Principles of Spectrum Sharing: Understanding the Value of Shared Spectrum

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Coleman Bazelon

Paroma Sanyal

Yong Paek

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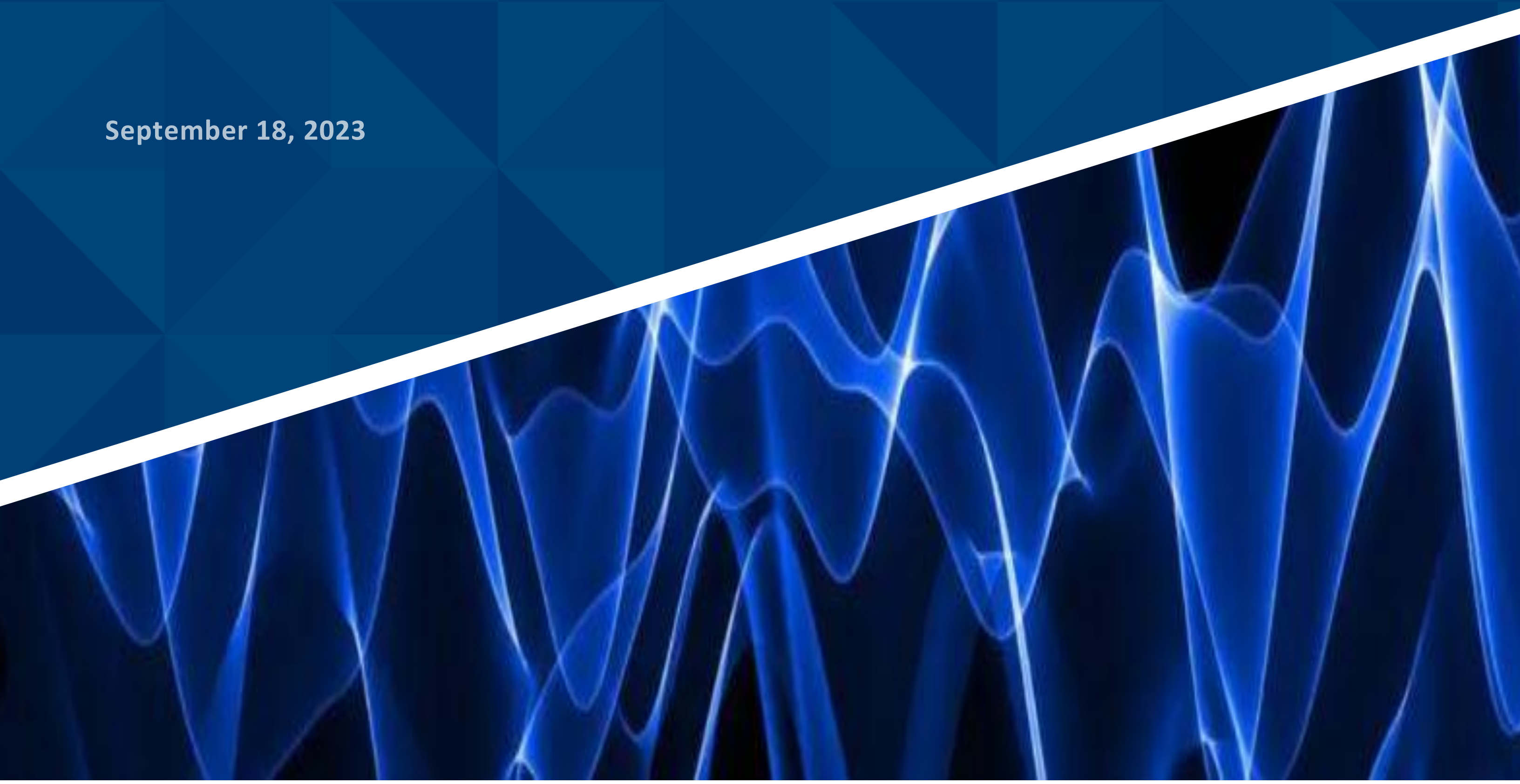

AUTHORS

Coleman Bazelon is an economic expert with much of his practice focused in regulation, strategy and valuation in the wireless, wireline and video sectors. His practice encompasses the modern information infrastructure and the content that fills it. He regularly advises regulators and Congress on radio spectrum policy.

Coleman.Bazelon@brattle.com

Paroma Sanyal is the co-leader of Brattle's Telecommunications, Media and Entertainment practice. She is an expert on telecom regulation and competition issues, spectrum policy, broadband data issues and consumer protection cases in the telecom and internet sphere. Prior to joining Brattle, she was the Chief Economist of the Federal Communications Commission's Wireless Telecommunications Bureau.

Paroma.Sanyal@brattle.com

Yong Paek is an expert in using econometric analysis and computational simulation models to offer insights on regulatory policy and damages calculation. He has experience supporting experts in competition and antitrust matters, regulation and strategy in the wireless sector and product liability and damage assessment in natural resources and agricultural products.

Yong.Paek@brattle.com

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CONTENTS

Executive Summary

As new spectrum based services come online, the demand for spectrum has increased significantly. At the same time, greenfield spectrum to meet these needs is becoming more scarce, and clearing government and other incumbent users from currently-allocated spectrum has become more challenging. For policymakers who have long sought to allocate spectrum to the most valuable uses, shared spectrum is an increasingly important tool for getting the most benefit from limited spectrum resources and maximizing both public and private returns.

In this paper, we develop a framework for accurately valuing a shared licensed regime. Our Principle of Spectrum Sharing suggests the rights to use spectrum should be granted based on a value maximizing principle, where the chosen set of rights maximizes the net aggregate value of spectrum. Policymakers should avoid a focus on auction revenues as a proxy for assessing a spectrum's aggregate economic and social value.

CBRS-style sharing provides an attractive option when completely clearing incumbent users out of large blocks of spectrum imposes significant costs. For example, a large share of valuable mid-band spectrum has been reserved for federal use and would be costly to vacate due to the military's reliance on those frequencies for mission-critical operations. Unlike an exclusive licensing regime, spectrum sharing offers a way to avoid these costs. Additionally, sharing adds significant non-private value from increased participation of non-traditional users and innovative uses of spectrum. Evidence suggests that, by opening spectrum to competition among a diverse group of operators, CBRS-style sharing fosters greater innovation and novel uses. These factors can lead to increases in economic value and consumer welfare. For example, sharing is particularly useful for private networks being used for manufacturing, automotive, agriculture, energy, retail, commercial real estate, communications, media, and supply chain industries, as well as schools and libraries. With sharing, these industries have many more options for investing in 5G applications as they look for innovative, purpose-built solutions to industrial needs, particularly in rural and remote areas that may not be served by traditional carriers.

Our Principle of Spectrum Sharing also illustrates the drawbacks of focusing on auction revenues as a proxy for assessing a spectrum's aggregate economic and social value. Unlike with exclusive licensing, where only one user can operate in the band and incumbents must be cleared at a cost, shared licensing regimes can generate additive values from multiple shared users of the bands and can save costs by not needing to fully clear or relocate incumbents.

For the 3.1-3.45 GHz band, our analysis suggests that the potential public- and private-sector benefits of exclusive licensing would be eclipsed by the public costs, yielding $41.38 billion in net economic losses. In contrast, a spectrum sharing regime following the successful CBRS model would yield a net gain of at least $18.61 billion for new users.

When deciding between a shared licensing versus an exclusive licensing regime careful attention should be paid to all the benefits and costs and then the set of rights – disaggregated or exclusive – should be chosen depending on which has a higher overall net value. Exclusive licensing and shared licensing regimes are complementary strategies to make more 5G spectrum available in the U.S. The choice between them should be based on complete value and cost estimates.

I. Introduction

The right to use radio spectrum is a collection or bundle of different rights.[1] Ronald Coase's classic example regarding land usage rights applies to spectrum as well: "[w]e may speak of a person owning land and using it as a factor of production but what the land-owner in fact possesses is the right to carry out a circumscribed list of actions."[2] The Federal Communications Commission ("FCC" or "the Commission") grants such usage rights to users of spectrum.[3] It is worth noting that, fundamentally, the entire radio spectrum is currently shared, first by dividing it into different frequency bands and then typically by geography amongst the same type of uses, or across uses in the same geography, with each regime defined by a set of property rights.[4] The need for granting spectrum usage rights arises because, in the absence of such rights, there may be a market failure in the spectrum market due to the presence of negative externalities, *i.e.* where one user's use of the resource creates costs for others.[5] In the context of spectrum, interference can be just such an externality, where the individual incentives for rational behavior can cause interference with other users, rendering spectrum unusable absent a mitigation

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1 For the concept of property as a bundle of rights, *see e.g.*, "Property: A Bundle of Rights?," *Econ Journal Watch*, 8(3) (September 2011), https://econjwatch.org/issues/volume-8-issue-3-september-2011. This concept has influenced spectrum discussions for years. *See e.g.*, Linda Doyle & Tim Forde, "Towards a Fluid Spectrum Market for Exclusive Usage Rights," paper presented at the 2nd IEE International Symposium on New Frontiers in Dynamic Access Networks, Dublin, Ireland April 17-20 2007, http://www.tara.tcd.ie/bitstream/handle/2262/23959/towardsafluid?sequence=1. For a discussion of the concept of property rights in the context of radio spectrum *see e.g.*, Thomas W. Hazlett, "Assigning Property Rights to Radio Spectrum Uses: Why Did the FCC License Auctions Take 67 Years?" *Journal of Law and Economics,* 41(S2) (October 1998), http://media.clemson.edu/economics/web/499/FCC/HazlettAssigning%20Property%20RIghts%20to%20Radio%20Spectrum.pdf.

2 Ronald H. Coase, "The Problem of Social Cost," *The Journal of Law & Economics* 3 (October 1960), https://www.law.uchicago.edu/sites/default/files/file/coase-problem.pdf, ("The Problem of Social Cost").

