely necessary for growth, but incumbent services are absolutely necessary for stability." She emphasized that the relevant stakeholders should consider the varied motivations in these

<sup>3</sup> See Silicon Flatirons: Frontiers in Spectrum Sharing, <https://www.siliconflatirons.org/events/frontiers-in-spectrum-sharing/>.

discussions and deliberately seek conversation to understand the contexts in which sharing decisions are made.

Lastly, Ambassador Koh firmly called for the reintroduction of trust into the entire process of spectrum allocation. She expressed her belief that, for new and resilient allocation and sharing agreements to occur, there must be a “nondramatic conversation” regarding what cooperation can achieve. Ambassador Koh also highlighted the importance of providing information about goals and strategies as a part of this process and contended that “[w]ithout information exchange between potentially coexisting services, sharing becomes impossible. And without sharing, it will be impossible to meet the challenges of the day.”

Ambassador Koh’s speech foreshadowed much of the content of the panels to come, and many of the themes she picked out in her keynote received further attention as the conference progressed. The need for a bespoke approach to each spectrum sharing problem was echoed in later panels, as was the ever-relevant issue of the role played by trust, both in allocation discussions and on a technological level. The conscientious distribution of information to achieve equitable spectrum solutions for both incumbents and new services also received a great deal of attention throughout the conference. Ambassador Koh raised these issues and drove home the critical role of these decisions as stakeholders move forward with new dynamic spectrum sharing approaches.

The subsequent panels each took up elements of these issues, highlighting further challenges as well as offering potential approaches to navigate the thorny issues of trust, engineering for coexistence, just what the “frontiers” of spectrum sharing look like at this moment, and how they might look in the future.

### **Panel One: Sharing at the Final Frontier – Spectrum in Space**

Moderated by Scott Palo, Associate Director of SpectrumX and Endowed Professor in the Smead Aerospace Engineering Sciences at the University of Colorado Boulder, this panel discussed the challenges, problems, and accomplishments of spectrum sharing in space. Spectrum management of space-based systems encompasses various services and technologies, ranging from small satellites (smallsats) to astronomy to commercial space exploration. This panel took a closer look at balancing the uses of spectrum resources in space, including techniques for spectrum sharing between space services, overall trends in new entrants, as well as historical and ongoing examples of spectrum sharing in space.

One issue that framed much of this panel’s discussion was the feasibility of sharing spectrum between incumbents, traditional new entrants, and new non-geostationary orbit (NGSO) satellite constellations. This discussion tied in neatly with Ambassador Koh’s keynote highlighting the tension between growth and stability and the need to balance these interests to achieve effective sharing.

To contextualize the panel, Peter Tenhula, formerly of the National Telecommunications and Information Administration’s Office of Spectrum Management, provided several examples to illustrate the spectrum sharing conflicts that can arise between terrestrial and satellite interests. Tenhula pointed to the closely watched issue of GPS interference and Ligado

Networks as an example of new entrants wanting to provide a terrestrial service facing off against the interests in adjacent bands and existing satellite services. He also touched on the C-band as an example of a band with more cooperation between terrestrial use and satellite operators. The panelists then discussed the current relationship between terrestrial entrants and broadcast satellites in the 12 GHz band, with David Goldman of SpaceX stating that, in his opinion, this band does not fit neatly into the dynamic of other bands, debating whether this can be cast as simply a case of “new entrant versus incumbent.”

Ashley VanderLey of the National Science Foundation (NSF) reframed the discussion of the competing spectrum systems present in space by noting that “[t]he traditional space-based system is nature.” As radio astronomy evolves, the scientific need for access to new spectral bands also develops. As Ambassador Koh discussed in her keynote, the idea of the “highest and best use” of any given piece of spectrum may be hard, if not impossible, to define.

A persistent issue in balancing spectrum interests in space is that stakeholders cannot just strike one static deal and then cease their efforts. Goldman gave an example of a satellite launch that included some reflective physical components of the satellites that had the unanticipated effect of interfering with optical astronomy due to the reflective nature of these components. He stated that this issue was addressed in the next launch, underscoring the need for ongoing collaborative discussion if these competing interests are to coexist.

New satellite launches incorporating changes based on issues present in previously launched satellites are part and parcel of technological development and serve as a strong example of the challenges in this area. Adaptation is critical and possible, but one of the issues inherent here is how technologies that have already deployed may or may not be mitigated. For example, it is difficult to bring a satellite back down to Earth for retrofitting and relaunching to address an issue that was only identified after the satellite’s initial launch.

Turning to international developments, Alexandre Vallet of the Radiocommunication Bureau at the International Telecommunication Union stated that the success of NGSOs and smallsats will likely be determined by the market and not spectrum availability. He noted that some areas of the geostationary-satellite orbit are already quite crowded, and that often small geostationary satellites are launched by governments for non-commercial purposes. Vallet also touched on the hot topic of commercial space exploration, observing that governments, the traditional leaders of space exploration, are growing more willing to offer room for the involvement of commercial programs. He did note that if there indeed turns out to be a lot of development in this area, new spectrum allocations may be necessary in the future because “all the spectrum allocated for this space exploration was done on the basis of the requirements of the space agencies.”



According to the panelists, current and prospective occupants must invest in “getting along” to actually open enough spectrum for all. Goldman argued that without meaningful incentives, there may be less cooperative interest at play because “In a shared environment, your incentive is actually to build a system that can’t share well, because then you can bump out all your competitors.” Many would argue that this issue is one of the core reasons that better, more thoroughly considered spectrum sharing incentives and policies are necessary to drive the flexible and collaborative sharing ecosystem for which many advocate.