3 We refer to spectrum usage rights instead of spectrum property rights in deference to the legal prohibition on granting property rights in spectrum. Nevertheless, thinking of the spectrum usage rights as a form of property rights is reasonable. *See e.g.*, Congressional Budget Office, "Improving Spectrum Management: The Next Steps" in *Where Do We Go From Here? The FCC Auctions and the Future of Radio Spectrum Management*, (Washington, D.C., 1997), https://www.cbo.gov/sites/default/files/105th-congress-1997-1998/reports/fccauct.pdf.

4 Radio spectrum is more formally known as the electromagnetic spectrum from 3 KHz to 300 GHz. *See*, National Aeronautical Space Administration ("NASA"), "Anatomy of an Electromagnetic Wave," accessed November 20, 2022, https://science.nasa.gov/ems/02_anatomy.

5 Econlib, "Market Failures, Public Goods, and Externalities," accessed November 20, 2022, https://www.econlib.org/library/Topics/College/marketfailures.html.

mechanism.[6] As Coase argued, allocation of well-defined property rights is a way to solve such a market failure.[7] The Coasian view of property can thus be interpreted as a bundle of rights, or as a collection of usage rights for the resource in question. For spectrum, this "requires limitations on the property rights of ownership in a market regime" where each user has well-defined rights along several dimensions such as frequency, geography, and time.[8]

In the context of spectrum, the regulatory approach has historically been fairly blunt. Either all (or most) of the rights are given to a single entity (referred to as exclusive use licenses), or the rights are dispersed to everyone (referred to as open access or license exempt). This blunt approach means potential reallocations may not happen, leaving value unclaimed. However, demand for spectrum continues to grow unabated. According to industry estimates, mobile data demand is projected to grow by a cumulative annual growth rate of 26% in the United States and by 2027 5G penetration is projected to be at 90%.[9] Additionally, new spectrum based services such as Fixed Wireless Access are coming online. This increasing demand highlights the importance of making more spectrum available and makes getting the most benefit from the limited spectrum resource ever more important.[10] Concurrently, clearing spectrum from incumbents and granting a full set of property rights to new users (*i.e.*, an exclusive license) is becoming more difficult – in essence, the low hanging fruits for reallocation have already been harvested.[11] As spectrum is repurposed for new, higher-valued uses, policy makers face choices about how to get the most value from a given band of spectrum. Broadly speaking, they have to decide if more value is created (net of the costs of facilitating the reallocation) from consolidated exclusive rights or from more fragmented, shared rights. As always, policy makers should consider the full set of social value created from a new band of spectrum. In the past, these choices were somewhat more straightforward when completely clearing incumbent users out of large blocks of spectrum was relatively less costly. Going forward, with the costs of fully clearing

[6] Gerald R. Faulhaber and David Farber, "Spectrum Management: Property Rights, Markets, and the Commons," p. 7, January 2002, https://users.ece.cmu.edu/~stancil/SPECTRUM_MANAGEMENTv43.pdf, ("Spectrum Management: Property Rights, Markets, and the Commons").

[7] It is not the only way, but one that economists believe has certain benefits. *See,* The Problem of Social Cost.

[8] Spectrum Management: Property Rights, Markets, and the Commons, p. 7.

[9] We use the North American estimates as a proxy for the United States. *See*, "Ericsson Mobility Report," Ericsson, June 2022, pp. 16, 39, https://www.ericsson.com/49d3a0/assets/local/reports-papers/mobility-report/documents/2022/ericsson-mobility-report-june-2022.pdf, ("Ericsson Mobility Report 2022").

[10] For example, according to Ericsson, in the first half of 2022 alone, in North America, 60% of all service providers offered 5G FWA. *See*, Ericsson Mobility Report 2022, p. 10.

[11] GSMA, "Spectrum Sharing," GSMA Public Policy Position, June 2021, p. 3, https://www.gsma.com/spectrum/wp-content/uploads/2021/06/Spectrum-Sharing-Positions.pdf, ("Spectrum Sharing GSMA 2021").

incumbents rising, the value from creating a shared allocation becomes increasingly more attractive. The Pentagon recently stated that vacating the mid-band for commercial 5G would cost the Department of Defense ("DoD") at least $120 billion to clear 350 megahertz of spectrum in the 3.1 – 3.45 GHz band.[12] To put this into context, this estimated figure is almost 50% greater than the total proceeds from the C-Band auction (280 megahertz of spectrum), the largest auction ever in the U.S., which raised $81.1 billion in net proceeds.[13] The CTIA had also recently stated, it too supported the "innovative uses of spectrum where it is appropriate and makes sense given technical and operational constraints."[14]

Consequently, this paper develops a framework for analyzing the value of different sets of disaggregated spectrum rights, from unlicensed, to sharing to exclusive use. We view the various collection of usage rights along a rights continuum with each regime encompassing a different configuration of those rights. In this paper, we focus on the set of disaggregated rights that are encompassed within a spectrum sharing regime. We explore a sharing regime where multiple users use the same frequency band in the same geography, subject to certain agreed-upon limitations. We develop a Principle of Spectrum Sharing to help guide policy makers through this decision making process. This Principle posits that the collection of spectrum property rights granted to users should be determined by a value maximizing principle, where the chosen set of granted rights maximizes the net aggregate value of spectrum, with value for these purposes encompassing both the private and non-private value of the spectrum.

This paper consists of five sections, including this introduction. Section II discusses the background of spectrum sharing, including the various types of sharing regimes and bands that are being currently discussed as potential candidates. Section III presents an empirical analysis of factors that influence the value of spectrum under exclusive versus sharing regimes. We focus on the CBRS Band, the C-Band and the 3.45 GHz auctions in this section. Section IV discusses and illustrates the principle that should guide a sharing versus exclusivity decision and the parameters that should weigh into the consideration of when to favor one regime versus the other. Section V concludes.

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12 Keith Kellog, "Congress May Sell Out National Security for 5G — There's a Better Way," The Hill, April 5, 2023, https://thehill.com/opinion/national-security/3932016-congress-may-sell-out-national-security-for-5g-theres-a-better-way/, ("Congress May Sell Out National Security for 5G — There's a Better Way").

13 FCC, "Auction 107: 3.7 GHz Service," accessed July 6, 2023, https://www.fcc.gov/auction/107.

14 CTIA, "CTIA Spectrum Ex Parte," December 12, 2022, p. 5, https://www.fcc.gov/ecfs/document/1212015633657/1.

II. Background on Spectrum Sharing

The idea of sharing extends to various aspects of life, such as sharing a home through services like Airbnb, or sharing a car through services like Turo or Zipcar. For some assets, such as a vehicle or a house, exclusive access has generally been the historical norm. For radio spectrum, however, sharing has had a long history. Indeed, as noted earlier, almost all spectrum (including so-called "exclusive licensed" spectrum) is in fact shared in some fashion. For instance, the same cellular frequencies are used by multiple operators in different geographic areas and such geographical separation offers a straightforward sharing solution. The primary focus of this paper is a more complex sharing mechanism where different entities wish to use the same spectrum dynamically in the same place, and possibly, at the same time.

The U.S. has had a long history of implementing shared spectrum regime in various frequency bands. For example, since 2014, federal systems and cellular networks have shared the AWS-3 band on a geographic basis.[15] In the 600 MHz white spaces, computing devices and television share the same frequency through the use of static coordination mechanisms.[16] More recently, various advanced sharing mechanism through the use of dynamic sharing and sensing technologies have been explored and are being actively deployed. Sharing between LTE and 5G NR in current cellular bands, between 5G and Wi-Fi (5G NR-Unlicensed) in the 5 GHz band, between fixed microwave and Wi-Fi in the 6 GHz band are some examples of such spectrum sharing.[17] In each instance, the configuration of usage rights defines the contours of the sharing regime. Below, we elaborate on the dimensions along which such sharing can occur, existing sharing mechanisms, and potential bands being considered for sharing.

A. Defining the Collection of Spectrum Usage Rights

Spectrum usage rights can be defined in the dimensions of frequency (which specific frequencies are authorized to be used), geography (where can the frequencies be used), time (when the frequencies can be used), priority (which uses or users have precedence over others), power

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15 NTIA, "Portal Opens for AWS-3 Spectrum Sharing Coordination," accessed September 5, 2023, https://ntia.gov/blog/portal-opens-aws-3-spectrum-sharing-coordination.

16 FCC, "In the Matter of Updating References to Standards…," ET Docket Nos. 04-186 and 14-165, Second Order on Reconsideration and Order, FCC-CIRC2201-05, January 6, 2022, https://docs.fcc.gov/public/attachments/DOC-378986A1.pdf.

17 Peter Rysavy, "Spectrum Sharing," Rysavy Research, February 2023, p. 7, https://rysavyresearch.files.wordpress.com/2023/02/2023-02-rysavy-spectrum-sharing.pdf.

(how much energy can be used on these frequencies), and so on. How many or how much these *complementary property / usage rights* a user has access to defines the continuum between exclusive use, sharing and unlicensed spectrum governance regimes.

On a spectrum usage rights continuum, exclusive licenses allow for the broadest set of consolidated rights within that bundle with fewer users; an unlicensed regime is the other bookend, with a severely limited set of rights but a large number of potential users. Often, spectrum sharing is contrasted with exclusive licensing where an operator has an exclusive license to the spectrum in a particular geography. As few bands are completely exclusively licensed – that is with a single licensee across the entire United States – most exclusively licensed frequencies are shared in the frequency (blocks within an allocation) and geographic (sub-national license areas) dimensions, which is called *exclusive sharing*.[18] The collection of rights that a spectrum user enjoys determines where in the spectrum property rights continuum they are situated.