“In a shared environment [without meaningful incentives], your incentive is actually to build a system that can’t share well, because then you can bump out all your competitors.”

-David Goldman

Takeaways from this panel included an apparent consensus that incentivizing cooperation (thereby incentivizing efficient sharing) is a critical component of instituting successful sharing schemes, but the questions of who sets the standards for efficiency and who defines the sharing scheme itself remain thorny and unresolved. Further, the constantly evolving needs of public safety services, commercial users, scientific users, and others create a moving target for sharing agreements. Given that innovation in this area is unlikely to grind to a halt any time soon, this challenge is not likely to disappear. The panel agreed that now is the time to share information between parties and to seek understanding of the evolving needs of fellow (and neighboring) spectrum occupants. Spectrum availability might not be the only determining factor when it comes to a service’s long-term success (as noted by Vallet), but in expanding areas like commercial space exploration, identifying new spectrum for this purpose may become an issue sooner rather than later.

Constant advances in technology and science can make it hard to reach long-term deals on how interests should be prioritized, given the relentless pace of advancement. These continual advances indicate the need for both adaptable systems and adaptable sharing agreements. Relying on goodwill to drive these agreements may not prove sufficient. Therefore, more robust incentive structures are likely needed as services continue to enter this arena and existing services continue to expand. Incentivizing parties to plan for evolution, particularly in the context of technology that will be sent into space for a significant length of time, looks deserving of a great deal of attention from technologists, scientists, and policymakers as well.

### **Panel Two: Frontiers in Coexistence Engineering**

It is likely uncontroversial to say that the need for effective spectrum sharing is increasing as demand for spectrum continues to grow. While the previous panel on spectrum in space discussed some of the issues in getting systems to share spectrum, this panel (moderated by Nomi Bergman, Senior Executive at Advance) focused more closely on technology itself and how it may be used in “coexistence engineering.” The notion of “engineering for coexistence” addresses the technical aspects of how to create systems that are capable of successful inter-service sharing. Much of the conversation centered on how we have engineered for coexistence in the past and how we might do so in the future. This panel

addressed several perceived challenges in the arena of coexistence engineering, including new and emerging technologies such as artificial intelligence (AI), the challenges of designing and implementing fair and effective enforcement models, the concept of “spectrum scarcity,” and ways to utilize lessons learned from sharing history to develop more effective sharing technology.

There was general agreement that spectrum sharing was becoming a necessity in the face of ever-increasing demand for spectrum, but the panel was somewhat split on where precisely the “scarcity” comes from. Professor Petri Mähönen, head of the Institute for Networked Systems at RWTH Aachen University, kicked off the discussion with an argument that “we have to remember that [incumbents] have, in one sense, economic incentives to hog spectrum and keep new entrants out.” In response, Mariam Sorond, Senior Vice President and Chief Research and Development Officer at CableLabs, argued that what may look like sitting on unused spectrum may often simply be a result of lag times between spectrum assignment and deployment for public use or careful planning for the future in areas such as ecosystem development and scaling up widespread deployment.

John Chapin of the NSF and Jonathan Ashdown of the Air Force Research Laboratory agreed that one of the biggest causes of spectrum scarcity is the current regulatory structure. Chapin argued that whether or not there was spectrum scarcity from a purely technical standpoint was in some ways irrelevant because we “have scarcity because of the system that we live in and the conditions that create that are not going to change on timescales less than decades.”

Another aspect of the conversation surrounding scarcity is the issue of enforcement and trust. How can scarcity best be managed, and how can parties feel assured that others are adhering to the sharing agreements in which they participate? Chapin and Mähönen found common ground on their mutual belief that one possible solution to this challenge is the implementation of strong *ex-post* enforcement. Mähönen argued that good enforcement is a mechanism for building trust, and that *ex-post* enforcement itself might be necessary to have real trust at all. He also added that another critical aspect of this problem is accountability, stating that we need “provability that the spectrum is shared properly” and that without accountability, “I don’t think we are able to trust, at least in areas where there is local scarcity.”

Chapin noted that “having some form of *ex-post* enforcement is really an absolutely necessary complement to the designed *ex-ante* sharing mechanisms,” and stated that a clear example is the 5 GHz Dynamic Frequency Selection (DFS) band. He said that, in that case, “sharing mechanisms ended up not working the way they were planned in the field in part because of user action. And it took quite a lot of effort to solve that, and we still have some ongoing interference issues as a result.” Chapin further stated his belief that sensing-based approaches actually serve to inhibit spectral efficiency as well as the evolvability of the system over time. He pointed to the 3.5 GHz Citizens Broadband Radio Service (CBRS) band as an example of an

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-John Chapin

instance “where there’s recognition that we need to evolve from the environmental sensing capability to some kind of incumbent informing capability.”

This theme of trust arose again as the panel turned to a discussion of the possible roles that AI and machine learning (ML) may play on the frontiers of spectrum sharing. Mähönen argued that despite a lot of conversation about the many uses of ML regarding complex and granular sharing problems, ML will find its best use “higher up the stack.” He stated that ML will perhaps be most useful in “traffic shaping,” handling tasks such as moving between frequencies or between fiber and wireless. Chapin highlighted that solutions like ML add significant complexity, and that “the more complexity we have, the harder it is to trust.” Ashdown agreed on this point, adding that he believes that AI and ML will inevitably play a role in spectrum sharing, but that “even if you were to get to pretty good solutions in terms of the optimality of sharing the spectrum with these techniques, there’s a lack of traceability.” This conversation underscored the challenges of creating dependability and trust in sharing schemes, as the introduction of new approaches like ML can add to pre-existing challenges even as they purport to solve others.

Concerning new or evolving spectrum sharing tools, Sorond raised the topic of convergence, the migration of multiple communications services into one network. For Sorond, “convergence promotes better interworking and information flow with various network elements,” making it “a key ingredient for enabling effective spectrum sharing.” With regard to the historical view of sharing, she noted that CBRS could also serve as an example of sensing-based dynamic sharing.

The panel turned to the importance of good data and measurement campaigns as a tool for good spectrum management, both on a technical level and on a policy level. Ashdown argued that measurement campaigns are needed “to really figure out what is needed to be able to effectively coexist, and what those harmful interference thresholds are,” and Chapin added that he believes that there is a clear need for what he called “access level agreements.” Chapin described these agreements as “something that specifies the quantitative thresholds that define when harmful interference occurs,” whether that threshold is based on power, time, or another metric. This, he argued, is necessary to move away from the non-functional “I-know-it-when-I-see-it” approach to harmful interference. Chapin observed that one challenge with this proposition is that regulators may need to take charge of establishing these thresholds, which would be a long and painful process. To illustrate the point, he emphasized that “5 GHz DFS took three years of negotiations and still didn’t get it right.”

Taken on the whole, this panel provided several key takeaways. The panelists debated just how to frame the idea of “spectrum scarcity” properly. Apart from disagreements on the motivations behind the acquisition of certain spectrum, there was general agreement that perhaps the biggest obstacle to sufficient spectrum for all is the current regulatory framework. Other obstacles to successful spectrum sharing identified by the panel were the challenges of trust and enforcement. The panelists felt that strong enforcement of clearly defined standards would increase trust between operators, and therefore might lead to more cooperation when it comes to sharing spectrum.

The panel also agreed that AI and ML will likely play a role in coexistence engineering, but just what that role might be failed to draw clear consensus. Some panelists felt that AI could even prove to be a step backwards when it comes to how “trustable” a given system’s sharing strategies are. Lastly, in its review of the history of sharing schemes, the panel hit on many of the recurring themes from the conference and highlighted both successes and failures of coexistence engineering. The topics of trust, enforcement, the inevitability of the need to share spectrum, and the desire to put a piece of spectrum to its “highest and best use” played key roles in this discussion and will likely play those roles again as the conversation on coexistence engineering continues to evolve.

### Day Two Keynote: FCC Commissioner Nathan Simington

Day two of the conference commenced with a keynote address from FCC Commissioner Nathan Simington. Commissioner Simington focused his remarks on the trade-offs between dynamic sharing and exclusive licensing regimes and the factors that must be accounted for in the healthy development of spectrum policy.

Commissioner Simington painted a hopeful picture for the future of spectrum sharing. He spoke of a vision of the future where “increasingly flexible radios and pervasively shared spectrum will allow a given device or network to select optimal and continually varying frequencies from moment to moment.” Using the framework outlined by John Leibovitz and Ruth Milkman, the Commissioner contrasted this vision with the current “informing” and “centralized” regime.<sup>4</sup>

Nonetheless, Commissioner Simington pointed out that “there are no free lunches.” Each model—exclusive licensing and dynamic sharing—has its trade-offs, and the “bristling complexity” of the spectrum policy environment limits the options available to policymakers. For one thing, he noted, “unfathomable amounts of capital have been deployed” under the current model. Furthermore, “while RF radiation may propagate in a vacuum,” the Commissioner said, “spectrum policy does not, and our policy options are constrained by government and business realities that may or may not easily integrate with notionally ideal policy in the abstract.”

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-Commissioner Nathan Simington

To illustrate these trade-offs and the complex policy decisions arising from them, the Commissioner compared the C-Band (a model of exclusive licensing) and CBRS (an example of dynamic sharing). While CBRS served its purpose in opening spectrum to new players, industry actors were far more motivated to pay up for exclusive licenses in the C-Band. This phenomenon, Commissioner Simington noted, “should give us pause” because it shows that

<sup>4</sup> See Leibowitz and Milkman’s article referenced in Appendix B.

heavy spectrum users (such as those in many private industries) continue to place a higher value on exclusive licensing.

Yet, even while recognizing the continued higher valuations of exclusive licensing by industry actors, Commissioner Simington warned that we must avoid “setting ourselves up to be short of something else down the road.” He emphasized that “the real answer is synthesis”: both dynamic sharing and exclusive use must be utilized to keep spectrum use viable. In closing, Commissioner Simington reminded listeners to keep “our eyes . . . trained on the future [while identifying] how to succeed today, in one year, in five years.”

Following his prepared remarks, Commissioner Simington entertained several audience questions. One particular topic of interest was the desirability of receiver standards. The Commissioner emphasized that while receiver standards are “very near and dear to my heart . . . [they] have always been a very fraught [topic] at the FCC.” He described the prevailing concern as one of sufficient care in crafting standards: “most people,” he said, “have been worried that the FCC finds it hard to have a sufficiently synoptic view of every possible circumstance to issue receiver standards.” In other words, the FCC must carefully tailor any set of standards to various operator types and circumstances to avoid doing more harm than good. But, he concluded, “we cannot continue ignoring [receiver standards] forever.”