The collection of rights granted to spectrum users also determines the dimension along which spectrum may be shared. For example, use-based sharing may place restrictions on the types of uses that are allowed in the band along with other restrictions.[19] As another example, frequency-based sharing may place limitations on the power limits included in the collection of rights to enable sharing by keeping signals within their assigned frequencies.[20] Alternatively, a geographic-based sharing regime, where multiple users use the same frequency in different geographic areas, may require limiting rights in certain geographic areas, and can facilitate exclusion zones to protect incumbent operations.[21] A time-based sharing regime, where licensed-sharing is achieved by taking advantage of users' active spectrum usage, may require granting priority rights on the time dimension to certain users.[22] Globally, over the past decade,

[18] Kyung Mun, "Different Shades of Spectrum Sharing: Mun," Fierce Wireless, December 22, 2020, accessed November 20, 2022, https://www.fiercewireless.com/tech/different-shades-spectrum-sharing-mun, ("Different Shades of Spectrum Sharing").

[19] For example, the 12 GHz Band is currently assigned on a co-primary basis to operators in three services - Direct Broadcast Satellite ("DBS") operators, the Multi-Channel Video and Data Distribution Service ("MVDDS") terrestrial licensees and non-geostationary orbit ("NGSO") satellite systems. *See*, FCC, "In the Matter of Expanding Flexible Use of the 12.2 – 12.7 GHz Band…," WT Docket No. 20-443, GN Docket No. 17-183, RM-11768, Notice of Proposed Rulemaking, FCC-21-13, adopted Jan 12, 2021, ¶ 1, https://www.fcc.gov/document/fcc-seeks-comment-maximizing-efficient-use-12-ghz-band, ("12 GHz NPRM").

[20] Spectrum Sharing GSMA 2021, pp. 3-7.

[21] Spectrum Sharing GSMA 2021, p. 7.

[22] Edward F. Drocella Jr., Robert L. Sole, and Nickolas LaSorte, "Technical Feasibility of Sharing Federal Spectrum with Future Commercial Operations in the 3450 – 3550 MHz Band," NTIA Technical Report TR-20-546, January

shared spectrum licensing has been actively encouraged, with the European Union, United Kingdom, Hong Kong and China all having implemented some form of spectrum sharing.[23]

The two primary disaggregated rights or shared-licensing approaches – a *coordinated sharing* approach and an *uncoordinated sharing* approach – are based on how these collection of rights are managed under shared-licensed access.[24] Under a coordinated sharing scheme, the focus is on sharable access governed by the existence of sharing rules.[25] Within this, there can be dynamic and static sharing of the band, with dynamic access facilitated by tiered licensed and generally authorized access, where "smart" systems can preserve a primary licensee's right to exclusive use of certain frequencies and guide the capabilities of secondary users, *e.g.*, the CBRS Band.[26] In the uncoordinated unlicensed sharing regime, often called coexistence/license-exempt access or concurrent shared access, multiple technologies use the same spectrum at the same time, *e.g.*, Bluetooth and Wi-Fi, with various technical protocols and significantly limited power levels facilitating sharing without priority access licenses.[27] This Report's primary focus is on exclusive and coordinated licensed sharing. However, the Principles of Spectrum Sharing can be applied more broadly, including to uncoordinated sharing as well.

2020, p. viii, https://its.ntia.gov/publications/details.aspx?pub=3236, ("NTIA Report TR-20-546 on Sharing Federal Spectrum with Future Commercial Operations").

[23] Since 2012, the European Union has urged its Member States to "foster the collective and shared use of spectrum where appropriate." Germany, France, Denmark, Hong Kong and China all have implemented some form of spectrum sharing. The United Kingdom had developed a framework for enabling shared use of spectrum on a localized basis in 2019. Hong Kong and China have designated 400 MHz of spectrum in the 26/28 GHz (27.95-28.35 GHz) bands to be available as shared spectrum for a localized wireless broadband service, in blocks of 100 megahertz. *See*, "A Global Overview of Spectrum Sharing Initiatives," Alpha Wireless, February 2, 2021, accessed November 20, 2022, https://alphawireless.com/a-global-overview-of-spectrum-sharing-initiatives/. *See also*, "Use of Shared Spectrum at the National Level," ITU and The World Bank, October 6, 2020, accessed November 20, 2022, https://digitalregulation.org/use-of-shared-spectrum-at-the-national-level/.

[24] You Han, Eylem Ekici, Haris Kremo, and Onur Altintas, "Spectrum Sharing Methods for the Coexistence of Multiple RF Systems: A Survey," *Ad Hoc Networks* 53 (2016), pp. 54-56, http://www.eleceng.ohio-state.edu/~ekici/papers/coexist_adhoc.pdf, ("Spectrum Sharing Methods Survey"). *See also*, Spectrum Sharing GSMA 2021, p. 4.

[25] Spectrum Sharing GSMA 2021, p. 5.

[26] NIST, "Spectrum Sharing," February 4, 2019, accessed November 20, 2022, https://www.nist.gov/advanced-communications/spectrum-sharing, ("Spectrum Sharing NIST").

[27] Spectrum Sharing Methods Survey, p. 54.

B. Usage Rights and the Efficient Use of an Increasingly Scarce Resource under Coordinated Licensed Sharing

In this section, we briefly discuss different types of coordinated shared-licensing. As noted, shared licensing can take several forms, ranging from spectrum shared by users, spectrum bands shared by different services that coexist in the same frequencies without interference, sharing dynamically along a time dimension and sharing only in certain geographies. We describe shared-licensing under three disaggregated usage rights scenarios – time/frequency/priority, geography, and type of use.

1. Sharing a Spectrum Band in Time and Frequency – Timing, Frequency and Priority Limitations on Spectrum Rights

Sometimes sharing can entail giving priority to a specific use or user. As discussed later in this section, some of the mid-band spectrum that is now being considered for 5G uses has federal incumbents, and clearing this incumbent use is not considered a feasible option. Auction 105, the CBRS/3.5 GHz auction, which concluded on August 25, 2020, exemplifies how sharing can be implemented between terrestrial wireless use and critical Department of Defense ("DOD") needs.[28] This band had federal incumbents and critical radars that needed to be protected from interference from all other users. Relocating them to another band to clear the CBRS band for exclusive licenses was determined to be too costly to their functionality.[29] Hence, sharing the band in a way that protected the federal incumbents and allowed terrestrial wireless use was a way of maximizing the use of the band.

[28] FCC, "3.5 GHz Band Overview: Tiers," accessed November, 2022, https://www.fcc.gov/wireless/bureau-divisions/mobility-division/35-ghz-band/35-ghz-band-overview, ("3.5 GHz Band Overview").

[29] "In this region of the spectrum multipath propagation problems decrease which is critical for the detection of targets at low elevation angles." *See*, Gary Locke and Lawrence E. Strickling, "An Assessment of the Near-Term Viability of Accommodating Wireless Broadband Systems in the 1675 – 1710 MHz, 1755 – 1780 MHz, 3500 – 3650 MHz, and 4200 – 4220 MHz, 4380 – 4400 MHz Bands," U.S. Department of Commerce, October 2010, accessed December 12, 2022, https://www.ntia.doc.gov/files/ntia/publications/fasttrackevaluation_11152010.pdf, FN 20.

The FCC created a three-tiered access and authorization framework to coordinate shared federal and non-federal use of 150 megahertz of spectrum in the band. [30] Incumbents comprised the first tier (Incumbent Access) and receive protection from all other users, followed by Priority Access Licenses ("PALs") in the second tier, and General Authorized Access ("GAA") users in the third tier.[31] The Incumbent Access tier includes authorized federal users, fixed satellite service earth stations, and some wireless broadband licensees, all of whom are protected from interference from all other users. The PALs have licensed access to the spectrum in this band and are protected from interference from GAA users.[32] The GAA users did not need to purchase licenses, and can be any entity using any part of the 3.5 GHz band on licensed-by-rule basis so long as they coordinate access through a Spectrum Access System ("SAS") and do not cause harmful interference to either the incumbents or PAL licensees.[33] Figure 1 below shows the tiers in this band.

FIGURE 1: TIERS IN THE 3.5 GHZ BAND

<table>
<tr><td>3550 MHz</td><td>3600 MHz</td><td>3650 MHz</td><td>3700 MHz</td></tr>
<tr><td colspan="2">Tier 1: Federal Radiolocation and Federal Aeronautical Radionavigation</td><td colspan="2" rowspan="4">Tier 1: Incumbent Federal Uses
Tier 3: General Authorized Access</td></tr>
<tr><td></td><td>Tier 1: Non-Federal Grandfathered Fixed Satellite Service (space-to-Earth)</td></tr>
<tr><td colspan="2">Tier 2: Priority Access Licenses</td></tr>
<tr><td colspan="2">Tier 3: General Authorized Access</td></tr>
</table>

Sources and Notes:
FCC, "Auction of Priority Access Licenses for the 3550-3650 Band; Notice and Filing Requirements, Minimum Opening Bids, Upfront Payments, and Other Procedures for Auction 105; Bidding in Auction 105 Scheduled to Begin June 25, 2020," AU Docket No. 19-244, Public Notice, adopted March 2, 2020, p. 38, https://docs.fcc.gov/public/attachments/FCC-20-18A1.pdf.

Ultimately, 70 megahertz of PAL licenses was auctioned for flexible, prioritized shared use at the county level, and each PAL user could hold up to four 10-megahertz licenses (out of a total of seven) within the band in any license area at any given time.[34] One important aspect of this

[30] FCC, "In the Matter of Amendment of the Commission's Rules with Regard to Commercial Operations in 3550 – 3650 MHz Band," GN-Docket No. 12-354, Report and Order and Second Further Notice of Proposed Rulemaking, FCC 15-47, adopted April 17, 2015, https://docs.fcc.gov/public/attachments/FCC-15-47A1.pdf.

[31] 3.5 GHz Band Overview: Tiers.

[32] "Priority Access Licenses," Spectrum Access System, accessed December 15, 2022, https://support.google.com/sas/answer/10399813?hl=en.