Overall, Commissioner Simington’s remarks synthesized many of the themes that had emerged from the previous day’s events and set the stage for the remainder of the conference. He stressed the importance of realistic optimism and the need for balance between addressing current needs and developing sustainable long-term policies. The following panel built on these themes by addressing the challenges for efficient governance in any dynamic spectrum sharing regime.

### **Panel Three: Frontier Justice – Governance and Incentives for Spectrum Sharing**

Where the previous day’s panels centered around new areas for sharing and the engineering considerations, panel three rounded out the conference with a discussion focused on two fundamental issues at the frontier of spectrum sharing: how to govern a spectrum-sharing regime and what incentives will make key stakeholders invest. Hogan Lovells partner and moderator Ari Fitzgerald guided this panel of diverse perspectives through a discussion on the necessity, requirements, and barriers in building a flourishing spectrum-sharing regime. Along the way, the panelists discussed the trade-offs of dynamic sharing and exclusive use and critically analyzed CBRS as a spectrum sharing experiment.

Fitzgerald opened the panel with a question that hit at the core of the conference: should we even encourage increased spectrum sharing? Panelists largely agreed; Coleman Bazelon of the Brattle Group took a nuanced stance, noting that three areas—technical, economic, and institutional—need to be aligned before sharing can expand. Google’s Andy Clegg went as far as to say that “we will see [spectrum sharing] becoming a necessity, not really an encouragement.” Vernita Harris of the Department of Defense (DoD) went even further, stating that “from a DoD perspective . . . sharing must be the new normal.”

A key area of disagreement among the panelists was how to define the most efficient use of spectrum—a perfect illustration of Ambassador Koh’s concern. No two panelists emphasized this difference better than DoD’s Harris and AT&T’s Leonard Cali. Speaking from an industry incumbent perspective, Cali noted that (reminiscent of Commissioner Simington) “hundreds of billions of dollars [have been] invested . . . based on exclusive-use spectrum.” For him, because exclusive licensing is a proven engine of investment, innovation, and growth, the first consideration should be “can we clear spectrum?” In contrast, Harris stressed that “everyone will tend to benefit if we share” and that the DoD’s “first question is always going to be ‘can we share?’”

Another fraught topic (as in the other panels) was the definition of “spectrum sharing” itself. For example, Clegg heavily emphasized that “[CBRS] enabled a much greater range of licensees—over 200 licensees in the CBRS band compared to effectively three in the 3.7 GHz band.” Bazelon responded, noting that “even though there [are] only three main licensees out of the [3.7 GHz band], there’s going to be three-hundred million users on that spectrum” and thus “if you . . . talk about actual people using [spectrum], it’s the most shared spectrum out there.”

“Even though there [are] only three main licensees out of the [3.7 GHz band], there’s going to be three-hundred million users on that spectrum” and thus “if you . . . talk about actual people using [spectrum], it’s the most shared spectrum out there.”

-Coleman Bazelon

Even when working from a common definition of sharing, the panelists split over the benefits of sharing versus reallocation. Cali, for example, took the position that “sharing may take more time [than reallocation].” One of the time-consuming challenges of sharing, he said, was that stakeholders “have to work out all the risks associated with it,” and that “any new sharing methodology is going to have [associated] operational risks . . . that can also create further delay.” Clegg disagreed, emphasizing that sharing “open[s] up spectrum access to entities that would not have the economic wherewithal to go after exclusive use licenses.” This exchange again showcased the difficulty of determining what the most “efficient” or “highest and best use” of spectrum actually is.

The debate on these topics underscored a significant barrier to increased spectrum sharing: lack of trust. The panelists entered this discussion through Clegg’s identification of the overprotection of incumbents as a roadblock. He chalked up the issue up to the use of “questionable interference criteria” and encouraged (several times, in fact) the move away from “worst-case assumptions” to a probabilistic model. Bazelon implicitly tied this topic back to trust by adding that this overprotection occurs “because there is no mechanism for resolving disputes efficiently between users.” When spectrum users see no efficient model for resolution, overprotection becomes inevitable and sharing impossible. To get out of this situation, Bazelon took a Coasean approach and suggested that “to reduce the transaction costs of a trade, you need good rules of the road and expectations about how disputes between spectrum users would be resolved.”

Another barrier noted by the panelists was the lack of investment in sharing technologies and, more broadly, the lack of investment incentives deriving from current sharing frameworks. Harris highlighted the success of CBRS as showing promise for sharing and

urged that any new spectrum sharing framework “needs to be rigorously tested [and] investments [into AI and ML] are necessary to meet the demands of the increasingly crowded spectrum environment.” Furthermore, Harris added, “the [current] U.S. regulatory framework is not flexible enough from [DoD’s] perspective,” and that going forward “[we] have to have flexibility in [our] regulatory approach.” But Cali pointed out that sharing models do not always provide incentive for investment in the underlying infrastructure needed to put spectrum to use, noting that “spectrum alone isn’t sufficient. You need . . . equipment, you need infrastructure, you need investment to make [sharing] work.”

In summary, this panel emphasized the inevitability of spectrum sharing and highlighted the variety of technical, economic, and institutional barriers to maximizing the potential of sharing. In particular, the panel was a microcosm for the differences of opinion found among disparate stakeholders with disparate priorities. But the panelists hinted that a common understanding of each stakeholders’ position might be the key to overcoming the barriers on the frontier of spectrum sharing.

#### **Panel Four: Moderators Wrap Up**

The conference concluded with a final panel featuring the moderators, moderated by Keith Gremban of Silicon Flatirons. Here, the moderators-turned-panelists had the opportunity to reflect on the discussions they had in their respective panels and the things they had heard in other panels and synthesize those thoughts into a new discussion of overarching themes, challenges, and recommendations. The panel also featured a non-moderator, David Redl, former Assistant Secretary for Communications and Information at the U.S. Department of Commerce, who provided an outside perspective on the previous discussions.

To open, each panelist presented takeaways from their specific panel. Speaking for panel one, Scott Palo noted that the discussion centered around the critical nature of trust, coordination, and collaboration. For panel two, Nomi Bergman highlighted the panelists’ discussion surrounding the definition of spectrum sharing and the existence of real spectrum “scarcity.” Finally, Ari Fitzgerald noted that panel three felt that “the gold standard still seems to be exclusive use spectrum” and that the panelists believed that efficient *ex-post* enforcement was an essential element of resolving the trust gap.

Redl then opened up the discussion to the overarching themes of the conference. One topic he immediately highlighted was the lack of common vocabulary among actors; “if you asked every one of the moderators to define spectrum sharing,” he said, “you’d probably get a different definition.” To some extent, this lack of common vocabulary extended beyond sharing itself; panel two featured disagreement over the existence of spectrum scarcity, highlighting a lack of concordance even about the premises of the discussion.

Another key theme that warranted great discussion was the trust deficit in sharing. Bergman suggested that one potential solution to closing the trust gap was technological investment, particularly in those technologies “that can improve identification, enforcement . . . , privacy and security.” Fitzgerald agreed and added that “focusing a little bit more on technology that helps build trust among stakeholders . . . is really important.” Furthermore, he reinforced Cali’s earlier point that increasing the efficiency and effectiveness of remediation would go a long way to building the trust necessary for a vibrant sharing environment.

“Focusing a little bit more on technology that actually helps build trust among stakeholders . . . is really important.”

-Ari Fitzgerald

Related to trust, the third theme of interest among the panelists was the idea of interference limits. Fitzgerald revived Clegg’s earlier suggestion that regulators should move to a probabilistic interference analysis to reduce the overprotection of incumbents. Unfortunately, Fitzgerald added, the power of the incumbents in these proceedings—perhaps motivated by fear of lack of enforcement against violators—leads to limited progress on the issue. Redl tied this topic into the recurring proposal of receiver limits and noted that “sometimes there is a tendency to believe that some services have an absolute right to exist without changing . . . and that can’t be the case.” Redl noted that while receiver standards can be a “third rail” among spectrum experts, they should be a “part of the conversation.”

A final theme brought up by Palo was the need for optimism. “We can choose to be optimists, or we can choose to be pessimists. That’s an active choice,” he said, “and choosing optimism leans into building trust . . . I think we have to decide to be optimistic, and that will move us [towards sharing].” The other panelists agreed but stressed the need for cautious and realistic optimism. “We should be optimistic, but we also should not be under any illusions that we’re going to get everything that we want,” added Fitzgerald. Redl concluded that “the sooner we recognize that each side has a legitimate starting point from which we can all work, the better off we’ll be . . . once we [have a decision to be optimistic by all the parties involved], I think we’ve got the technology.”

“We can choose to be optimists, or we can choose to be pessimists. That’s an active choice, and choosing optimism leans into building trust.”

-Scott Palo

## Conclusions and Recommendations

The ultimate takeaway from the Silicon Flatirons Frontiers in Spectrum Sharing conference is that trust and optimism among disparate spectrum stakeholders are essential to opening the door for continued growth and development in spectrum sharing. Throughout the conference, panelists and moderators alike highlighted the various benefits and barriers to spectrum sharing, including trust and optimism, but also the need for a common vocabulary, the definition and method of measurement for efficiency, the inevitability of sharing, and the solutions to the tension between incumbents and continuing innovation.

Many participants recognized that there were few, if any, strict dichotomies within these themes. Optimism, they noted, should be cautious and realistic. Increased sharing is



inevitable, but exclusive licensing need not—and should not—disappear altogether. A common understanding may simply mean a mutual understanding; perhaps, as Redl suggested, parties need only “recognize that each side has a legitimate starting point from which we can all work.” As such, it may not be necessary for parties—even with priorities as “wildly disparate” as Commissioner Simington mentioned—to have the same definition of “efficiency.” An empathetic understanding of other stakeholders’ perspectives will go a long way toward fostering the “nondramatic conversation” that Ambassador Koh recognized as essential for progress.

At the same time, participants were well aware of the hard work that must be done and sacrifices that must be made to realize the economic and social benefits of spectrum sharing. Fitzgerald opined that “we . . . should not be under any illusions that we’re going to get everything that we want.” Instead, he noted that parties must be willing to look beyond themselves and search for ways to achieve their goals in conjunction with one another.

The recommendations made by speakers during the conference can be described in Bazelon’s three categories: technical, economic, and institutional. However, it was clear that all participants felt that none of these could be implemented in a vacuum; instead, a recurring theme was that only the combination of various recommendations within and between these categories could lead to meaningful changes conducive to the growth of dynamic spectrum sharing.