[33] 3.5 GHz Band Overview: Tiers.

[34] This auction offered seven PALs, each of which consists of a ten-year renewable, 10 megahertz license, in each county-based license area, for a total of 22,631 PALs. *See*, FCC, "Auction of Priority Access Licenses for the 3550 – 3650 Band; Notice and Filing Requirements, Minimum Opening Bids, Upfront Payments, and Other Procedures for Auction 105; Bidding in Auction 105 Scheduled to Begin June 25, 2020," AU Docket No. 19-244, Public Notice,

arrangement is that PAL licenses do not have guaranteed usage rights to specific frequencies, but rather have priority access rights to the amount of spectrum specified by the license, and a SAS can "dynamically reassign a PAL to a different channel as needed to accommodate a higher priority Incumbent Access user."[35] This innovative rights regime makes the CBRS band a potential model for maximizing the utility of vital mid-band spectrum in cases where moving federal incumbents is extremely costly.[36]

The mixed-use sharing regime of the CBRS Band ensured that valuable rights to use the spectrum did not go fallow. Had the entire band needed to be cleared, it likely would not have been since that was seen as cost prohibitive, and the set of rights in the band complementary to the incumbent governmental uses would have remained unused.[37] Absent the use of innovative PALs (*i.e.*, shared licenses), the band would have been split between incumbent users and GAA licenses.[38] Under the shared-licensed approach chosen, some portion of the band (70 megahertz) is expected to be available everywhere and all the time, and all of the band (150 megahertz) can be used for new uses at the times and geographic areas when and where the spectrum is not needed by the incumbent governmental users. The approach was based on creating disaggregated rights in the band, and making the most value of each right.

adopted March 2, 2020, ¶¶ 3, 8, 161, https://docs.fcc.gov/public/attachments/FCC-20-18A1.pdf, ("Auction 105 PN").

35 Auction 105 PN, ¶ 8.

SAS is a cloud-based service that manages the wireless communications of devices transmitting in the CBRS Band, in order to prevent harmful interference to higher priority users. *See*, SAS, "How SAS Works," accessed November 21, 2022, https://support.google.com/sas/answer/9539282?hl=en.

36 We note that going forward, newer technologies such as Automated Frequency Coordination (AFC) may be used for sharing spectrum resources. Our analysis is agnostic about the technology that enables sharing. Also note that some commentators have pointed to challenges faced by the CBRS sharing scheme. *See* Comments of Ericsson, "An Analysis of Aggregate CBRS SAS Data from April 2021 to January 2023," NTIA Report 23-567, May 31, 2023, https://its.ntia.gov/media/sxipld5c/ericsson-comments-on-tr-23-567.pdf.

37 We understand that there were no frequencies in the band that could be available to new uses in all geographic areas and at all times, making a smaller set of exclusive usage rights not feasible.

38 With the non-incumbent access provided either through a managed access system or a more limited set of rights through a subset of frequencies and geographies with more traditional (passive or unmanaged) unlicensed access. Without the PALs, how the cost of the spectrum access managers' services would have been paid for would be uncertain.

2. Sharing a Spectrum Band in Defined Geographies – Geographic Limitations on Spectrum Usage rights

Some bands have distinct geographic partitions with very different rules governing different geographic areas. Auction 110, which closed on January 4, 2022, auctioned 100 megahertz of spectrum in the 3.45 GHz band organized into 4,060 licenses.[39] The licenses auctioned were flexible-use licenses for ten 10-megahertz blocks in each of the 406 PEAs in the band.[40] The 3.45 GHz band is used by the DOD for radar systems, but in the geographic areas where relocating the DOD systems was inexpensive, or where the DOD did not use the band, exclusive licenses were offered.[41] In areas where the DOD could not move, the FCC auctioned flexible-use shared licenses, with a requirement to share the spectrum with DOD incumbent users.[42] In addition to the federal users, there were secondary non-federal licensees that were relocated to the 2.9 – 3.0 GHz band, and the Auction 110 winners were required to pay for these non-federal relocation costs in addition to their winning bid amounts.[43]

3. Sharing a Band between Different Types of Services – Spectrum Usage Rights Defined by Types of Use

Most bands are shared in some way with various services having primary and secondary rights to the band.[44] The 12 GHz band (12.2 GHz – 12.7 GHz) is a good example of a band that is currently shared by different types of services. The band incudes DBS operators such as Dish Network and DirecTV; MVDDS terrestrial licensees "operating on a non-harmful interference basis to DBS under the co-primary Fixed Service allocation"; and NGSOs such as SpaceX and One Web

[39] FCC, "Auction 110: 3.45 GHz Service," Summary and Fact Sheet, accessed December 6, 2022, https://www.fcc.gov/auction/110. *See also*, FCC "In the Matter of Facilitating Shared Use in the 3100 – 3550 MHz Band," WT Docket No. 19-348, Second Report and Order, Order on Reconsideration, and Order of Proposed Modification, FCC 21-32, March 18, 2021, https://docs.fcc.gov/public/attachments/FCC-21-32A1.pdf, ("Auction 110 Report and Order").

[40] FCC, "Auction of Flexible-Use Service Licenses in the 3.45 – 3.55 GHz Band for Next-Generation Wireless Services; Comment Sought on Competitive Bidding Procedures for Auction 110," AU Docket No. 21-62, Public Notice, FCC 21-33, March 18, 2021, ¶¶ 9, 29, 47, https://www.fcc.gov/document/fcc-seeks-comment-mid-band-spectrum-auction-0, ("Auction 110 PN").

[41] Auction 110 Report and Order, ¶¶ 20, 21.

[42] Auction 110 Report and Order, ¶¶ 21-23.

[43] Auction 110 Report and Order, ¶ 154. Note that these costs were not a significant share of license prices.

[44] U.S. Department of Commerce, "Annual Report on the Status of Spectrum Repurposing," August 2019, https://www.ntia.gov/files/ntia/publications/spectrum_repurposing_report_august_2019.pdf.

"operating on a non-harmful interference basis to DBS under the co-primary NGSO FSS allocation," as mentioned earlier in this report.[45]

The DBS allocation and assignment of licenses in the 12 GHz band were granted in the early 1980s and early 1990s, and operations using the spectrum began in 1994.[46] DBS operators have "exclusive rights to transmit from each of their orbital slots" but, they do not have exclusive rights in terms of geographic coverage, i.e., each DBS provider can use the full 500 megahertz in the band "on a shared basis" with the other DBS providers.[47] In 2000, the FCC allowed MVDDS to operate on a non-harmful interference basis with respect to incumbent DBS providers and allowed "one-way digital fixed non-broadcast service, including one-way direct-to-home/office wireless service."[48] The FCC auctioned MVDDS licenses in 2004 and 2005.[49] Currently, eight companies hold 191 of the 214 terrestrial fixed licenses.[50] In 2017, the Commission allowed the deployment of a new generation of NGSO FSS systems with hundreds of small satellites, and companies such as SpaceX, OneWeb and Kepler Communications have begun to launch Low Earth Orbit (LEO) NGSO satellite constellations.[51]

In January 2021, the FCC opened an inquiry about allowing terrestrial flexible use in this band and whether it could be shared with the existing services in the band.[52] In 2023, the Commission issued a Further Notice of Proposed Rulemaking ("NPRM") in which it is seeking comment on further sharing the band with other services such as terrestrial fixed use.[53]

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45 12 GHz NPRM, ¶ 3. Note FSS represents Fixed Satellite Service (space-to-Earth).

46 12 GHz NPRM, ¶ 6.

47 12 GHz NPRM, ¶ 36.

48 12 GHz NPRM, ¶¶ 6-7.

49 FCC. "Auction 63: Multichannel Video Distribution & Data Service (MVDDS)," https://www.fcc.gov/auction/53/factsheet, and FCC, "Auction 63: Multichannel Video Distribution & Data Service (MVDDS)," accessed May 1, 2021, https://www.fcc.gov/auction/63/factsheet.

50 12 GHz NPRM, ¶ 11.

51 12 GHz NPRM, ¶ 10; Bernardo Schneiderman, "The Next Wave: Low Earth Orbit Constellations," Satellite Markets & Research, March 4, 2019, accessed September 14, 2023, https://satellitemarkets.com/news-analysis/next-wave-low-earth-orbit-constellations.

52 12 GHz NPRM.

53 FCC, "In the Matter of Expanding Flexible Use of the 12.2 – 12.7 GHz Band; Expanding Use of the 12.7 – 13.25 GHz Band for Mobile Broadband or Other Expanded Use," WT Docket No. 20-443, GN Docket No. 22-352, Report and Order and Further Notice of Proposed Rulemaking and Notice of Proposed Rulemaking and Order , FCC 23-36, adopted May 18, 2023, ¶ 49, https://docs.fcc.gov/public/attachments/FCC-23-36A1.pdf, ("2023 12.7 GHz NPRM").

C. Spectrum Bands Being Considered for Reallocation

The U.S. is at a juncture where low- or mid-band spectrum can only be reallocated to mobile uses at larger and larger costs. Technological advances in recent years make shared spectrum licensing possible and highly viable as greenfield spectrum diminishes. It is becoming increasingly expensive to completely remove incumbents from bands, and attempting to clear bands often fails and leads to costly delays. For example, the 1.3 GHz band was under discussion for a potential auction by 2021, but compensating incumbents has been an impediment.[54] The old model of "clear & auction" is not the only approach available to policy makers. Spectrum sharing may be a viable option for some spectrum bands. In fact, spectrum sharing may be necessary because of the growing demand for spectrum and the lack of available spectrum that can be reallocated for exclusive licensing.

The primary mid-band spectrum that can meet the ever-increasing data demands are with the DOD, and these bands are often used for national security systems, such as high power radars.[55] Such uses are unambiguously valuable to the United States and often cannot be relocated to other bands. Consequently, some of the mid-band spectrum that the DOD holds cannot be cleared for exclusive mobile use, and certainly not for a reasonable cost. However, it is also true that these bands are not being fully utilized by the DOD.[56] Thus, there are valuable opportunities for using this spectrum for mobile telecommunications uses, and new sharing approaches, such as in the CBRS Band, demonstrate that doing so can be facilitated while accommodating incumbent needs.

The primary purpose of any shared spectrum licensing scheme is to "ensure that when the primary user does not need the spectrum, another party can put it to good use, as opposed to

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[54] FAA, "Spectrum Efficient National Surveillance Radar (SENSR)," accessed November 20, 2022, https://www.faa.gov/air_traffic/technology/sensr.

[55] NTIA, "How the Spectrum is Used," accessed November 20, 2022, https://www.ntia.doc.gov/book-page/how-spectrum-used, ("How the Spectrum is Used"). *See also*, Kelly Hill, "Limitations on US Midband 5G Spectrum," RCR Wireless News, October 14, 2022, accessed November 20, 2022, https://www.rcrwireless.com/20221014/featured/limitations-on-us-midband-5g-spectrum.

[56] How the Spectrum is Used.

allowing it to remain fallow."[57] For example, while a DOD radar system may depend on spectrum being available instantaneously in certain geographies at specific times, that spectrum can be freed up for commercial purposes at other times and other geographies while protecting the critical national security need. In fact, as early as 2012, the President's Council of Advisors on Science and Technology ("PCAST") recommended that the President declare it is "the policy of the U.S. government to share underutilized Federal spectrum to the maximum extent possible that is consistent with the Federal mission, and require the Secretary of Commerce to immediately identify 1,000 MHz of Federal spectrum in which to implement the new architecture and thereby create the first shared-use spectrum superhighways."[58] Such a use-it-or-share-it regime, when implemented using our Principal of Spectrum Sharing, can lead to enhanced efficiency in spectrum use without harming any primary users such as DOD.[59] The 2021 Investment, Infrastructure and Jobs Act ("IIJA") tasks the FCC and the National Telecommunications and Information Administration ("NTIA") with identifying frequencies/bands where sharing between federal and non-federal commercial users would be feasible under flexible-use licensed and unlicensed service rules.[60] Even before the IIJA, the NTIA and the FCC were exploring spectrum bands suitable for 5G deployments.[61] Below we briefly describe these bands under two categories – (i) those that are now being actively considered by the FCC and where the FCC has initiated a formal inquiry such as a Notice of Inquiry ("NOI") or a NPRM; and (ii) other high mid- bands that are under consideration but no formal action has been taken.

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[57] Jason Furman and John P. Holdren, "Making the Most of the Wireless Spectrum," The White House, July 20, 2012, https://obamawhitehouse.archives.gov/blog/2012/07/20/making-most-wireless-spectrum.

[58] "Report to the President: Realizing the Full Potential of Government-Held Spectrum to Spur Economic Growth," Executive Office of the President, President's Council of Advisers on Science and Technology, July 2012, p. vii, https://obamawhitehouse.archives.gov/sites/default/files/microsites/ostp/pcast_spectrum_report_final_july_20_2012.pdf.

[59] Michael Calabrese, "Use It or Share It: A New Default Policy for Spectrum Management," New America, March 2021, p. 5, https://d1y8sb8igg2f8e.cloudfront.net/documents/Use_It_or_Share_It.pdf.

[60] "Public Law 117–58: Infrastructure Investment and Jobs Act," 117th Congress, November 15, 2021, p. 921, https://www.congress.gov/117/plaws/publ58/PLAW-117publ58.pdf, ("Infrastructure Investment and Jobs Act 2021"). The Bill also stipulates that identifying such bands should happen within 21 months of the Bill being signed into law.

[61] US Department of Commerce, "Annual Report on the Status of Spectrum Repurposing," August 2019, https://www.ntia.gov/files/ntia/publications/spectrum_repurposing_report_august_2019.pdf.

1. Bands under Active Consideration by the FCC

a. 3.1-3.45 GHz Band

The 350 megahertz of spectrum in the 3.1-3.45 GHz band is used internationally for 5G, and has received a significant amount of attention in the past couple of years.[62] In the U.S. Table of Frequency Allocations, this frequency range is divided into the 3.1-3.3 GHz and 3.3-3.5 GHz bands.[63] The 3.1-3.3 GHz band is allocated to "federal radiolocation on a primary basis and to Earth exploration-satellite (active) and space research (active) on a secondary basis," and the 3.3-3.5 GHz is allocated to "federal radiolocation on a primary basis."[64] In 2020, a report authored by the NTIA (National Telecom and Information Administration) determined some sharing could be possible below the 3.45 GHz band.[65] The 2021 IIJA specifically identifies the 3.1-3.45 GHz band as a potential candidate for reallocation to 5G.[66] To incentivize the federal incumbents to explore reallocating the band for non-federal use, the bill provides that a federal incumbent in the 3.1 GHz band may receive a payment of up to $50 million from the Spectrum Relocation Fund for technical or economic research in order to make the band available "on a shared basis between Federal use and non-Federal commercial licensed use, subject to flexible-use service rules."[67]

Currently, the 3.1-3.45 GHz band is allocated for both federal and non-federal radiolocation services. With the federal radiolocation services operating on a primary basis and the non-federal users (private land mobile services) operating on a secondary basis, and the DOD "operates high-powered defense radar systems on fixed, mobile, shipborne, and airborne platforms in this band."[68] The non-federal allocations in the lower part this band include radiolocation licenses held by utility companies and municipalities, amateur services, and holders of experimental licenses such as special temporary authorizations ("STAs").[69]

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[62] Bevin Fletcher, "What the Latest Infrastructure Bill Says About 3.1 – 3.45 GHz," Fierce Wireless, August 2, 2021, https://www.fiercewireless.com/regulatory/what-latest-infrastructure-bill-says-about-3-1-3-45-ghz, ("What the Latest Infrastructure Bill Says About 3.1 – 3.45 GHz").

[63] NTIA Report TR-20-546 on Sharing Federal Spectrum with Future Commercial Operations, p. 4.

[64] NTIA Report TR-20-546 on Sharing Federal Spectrum with Future Commercial Operations, p. 4.

[65] NTIA Report TR-20-546 on Sharing Federal Spectrum with Future Commercial Operations, pp. 126-127.

[66] What the Latest Infrastructure Bill Says About 3.1 – 3.45 GHz.

[67] Infrastructure Investment and Jobs Act 2021, p. 135.

[68] FCC, "Facilitating Shared Use in the 3100 – 3550 MHz Band," WT Docket No. 19-348, Final Rule, FCC 20-138, October 9, 2020, ¶ 6, https://www.govinfo.gov/content/pkg/FR-2020-10-09/pdf/2020-22528.pdf, ("Facilitating Shared Use in the 3100 – 3550 MHz Band").

[69] Facilitating Shared Use in the 3100 – 3550 MHz Band, at ¶ 7.

In April 2022, Senators Ben Ray Luján and John Thune introduced the Spectrum Innovation Act of 2022, which required the identification of "at least 200 megahertz of frequencies in the covered band for non-Federal use, shared Federal and non-Federal use, or a combination thereof."[70] In September 2022, Senator Mike Lee introduced a bill (S. 4820) that requires the Commerce Secretary to identify 350 megahertz of spectrum in that band to be reallocated by the Commission through an auction for non-Federal use or shared Federal and non-Federal use, or a combination thereof.[71] In May 2023, the U.S. House Committee on Energy and Commerce approved a bill that would amend the IIJA by requiring the Secretary of Commerce to identify 350 megahertz of spectrum in the 3.1-3.45 spectrum band for "non-Federal use, shared Federal and non-Federal use, or a combination thereof," and directing the Commission to commence an auction not later than January 15, 2028, of the frequencies identified by the Secretary as suitable for an auction.[72] Under both bills, proceeds from the auction would be used to cover 110% of the relocation and/or sharing costs for federal entities.

In recent months, there has been discussions about whether the Congress should allow the DOD to complete its study and determine the frequencies it can share with non-federal users, or whether the Congress should ask DOD to study the 3.1-3.45 GHz segment and its suitability for non-federal use.[73] On March 5, 2023, the Secretaries of Defense and Commerce recommended that any decision regarding the availability of the specific segment for commercial use should be dependent on conducting a comprehensive study to evaluate its potential impact on federal operations.[74] Additionally as discussed earlier, the DOD has put a $120 billion price tag (if not higher) on clearing this band.[75]

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70 "S.4117 - Spectrum Innovation Act of 2022," 117th Congress, April 28, 2022, p. 5, https://www.govinfo.gov/content/pkg/BILLS-117s4117is/pdf/BILLS-117s4117is.pdf.

71 "S.4820 - Protecting Communications Networks from Chinese Communist Party Espionage Act," 117th Congress, September 12, 2022, p. 2, https://www.congress.gov/117/bills/s4820/BILLS-117s4820is.pdf, ("S.4820 Senate Spectrum Bill").

72 H.R. 3565, 118th Cong. (reported May 24, 2023). The bill would also extend the Commission's general auction authority until September 30, 2026.

73 Congressional Research Service, "Repurposing 3.1 – 3.55 GHz Spectrum: Issues for Congress," March 16, 2023, p. 3, https://sgp.fas.org/crs/misc/IF12351.pdf, ("Repurposing 3.1 – 3.55 GHz Spectrum: Issues for Congress").