From a technical standpoint, many participants agreed that steps could be taken toward building trust by increasing investment in interference detection and identification technologies. While recognizing that dynamic sharing technologies (including AI and ML) are essential to building a novel sharing environment, participants felt that neglecting those auxiliary technologies which allow actors to detect and diagnose interference events—and provide the basis for enforcement—would force incumbents to take a cautious approach and prevent new dynamic sharing initiatives from getting off the ground.

But this is not to say that continued and increased investment in direct dynamic sharing technologies is unimportant. In contrast, the participants agreed that current sharing initiatives such as CBRS have shown promise and should serve as an encouragement to both government and private industry to develop new technologies—particularly AI and ML—that can make dynamic sharing more accessible.

Participants also emphasized the importance of finding ways to rebalance economic incentives to share. As noted in panel three, the comparison of investment in C-band (exclusive licenses) and CBRS (dynamic sharing) shows that the current structure still heavily favors exclusive use. Recommendations to tackle this disparity included shifting the understanding of “highest and best use” or “efficiency” to incorporate socially valuable uses of spectrum that do not have comparable “economic” value, such as radio astronomy and other scientific uses. One particular (if imperfect) suggestion was to increase subsidies into these uses to make them more competitive candidates for sharing.

Finally, panelists and moderators highlighted the importance of updating the institutional governance regimes to facilitate the expansion of dynamic spectrum sharing. One

recommendation centered on heightened *ex post* remediation of actual interference events.<sup>5</sup> Participants almost universally put forth this recommendation as the number-one way to increase trust between parties to the level necessary to develop dynamic spectrum sharing environments on a broad scale. If parties—particularly incumbents—are confident that their interference events will be efficiently resolved, they will be more willing to allow new parties to come into and share their bands. This recommendation is tied in with a technological recommendation for automated enforcement; immediate automatic action against bad actors will send a clear message and greatly expand willingness to share.

Another institutional reform suggested in panel three was a rethinking of interference protection criteria. Panelists identified the current system as one that, as Redl phrased it, allows some parties to feel as though they have an “absolute right to exist without changing.” To combat this, Clegg suggested a move to a probabilistic analysis to reduce overprotection. This recommendation could serve the goals of dynamic sharing on two fronts. First, it would free up a lot of spectrum and allow for tighter operations. Second, and more importantly for dynamic sharing, it would provide a more flexible and realistic framework for the heightened enforcement regime described above.

In summary, the conference opened the door to new ideas for the future of dynamic spectrum sharing. It also provided some concrete recommendations that could be implemented to restructure the existing system to bring those ideas into reality. Participants analyzed recent experiences in spectrum sharing, such as CBRS, and identified the essential technical, economic, and institutional barriers that must be overcome to build trust, formulate a common vocabulary and understanding, and promote the optimistic perspective necessary to the spread of dynamic spectrum sharing throughout the spectrum world.

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<sup>5</sup> “*Ex post* remediation” refers to measures taken *after the fact* to reduce or eliminate the negative effects of significant (“harmful”) interference, such as signal interruption, signal loss, etc. “Actual interference events” refers to interference which has a non-trivial effect on the operation of a system, as opposed to the low level of interference that inheres in almost all spectrum usage.

## Appendix A: Event Agenda

### September 9, 2021 - Day One

- 1:00 pm – 1:05 pm      **Day One Welcome and Introduction**  
Keith Gremban, Amie Stepanovich
- 1:05 pm – 1:30 pm      **Day One Keynote**  
Ambassador Grace Koh
- 1:30 pm – 2:45 pm      **Sharing at the Final Frontier - Spectrum in Space**  
David Goldman, Scott Palo, Peter Tenhula, Alexandre Vallet,  
Ashley VanderLey
- 2:45 pm – 3:00 pm      **Break**
- 3:00 pm – 4:15 pm      **Frontiers in Coexistence Engineering**  
Jonathan Ashdown, Nomi Bergman, John Chapin, Petri  
Mähönen, Mariam Sorond
- 4:15 pm – 6:00 pm      **Reception**

### September 10, 2021 - Day Two

- 9:00 am – 9:05 am      **Day Two Welcome and Introduction**  
Keith Gremban
- 9:05 am – 9:30 am      **Day Two Keynote**  
FCC Commissioner Nathan Simington
- 9:30 am – 10:45 am      **Frontier Justice - Governance and Incentives for Spectrum  
Sharing**  
Coleman Bazelon, Leonard Cali, Andrew Clegg, Ari Q.  
Fitzgerald, Vernita Harris
- 10:45 am – 11:00 am      **Break**
- 11:00 am – 11:55 am      **Moderators' Wrap Up**  
Nomi Bergman, Ari Q. Fitzgerald, Keith Gremban, Scott Palo,  
David Redl
- 11:55 am – 12:00 pm      **Closing Remarks and Special Announcement**  
Keith Gremban, Scott Palo

## Appendix B: References

### From the Conference Webpage

President Obama's 2013 Presidential Memorandum:

White House, Memorandum for the Heads of Executive Departments and Agencies, "Expanding America's Leadership in Wireless Innovation" (June 14, 2013), 78 Fed. Reg. 37431 (June 20, 2013), *available at* <http://go.usa.gov/DaPR>.

President Trump's October 25, 2018 Presidential Memorandum:

White House, Memorandum for the Heads of Executive Departments and Agencies, "Developing a Sustainable Spectrum Strategy for America's Future" (Oct. 25, 2018), 83 Fed. Reg. 54513 (Oct. 30, 2018), *available at* <https://go.usa.gov/xMKRe>.