74 Repurposing 3.1 – 3.55 GHz Spectrum: Issues for Congress, p. 2.

75 Congress May Sell Out National Security for 5G — There's a Better Way. *See also*, "Transcript of House Armed Services Subcommittee on Strategic Forces Hearing on Strategic Forces Posture," March 08, 2023, https://www.stratcom.mil/Media/Speeches/Article/3325743/hasc-sf-subcommittee-fiscal-year-2024-strategic-forces-posture-hearing/.

b. 12.7 GHz Band

The FCC is exploring the use of the 550 megahertz of spectrum between 12.7-13.25 GHz (12.7 GHz band), for terrestrial mobile use.[76] The Commission specifically wants to investigate sharing approaches that could "promote coexistence in the band" with minimal potential for harmful interference, potential relocation of some or all of the current incumbents to clear the band, as well as potential for accelerated relocation or repacking of incumbent licensees to make this spectrum more rapidly available for new uses."[77]

In the U.S., the 12.7 GHz band is shared among Fixed Microwave Services, Broadcast Auxiliary Services, Cable Television Relay Services, and Fixed Satellite Services; its limited Federal use is by the NASA, which "operates a receive-only earth station for its Deep Space Network (DSN) at Goldstone, California that is authorized to receive transmissions across the entire 12.75-13.25 GHz band."[78] Given the existing incumbent uses of the band, the FCC explores two potential options for flexible use of the band – a scenario where new entrants could share the band with incumbent users, or a scenario where incumbent users could relocate to other spectrum or technologies and the band could be cleared for exclusive use.[79] The FCC also seeks comments "on the costs and benefits that should be considered in deciding whether to promote new service opportunities in the band through sharing or relocation, as well as whether we should consider some combination of these methods."[80]

2. Other Bands

a. 4.4-4.94 GHz Band

The 400 megahertz of spectrum in the 4.4-4.94 GHz band, which is currently allocated to wireless carriers in many other nations, is one of the bands that has been identified as a possibility for commercial 5G services.[81]

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[76] FCC, "In the Matter of Expanding Use of the 12.7 – 13.25 GHz Band for Mobile Broadband or Other Expanded Use," GN Docket No. 22-352, Notice of Inquiry, FCC 22-80, adopted October 27, 2022, p. 2, https://docs.fcc.gov/public/attachments/FCC-22-80A1.pdf, ("12.7 GHz NOI").

[77] 12.7 GHz NOI.

[78] 12.7 GHz NOI, ¶ 6.

[79] 12.7 GHz NOI, ¶ 12.

[80] 12.7 GHz NOI, ¶ 12.

[81] Accenture, "Spectrum Allocation in the United States," CTIA, September 2022, p. 4, https://api.ctia.org/wp-content/uploads/2022/09/Spectrum-Allocation-in-the-United-States-2022.09.pdf, ("CTIA Report on Spectrum Allocation in the United States").

b. 7.1-8.4 GHz Band

The 1,275 megahertz of the 7.1-8.4 GHz band, a high mid-band spectrum block, are currently used by classified military radar and satellite, fixed satellite and earth exploration users. Wi-Fi providers and manufacturers have identified this band as a critical extension of the 6 GHz unlicensed band to enable multi-gigabit, highly data-intensive applications, like remote healthcare, virtual learning, augmented reality ("AR"), virtual reality ("VR"), and mixed reality ("XR"), in the home, office, and other venues. Mobile carriers have identified 400 megahertz of this band as a potential candidate for 5G deployment as the "capacity characteristics of this range make it ideal for serving densely populated areas such as urban centers, where traffic requirements are greater," and this band has also been identified for 6G deployment.[82] Additionally, because of the extensive and pervasive military incumbents, and unlicensed users' requirement to operate at lower power and accept and not cause interference, some parts of this band maybe a candidate for shared use including unlicensed sharing.[83]

c. Lower 37 GHz Band

The lower 37 GHz band is currently allocated for both federal government and commercial use, with little or no incumbent use.[84] At very high frequencies, radio wave propagation is more limited. These technical characteristics of millimeter wave spectrum allow simple sharing mechanisms. Federal and commercial operators should be able to co-exist and maximize use of the band.

The crucial question that follows is how policy makers should decide the spectrum management regime for these possible spectrum bands, *i.e.*, whether a band should be shared or have exclusive licenses, and if shared, which collection of disaggregated usage rights should be incorporated. For this, we turn to the Principle of Spectrum Sharing, which states that a band should be shared if the aggregate value from shared use of the band minus the cost of sharing is greater than the aggregate value of exclusive use minus clearing costs. The next section

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[82] CTIA Report on Spectrum Allocation in the United States, p. 4. *See also*, Stephen G. Rayment, "7 ~ 8 GHz," Ericsson North America CTO Office, WInnComm 2022, December 15, 2022, https://winnf.memberclicks.net/assets/Proceedings/2022Virtual/WInnComm%202022%207-8GHz%20Summary%20Rayment.pdf.

[83] Communications Daily "NTIA Studying Sharing in 7.125 – 8.4 GHz Band; Controversy Expected," October 2, 2019, https://www.newamerica.org/oti/in-the-news/ntia-studying-sharing-7125-84-ghz-band-controversy-expected/.

[84] John Leibovitz and Ruth Milkman, "Taking Stock of Spectrum Sharing," *Schmidt Futures*, September 3, 2021, p. 4, https://papers.ssrn.com/sol3/papers.cfm?abstract_id=3916386, ("Taking Stock of Spectrum Sharing").

demonstrates a framework through which the Principle of Spectrum Sharing can be implemented.

III. The Value of Shared Spectrum – Disaggregated Spectrum Usage rights

Spectrum's worth is based on the value derived by and for the benefit of consumers and businesses over time. Various factors – such as propagation characteristics of the spectrum band, restrictions on its use, the relative supply and demand for the spectrum, the demand for and utilization of services transmitted via spectrum, various impairments, cost of relocation of incumbents, and the timing and uncertainty over availability – all affect spectrum value.[85] In this section we compare the configuration of usage rights under shared licensed versus exclusive licensed regimes and quantify the impact of different usage rights on spectrum value.

A. Valuing the Collection of Spectrum Usage Rights under Sharing Versus an Exclusive Use Paradigm

The value of spectrum should most appropriately be thought of as a totality of private and non-private values derived from using it. Policymakers have often focused on auction revenue without a full accounting of the range of private and non-private values at play. In this section, we take a closer look at how private values are often calculated by the individual license holder and address non-private values in Section IV.B.

In the context of exclusive licenses, it is obvious that if a license gives only one designated user the rights to use a section of a frequency band at all times, in a given area, the private value of that license must be the value that accrues to the license holder for using that spectrum.[86] In such contexts, "value" can be interpreted through price signals observed in efficient markets for

[85] Coleman Bazelon and Giulia McHenry, "Spectrum Value," *Telecommunications Policy* 37(9) (October 2013), https://www.sciencedirect.com/science/article/abs/pii/S0308596113001006, ("Spectrum Value"). *See also*, Coleman Bazelon, Paroma Sanyal, Jonathan Lee, Ezra Frankel and Ryan Taylor, "Network Value drivers in a 5G World," Conference Paper, Telecommunications Policy Research Conference 47, February 12, 2021, p. 5, https://papers.ssrn.com/sol3/papers.cfm?abstract_id=3749891.

[86] This is no different from any private property right that can be used to create value, for example, land for farming. Exclusive use can also have positive externalities, i.e. non-private values, such a societal benefits that can arise from deploying the spectrum for broadband.

these exclusive usage rights. Globally, regulators and governments have carefully designed market mechanisms (most commonly auctions) to resemble a competitive market to allocate spectrum use, and many academics, policy makers, and regulators have relied on the price signals generated from these market mechanisms to infer the value of the underlying asset, *i.e.*, spectrum, being sold. [87]

In the U.S., a sequence of auctions have taken place since the mid-1990s. Given the inevitable shortage of spectrum that can be cleared at relatively low cost, we are increasingly observing auctions of spectrum bands that incorporate sharing requirements.[88] Most notably, the market mechanism for the CBRS Band was built from the ground up with spectrum sharing in mind. Instead of the bidders bidding on exclusive use licenses, in the CBRS auction, the bidders were bidding on the right to priority access. As discussed earlier in Section II.B.1, in the CBRS auction, there were three different types of users (Incumbents, PALs, and GAA) with differing rights. This auction saw more disaggregated sharing on the geography dimension (as the license sizes were counties and not PEAs), and the rights offered by the PALs are relatively more "shared" on the time and frequency dimensions. In other words, different users could be using the same frequencies in the same geographies at different times.

The CBRS Band is a useful paradigm for better understanding the differences in thinking about spectrum value. There are two important anchor points – the additivity of private values, and the positive externalities generated from the CBRS-style sharing regime. Under shared spectrum use, value is additive across all shared uses, for every user that the sharing rules and technology can accommodate. Note that as foreshadowed in Section II, this is not a radical change in the way economists think about how spectrum value should be aggregated. In fact, the way exclusive use licenses are valued in the U.S. is consistent with the idea that value is additive over all uses. For example, when we consider the value of exclusive use licenses that cover the territory of the U.S., we add up the revenues raised by licenses across the dimensions that the band is "shared," geography (*e.g.,* PEAs) and frequency (*e.g.*, 10 MHz license blocks). A sharing regime can be thought of as taking this analogy further to include more granular designations of geography,

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[87] *See e.g.*, Spectrum Value. *See also*, Michelle Connolly, et al., "The Evolution of U.S. Spectrum Values Over Time," Brandeis University Working Paper Series, 2018, https://www.brandeis.edu/economics/RePEc/brd/doc/Brandeis_WP121.pdf.

[88] There is limited coordinated spectrum sharing in the AWS-3 Band but most federal systems were transitioned and relocated to other bands, such that the vast majority of the licenses in this band are exclusive use licenses. See FCC, "The Federal Communications Commission and the National Telecommunications and Information Administration: Coordination Procedures in the 1695 – 1710 MHz and 1755 – 1780 MHz Bands," GN Docket No. 13-185, Public Notice, DA 14-1023, July 18, 2018, https://docs.fcc.gov/public/attachments/DA-14-1023A1.pdf.

frequency, and time allowing for more flexible use cases and types of users. When doing so, a more accurate and complete picture of shared spectrum value emerges.