President Biden's first budget proposal to Congress calling for increased funding for the National Telecommunications and Information Administration (NTIA) to "support the development and deployment of broadband and 5G technologies by identifying innovative approaches to spectrum sharing":

U.S. Dept. of Commerce, FY 2022 Budget in Brief at 1 (May 2021), *available at* <https://go.usa.gov/xMKnk>.

### Post-Conference News Coverage

Some Space Trends Raise Spectrum Sharing Concerns, *Communications Daily* (Sep. 10, 2021).

"Need for FCC Receiver Standards Won't Go Away: Simington", *Communications Daily* (Sep. 13, 2021).

Kirby, Paul, "Simington Cites Benefits of Shared, Exclusive Spectrum", *TR Daily* (Sep. 10, 2021).

Egerton, John, "FCC's Simington Has Dynamic View of Spectrum Sharing", *Multichannel News* (Sep. 12, 2021), *available at* <https://bit.ly/3lKt7bj>.

*World Radiocommunication Week*, Vol. 12, No. 31 (Sep. 27, 2021).

High, Lucas, "Silicon Flatirons: Future of airwave, communication spectrum in space requires cooperation", *Colorado Daily* (Sep. 10, 2021), *available at* <https://bit.ly/3rl3yeG>.

### References Made During the Conference<sup>6</sup>

Ambassador Grace Koh mentioned that the pending 1,450-page infrastructure bill contains a spectrum provision. Section 90008 of the Senate version of the Infrastructure Investment and

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<sup>6</sup> The authors thank Peter Tenhula for compiling this list of references.

Jobs Act would require some or all of the 3.1-3.45 GHz band be reallocated on a shared basis between federal and non-federal users and auctioned for commercial use.

H.R.3684, Sec. 90008, 117th Cong. (engrossed Senate amendment Aug. 10, 2021), available at <https://www.congress.gov/bill/117th-congress/house-bill/3684>, which became Pub. Law No. 117-58 on Nov. 15, 2021.

Commissioner Simington mentioned the recent report on spectrum sharing entitled "Taking Stock of Spectrum Sharing" by John Leibovitz and Ruth Milkman, which he encouraged everyone to read. Of the report, Simington said, "I don't think it's possible to provide a more lucid, thoughtful account of the theory and practice of spectrum sharing."

Leibovitz, John and Milkman, Ruth, "Taking Stock of Spectrum Sharing" (September 3, 2021), available at <https://ssrn.com/abstract=3916386>.

Peter Tenhula mentioned during the first panel a recent GAO report regarding 24 GHz sharing battles.

Government Accountability Office, "Spectrum Management: Agencies Should Strengthen Collaborative Mechanisms and Processes to Address Potential Interference", Report to the Committee on Science, Space, and Technology, House of Representatives, GAO-21-474 (July 19, 2021), available at <https://www.gao.gov/assets/gao-21-474.pdf>.

Peter Tenhula and David Goldman mentioned the 12 GHz sharing battle at the FCC, which is the subject of a pending proceeding.

Expanding Flexible Use of the 12.2-12.7 GHz Band, *Notice of Proposed Rulemaking*, WT Docket No. 20-443, 36 FCC Rcd. 606 (Jan. 12, 2020), available at <https://go.usa.gov/xMKm2>.

David Goldman mentioned a petition filed by SpaceX at the FCC about rewarding satellite operators who are most efficient.

Space Exploration Holdings, LLC, "Revision of Section 25.261 of the Commission's Rules to Increase Certainty in Spectrum Sharing Obligations Among Non-Geostationary Orbit Fixed-Satellite Service Systems", Petition for Rulemaking, RM-11855 (filed Apr. 30, 2020), available at <https://go.usa.gov/xMKHz>.

[Note: post-conference, the FCC, on December 14, 2021, granted in part the SpaceX petition. See Revising Spectrum Sharing Rules for Non-Geostationary Orbit, Fixed-Satellite Service Systems, *Order and Notice of Proposed Rulemaking*, IB Docket No. 21-456, FCC 21-123 (Dec. 15, 2021), available at <https://go.usa.gov/xFrS>.]

Peter Tenhula also mentioned legislation that authorized a "prize" for spectrum efficient technology, the "Spectrum Challenge Prize Act", which is a provision of the MOBILE NOW Act enacted in 2018 (not the Spectrum Pipeline Act). The provision has yet to be implemented.

Making Opportunities for Broadband Investment and Limiting Excessive and Needless Obstacles to Wireless Act (MOBILE NOW Act), Pub. L. 115-141, div. P, title VI, § 619, 132 Stat. 1113-14 (Mar. 23, 2018), *codified at* 47 U.S.C. § 1509, *available at* <https://go.usa.gov/xe3EA>.

John Chapin mentioned during the second panel an article he co-authored with Bill Lehr (MIT) on time-limited leases of spectrum, which was published in 2007 in IEEE Communications Magazine.

Chapin, John and Lehr, William, "Time-limited Leases in Radio Systems", IEEE Communications Magazine, 45(6):76-82 (July 2007), *available at* <https://ieeexplore.ieee.org/stamp/stamp.jsp?tp=&arnumber=4251074>.

John Chapin mentioned what happened in the 5 gigahertz DFS band as one example of where having some form of *ex post* enforcement is a necessary complement to the designed *ex ante* sharing mechanisms.