B. Spectrum Use Licenses as an Aggregation of Complementary Usage Rights

To make the *complementary usage rights* framework discussed previously more concrete, here we ground it in a real world example of the CBRS and 3.45 GHz bands. Using these bands as examples, we calibrate the effect of differing set of usage rights on private spectrum value, *i.e.*, the auction price, and use these estimates to compare the effect of shared licensing versus exclusive licensing in the 3.1 GHz band. While in practice the encumbrances on the CBRS band would have made it impractical to impose the same licensing scheme subsequently adopted for the 3.45 GHz band, this exercise allows us to estimate the difference in private value due to differences in components of usage rights, taking into account all of indicia of private value generated by each mode of licensing. This exercise illustrates that sharing versus exclusive licensing is not the driver of market value, but rather that market value depends on the collection of other usage rights.

The choice of these bands for calibration purposes is guided by their proximity to the 3.1 GHz band. Considering the physics of these two bands, they are not too different sitting at 3.55 GHz-3.7 GHz and 3.45 GHz-3.55 GHz, respectively, on the electromagnetic spectrum. Both offered unpaired spectrum licenses of 10 megahertz each with a limit of 4 licenses per winning bidder (*i.e.*, 40 megahertz).[89] However, they differ greatly in what the licenses that assign usage rights in each band allow each user to do. For example, the CBRS Band licenses cover counties, while the 3.45 GHz licenses cover PEAs, *i.e.,* along the geography dimension, CBRS licenses offer less aggregated rights than 3.45 GHz licenses.[90] Similar comparisons can be made along the dimension of power (for example, lower power limits for CBRS and higher power limits for 3.45 GHz and C-Band).[91]

Note that we are not drawing an equivalence between disaggregated rights and a spectrum sharing regime. Rights can be disaggregated without a sharing regime at the center of the license

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[89] *See* Auction 110 Report and Order. *See also*, Auction 105 PN.

[90] See Auction 110 Report and Order. See also, Auction 105 PN.

[91] See Auction 107 Report and Order. See also, Auction 105 PN.

design. For example, Verizon leases its exclusive use licenses in rural areas for the 700 MHz Upper C Block spectrum,[92] effectively disaggregating its rights over frequency and geography where it knows it has excess capacity. Although this example is not an example of a shared spectrum regime, it is still consistent within our framework of valuing spectrum, *i.e.,* the value generated by the lessee of the spectrum is *additive* to the value that Verizon is already generating in the band. In this Report, we focus on scenarios where the federal government users of the spectrum, such as the DOD, may not have sufficient incentive or ability to disaggregate the usage rights, so regulators have to intervene to create a collection of complementary usage rights for new users that will facilitate sharing a spectrum band with incumbents.

How do we characterize a spectrum sharing regime within this framework of viewing licenses as an aggregation of complementary usage rights? First, a spectrum sharing regime needs to define usage rights in a sufficiently disaggregated manner, *i.e.,* a license should not grant exclusive use along most dimensions. Second, it must be technologically possible to implement, *i.e.,* there must be technology and protocols that coordinate and allocate these disaggregated usage rights consistently and predictably. For example, in the CBRS Band, the SAS coordinates shared use in a band with predetermined rules. Third, these usage rights must be priced by a mechanism (*e.g.*, an auction) designed such that it accounts for the disaggregated rights, the sharing technology. For example, in the CBRS auction, the $/MHz-Pop average bid on PALs was a direct bi-product of the uncertainty associated with the sharing protocol and disaggregated rights that defined the PALs.[93]

C. Drivers of Spectrum Value in a Disaggregated Use Rights Framework

There is nothing inherent in spectrum sharing that decreases a band's value – it is the composition and extent of rights under various licensing regimes that influence the value of the band to private users. Spectrum value is driven by an aggregation of usage rights, such as the type of frequency, level of allowed power (both of which will influence propagation characteristics), uncertainty regarding any novel licensing mechanism, license sizes, and so on. Although early shared-licensed auctions, like the CBRS auction, may have raised less money than

[92] Phil Goldstein, "Verizon: All 21 LTE in Rural America Carrier Partners Have Launched Service," Fierce Wireless, October 15, 2015, accessed November 22, 2022, https://www.fiercewireless.com/wireless/verizon-all-21-lte-rural-america-carrier-partners-have-launched-service.

[93] "CBRS Incumbent Protections and Encumbrances Overview," Wireless Innovation Forum, April 28, 2020, https://winnf.memberclicks.net/assets/CBRS/WINNF-TR-5003.pdf.

exclusive license auctions, lower auction revenues need not imply that the underlying value of the spectrum has decreased. This is because, as described in Section III.A, the value generated by *all* users is cumulative and must be summed up, and weighed against the estimated costs of clearing incumbent operations or savings in the case of shared-licensed spectrum. This includes value that is not internalized by the licensing mechanism by design. The value generated by federal use incumbents and the value generated by users of shared-licensed or unlicensed bands where by design of the sharing regime, the users were not required to buy a license for the market (*e.g.*, GAA licenses in the CBRS Band), are some examples of value not internalized by auction revenues. A part of that lower revenue can be attributed to the uncertainty (at the time) around the hitherto untested spectrum sharing technologies, new governing regimes, and deployment costs needed to support them.

In Table 1 below, we describe the drivers of private spectrum value in recent mid-band auctions and explore how these drivers are reflected in the price of a license.

TABLE 1: PRIVATE VALUE DRIVERS

Value Drivers	3.5 GHz (CBRS) $0.22/MHz-pop	3.45 GHz $0.72/MHz-pop	3.7 – 4.2 GHz (C-Band) $0.94/MHz-pop
Uncertainty in Spectrum Sharing Rules	**Coordinated sharing with Tiered Access** Encumbrances existed at 100% of geographies although in different forms for each geography making the spectrum sharing rule critical. Sharing system prioritizes incumbents and PAL holders automatically and dynamically. **Significant uncertainty at the time of auction.**	**Geographic Sharing** 41% of pops encumbered Designation of Cooperative Planning Area (CPA) or Periodic Use Area. Exact details of how the cooperation will take place faced a lot of uncertainty. Hopes of efficient cooperation based on post-auction case-by-case interference analysis of DoD and license holder. **Uncertain sharing rules at the time of auction**.	**No Sharing Required** No perceived encumbrances at time of auction. Satellite incumbents paid to clear the band. Required to clear band by Dec. 2023. However, there have been issues with the Federal Aviation Administration incumbents post-auction.
Propagation Characteristics	Low power, Geared for smaller footprint infrastructure such as small cells.	High power, same as C-Band.	High power. Made its propagation characteristics like 2.5GHz, a lower band that can propagate further.
Frequency Band Size per License	10 MHz, 4 license limit.	10 MHz, 4 license limit.	20 MHz, no limits.
Geographic Size of License	County	PEA	PEA
Length of License	10 years with expectation of renewal	15 years with expectation of renewal	15 years with expectation of renewal
Interest from national carriers	Low. Expectation that C-Band is coming, and not very desirable for national carriers given low power limits and resulting propagation relative to C-Band.	Medium	High, very desirable to national carriers.

Sources and Notes:

FCC, "Auction 105: 3.5 GHz Band," accessed September 18, 2023, https://www.fcc.gov/auction/105; Sasha Javid, "Auction 105 Summary (3550-3650 MHz Band)," accessed September 18, 2023, https://sashajavid.com/FCC_Auction105.php.

FCC, "Auction 110: 3.45 GHz Band," accessed September 18, 2023, https://www.fcc.gov/auction/110; Sasha Javid, "Clock Stage Analysis: Auction 110 Summary (3450-3550 MHz Band)," accessed September 18, 2023, https://sashajavid.com/FCC_Auction110.php.

FCC, “Auction 107: 3.7 GHz Band,” accessed September 18, 2023, https://www.fcc.gov/auction/107; Sasha Javid, “Clock Stage Analysis: Auction 107 Summary (3700-3980 MHz Band),” accessed September 18, 2023, https://sashajavid.com/FCC_Auction105.php.

In Table 1 we report the national average price realized for the CBRS Band, 3.45 GHz, and C-Band auctions. It is immediately clear that there were a wide range in prices realized across these bands, from $0.22/MHz-pop to $0.94/MHz-pop.[94] Recall that the auction prices only reflect the value that is internalized by the auction mechanism. Hence, to put the wide range in market prices (based on the usage rights defined and internalized by each auction) in proper context we must look at the full sets of usage rights including the non-market values created by the configuration of rights.

D. Deconstructing the Value of Shared Licensed Spectrum

The conceptual framework we have established above implies that, as spectrum licenses aggregate or disaggregate usage rights at varying levels, spectrum value should not be negatively impacted *per se* by whether the band is being shared or not. In fact, it is theoretically ambiguous whether defining usage rights in a sufficiently disaggregated manner could create or destroy value.[95] To demonstrate this, we estimate the standalone impacts on auction revenue of spectrum reach (frequency plus power) and uncertainty. This allows us to deconstruct the price differences realized in different auctions. Although we empirically isolate the impact of specific differences between bands and auctions, such as the impact of uncertainty on prices bid, the

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[94] Due to the approximate $15 Billion in clearing costs that the bidders need to pay to get exclusive usage rights in the C-Band, the actual amount of spend for each bidder in the C-Band auction would imply a higher average price of $1.10/MHz-pop. *See*, Sasha Javid, “Post-Auction Analysis for Auction 107 (3700 – 3980 MHz Band)”, https://sashajavid.com/FCC_Auction107.php.