Frank H. Sanders; Edward F. Drocella Jr.; Robert L. Sole; John E. Carroll, "Lessons Learned from the Development and Deployment of 5 GHz Unlicensed National Information Infrastructure (U -NII) Dynamic Frequency Selection (DFS) Devices", NTIA Technical Report TR-20-544 (Dec. 2019), *available at* <https://go.usa.gov/xe3mf>.

Ari Fitzgerald and others on the third panel mentioned the July 2012 report of the President's Council of Advisors on Science and Technology (PCAST) entitled "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, "Realizing the Full Potential of Government-Held Spectrum to Spur Economic Growth" (July 2012), *available at* <https://go.usa.gov/xpcAV>.

Vernita Harris mentioned on the third panel the DoD "Electromagnetic Spectrum Superiority Strategy" published in October 2020.

U.S. Dept. of Defense, "Electromagnetic Spectrum Superiority Strategy" (Oct. 2020), *available at* <https://go.usa.gov/xMK8e>.

David Redl mentioned on the last panel proposed legislation recently released by the House Committee on Energy and Commerce that would authorize "opportunistic use" of the 3.1-3.45 GHz band until it is auctioned.

Committee on Energy and Commerce, U.S. House of Representatives, Build Back Better Act, Title III, Subtitle L, Sec. 31201(b)(7) (Committee Print Sept. 9, 2021), *available at* <https://go.usa.gov/xe3yC>.

[Note: post conference, the Energy and Commerce Committee approved an amended version of Subtitle L (Spectrum Auctions), including similar language re "opportunistic use". See Amendment in the nature of a substitute #1 (SUB\_L\_ANS\_01), offered by Mr. Doyle, agreed to by a voice vote (Sept. 12, 2021), *available at* <https://go.usa.gov/xe3yZ>.]

## Recommended Further Reading<sup>7</sup>

Goodman, Ellen P., "Spectrum Rights in the Telecosm to Come", 41 San Diego L. Rev. 269 (2004), *available at* <https://digital.sandiego.edu/sdlr/vol41/iss1/16>.

Weiser, Phil and Hatfield, Dale N., "Spectrum Policy Reform and the Next Frontier of Property Rights", 60 Geo. Mason L. Rev. 549 (2008), *available at* <http://ssrn.com/abstract=1097391>.

Coase, Ronald, Meckling, William, and Minasian, Jora, "Problems of Radio Frequency Allocation," Rand Corporation (1962 and Sept. 1995\*), *available at* <http://www.rand.org/pubs/drafts/DRU1219.html>.

[Note: Rand publication date, although this was written in 1962; see Coase, Ronald H., "Assigning Property Rights to Radio Spectrum Users: Why Did FCC License Auctions Take 67 Years?: Comment on Hazlett", 41 J.L. & Econ. 577-80 (1998)]

Coase, Ronald H., "The Federal Communications Commission", 2 J. L. & Econ. 1-40 (1959), *available at* <https://www.journals.uchicago.edu/doi/abs/10.1086/466549>.

Weiser, Phil, "The Right and Wrong Ways to Manage Water: Lessons from Spectrum and Australia", Attorney General Phil Weiser Prepared Remarks at the Colorado Water Congress 2021 Annual Convention (Feb. 16, 2021), *available at* <https://coag.gov/blog-post/prepared-remarks-attorney-general-phil-weiser-at-the-colorado-water-congress-2021-annual-convention-feb-16-2021/>.

Hazlett, Thomas W. and Skorup, Brent, "Tragedy of the Regulatory Commons: LightSquared and the Missing Spectrum Rights", 13 Duke Law & Technology Review 1-35 (2014), *available at* <https://scholarship.law.duke.edu/dltr/vol13/iss1/1>.

Matheson, R. and Morris, A., "The Technical Basis for Spectrum Rights: Policies to Enhance Market Efficiency", Brookings (Mar. 3, 2011), *available at* [https://www.brookings.edu/wp-content/uploads/2016/06/0303\\_spectrum\\_rights\\_matheson\\_morris.pdf](https://www.brookings.edu/wp-content/uploads/2016/06/0303_spectrum_rights_matheson_morris.pdf).

Hearing before the House Committee on Science, Space, and Technology, "Spectrum Needs for Observations in Earth and Space Sciences" (July 20, 2021), *available at* <https://science.house.gov/hearings/spectrum-needs-for-observations-in-earth-and-space-sciences>.

Agre, Jonathan R., and Gordon, Karen D., Institute for Defense Analyses, Science and Technology Policy Institute, "A Summary of Recent Federal Government Activities to Promote Spectrum Sharing", IDA Paper P-5186 (Sept. 2015), *available at* <https://www.ida.org/~media/Corporate/Files/Publications/STPIPubs/2015/p5186final.ashx>.

National Telecommunications and Information Administration, "The Spectrum Needs of U.S.-Based Space Operations" (July 2021), *available at* <https://go.usa.gov/xMKG5>. [Credit to Bruce Jacobs for referencing this source during the conference.]

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<sup>7</sup> The authors thank Peter Tenhula for compiling this list.

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Silicon Flatirons' mission is to elevate the debate surrounding technology policy issues; support and enable entrepreneurship in the technology community; and inspire, prepare, and place students in these important areas.

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Spectrum policy dictates how, where, and when wireless services can be delivered to devices—and it has deep ramifications for the economy, scientific development, national security, personal enjoyment, and more. Since 2005, Silicon Flatirons has explored the intersection of policy and engineering in the heavily regulated and rapidly changing wireless services industry.

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