[95] For example, the positive value created from disaggregated rights can be seen in the CBRS auction that brought in new types of spectrum bidders. Companies who may want to expand wireless coverage in or around their facilities, *i.e.*, have a private wireless network, and thus far, have had to rely on either Wi-Fi or 4G. However, Wi-Fi has interference issues that may be problematic for the reliable operations of a company. 4G LTE provided by commercial wireless providers may not be fully customizable or allow for sufficient proprietary control. The CBRS Band could solve these problems by providing such access to spectrum over which they could deploy their private wireless networks. On the flip side however, disaggregation of rights could also lead to the tragedy of the anti-commons where there are too many rights holders leading to the underuse of the shared resource. For the positive value, *see e.g.*, “The New Spectrum That’s Expanding Wireless Connectivity,” Crown Castle, accessed December 1, 2022, https://www.crowncastle.com/innovation-spotlight/cbrs. For the anti-commons argument, see for example, Michael Heller, “The Tragedy of the Anticommons: A Concise Introduction and Lexicon,” *The Modern Law Review* 76 (2013), https://scholarship.law.columbia.edu/faculty_scholarship/1778.

impact of these differences cannot be evaluated along a single dimension. For example, a smaller reach of a lower powered cell site might have a negative impact on auction value from the perspective of a national mobile network operator, but a positive value from the perspective of new users drawn into the auction and the greater macroeconomic impact of making spectrum available for wider and more innovative uses

This section demonstrates empirically the theoretical construct. To do this we follow three steps:

1. *Disaggregation of Rights Regarding Reach of Spectrum*: To estimate this effect we use the CBRS spectrum band. To facilitate sharing, the reach of CBRS spectrum is less than other commercial bands. We estimate what portion of the price difference between the CBRS Band and 3.45 GHz can be explained by the disaggregation of rights along geographic reach of frequencies, as characterized by power allowances and propagation. We do this by simulating a purely hypothetical "re-aggregation" of usage rights along this dimension such that the CBRS Band propagation characteristics are similar to that of the exclusively licenced or geographically shared adjacent bands.

2. *Uncertainty of Rights*: The novel sharing regime implemented in the CBRS band created some uncertainty. We estimate what portion of license value is lost due to the presence of uncertainty around how usable a block of spectrum would be. The concept of uncertainty is the risk surrounding a new type of sharing mechanism, here the dynamic sharing with a SAS coordinator that was first implemented under the CBRS regime.[96] To estimate this uncertainty effect we use the 3.45 GHz spectrum band since the sharing regime implemented in the band allows us to obtain a cleaner estimation of uncertainty by using variation in auction prices for licenses that were subject to uncertainty and those that were not. In the 3.45 GHz auction, risk surrounded the post-auction coordination that would be required in the shared geographic areas. Both types of uncertainty are focused on post-auction events (SAS working or ability to negotiate) causing the spectrum to be unused. In our model, we use the encumbrances in the 3.45 GHz band to estimate an uncertainty effect that can be applied to evaluate the effect of uncertainty on the CBRS band.[97]

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[96] The CBRS auction was the first instance where SAS coordinators dynamically allocated capacity to users, and whether this would work or not was surrounded by uncertainty. *See*, Frank Rayal, "CBRS PAL Spectrum Valuation," Frank Rayal, January 31, 2020, accessed November 21, 2022, https://frankrayal.com/2020/01/31/cbrs-spectrum-valuation/, ("CBRS PAL Spectrum Valuation").

[97] The 3.45 GHz auction provides a unique opportunity to measure the uncertainty surrounding a sharing protocol. This is due to the within-auction variation in the type and amount of encumbrance, and the resulting uncertainty, by license geography.

3. *Re-aggregating the Rights*: Given observed CBRS Band prices and the estimates in steps 1 and 2, we determine how much value the CBRS Band would have generated if the spectrum reach and uncertainty rights were re-aggregated. This also yields the incremental value that could potentially be added or taken away by the other factors of a shared band, such as it being more conducive to a wider variety of use cases and types of bidders. This 'as if' exercise should not be taken as suggesting the rights should be re-aggregated – that question is addressed below considering the full set of costs and benefits of doing so.

1. Disaggregation of Rights Regarding Spectrum Reach: Comparing the CBRS and the C-Band

Our estimation methodology starts with the $/MHz-pop price of the CBRS Band and focuses on the effect of the disaggregation of various usage rights on CBRS private band value to new users, inferring what that implies if these rights were to be re-aggregated. As discussed earlier, the allowed power levels in the CBRS Band were lower than that of neighboring bands and effectively limited use by wireless providers to using small cells.[98] These relatively lower power allowances which restricted output power and limited the coverage range were intended to allow greater spatial re-use of the band and reduce coexistence challenges, *i.e.,* to disaggregate usage rights on coverage area.[99]

It is worth noting that low power facilitates spectrum sharing primarily because it reduces the potential for interference between different users or services operating in the same frequency band. Low-power transmissions have a limited range, which means they cover a smaller geographical area. This decreases the likelihood of their signals interfering with other transmissions operating in the same frequency band but at a different location. As a result, multiple devices or services can utilize the same frequency band with a lower chance of causing excessive interference.[100] This flexibility supports dynamic sharing of the spectrum without causing unacceptable levels of interference. However, as discussed earlier, a lower power limit also implies a lower coverage area and compared to a higher power band. Our comparison base is the portfolio of usage rights, including higher power limits with larger reach, that have been

[98] CBRS PAL Spectrum Valuation.

[99] CBRS PAL Spectrum Valuation.

[100] NCTA, "Shared Spectrum Promotes Innovation, Competition and Consumer Savings," June 5, 2023, accessed August 5, 2023, https://www.ncta.com/whats-new/shared-spectrum-promotes-innovation-competition-and-consumer-savings.

traditionally used to deploy terrestrial mobile services under exclusive or geographically-shared licensing.

To motivate the value of re-aggregating usage rights over geography, we estimate the geographical and population coverage difference that would occur if the CBRS Band with lower power limits were deployed on the same macro tower network as the C-Band/3.45 GHz with higher power limits.[101] This yields the user value difference between base portfolio of usage rights as exemplified by the C-Band/3.45 GHz and the usage rights in the CBRS band based on the comparative coverage benefit of the bands.[102] We adjust the realized CBRS Band price by this estimated population coverage difference and interpret it as an estimate of what the CBRS Band prices would have been if the usage rights were hypothetically as aggregated as in the adjacent bands to enable comparable coverage characteristics in the two bands.[103] The residual between the adjusted CBRS Band price and the adjacent band contains the impact of the other factors that drive spectrum value, including uncertainty.[104] The table below reports these estimates.

TABLE 2: SIMULATED RE-AGGREGATING OF GEOGRAPHIC USAGE RIGHTS

Propagation Discount	[A]		32%
Net Price per MHz-POP (CBRS)	[B]		$0.22
Net Price per MHz-POP (Unencumbered 3.45 GHz)	[C]		$0.79
Value of CBRS with 3.45 GHz/C-Band allowed power levels	[D]	[B]/[A]	$0.68
Residual Private Value Drivers	**[E]**	**[C]-[D]**	**$0.11**

Sources and Notes:
[A]: Propagation of the CBRS band (as proxied by the 3.6 GHz spectrum) versus 2.6 GHz spectrum in the contiguous United States. We use 2.6 GHz as a propagation proxy for C-Band or 3.45 GHz spectrum, since these bands' coverage area per site is expected to be roughly

101 The power limit in the 3.45 GHz Band is similar to the C-Band at EiRP 1640 W/MHz in non-rural areas and double that in rural areas. This is unlike the CBRS Band. *See* Frank Rayal, "Overview of FCC Auction 110 in 3.45 GHz," Frank Rayal, October 4, 2021, accessed November 21, 2022, https://frankrayal.com/2021/10/04/overview-of-fcc-auction-110-in-3-45-ghz/. We provide a detailed description of our spectrum deployment coverage model in 0.

102 This does not assume that CBRS would only be deployed on macro towers by C-Band/3.45 GHz users, but that any additional value from adding nodes to the network is roughly offset by the added cost of adding those nodes.

103 Note that this does not imply that the CBRS Band would be more valuable with more aggregate usage rights. As explained in detail above, in a shared band the value of the spectrum needs to account for all uses, not just the ones that are captured by the licensing mechanism.

104 The details of our deployment simulation is contained in 0.

equivalent to that of 2.5 GHz as a result of transmit power levels and antenna gains, and we only had access to 2.6 GHz propagation characteristics. *See*, 0.
[B]: *See*, Sasha Javid, "Post-Auction Analysis for Auction 107 (3700 – 3980 MHz Band)", https://sashajavid.com/FCC_Auction107.php. Per Brattle Estimates, the estimated unencumbered national $/MHz-pop is $0.79/MHz-Pop.
[C]: Weighted average price of unencumbered licenses in Auction 110, scaled up based on historical license relative values. [105]

We find that on a macro tower network calibrated to a C-Band buildout, the CBRS Band under current power allowances would cover around 32% of the population that would be covered by C-Band or 3.45 GHz.[106] We take this to imply that based just on the reach of signals, the CBRS Band has 32% of the value of the C-Band/3.45 GHz band. We scale the realized CBRS Band price by this factor to estimate that the CBRS Band, if it had propagation characteristics that could fully utilize the existing tower infrastructure of the wireless operators, would have been priced at $0.68/MHz-pop. As an estimate of the price of the adjacent bands, we have taken the estimated national average unencumbered 3.45 GHz prices $0.79/MHz-pop.[107] Using these two estimates, we find that propagation characteristics make up a portion of the auction price difference observed between our base portfolio of usage rights and those encompassed by the CBRS Band.[108]

We offer these calculations solely to model the comparative "but-for" value due to different power levels between the two band. The calculated price difference should not be taken to mean that low-power sharing in the CBRS band hurt the total value of this spectrum or that if power limits only were increased it would have maximized the value of the CBRS spectrum band. To the contrary, as demonstrated below, it is precisely these lower power limits that contributed to the

[105] The price we calculate for an unencumbered 3.45 GHz band is based on the clock phase results. Since there was no assignment phase in the auction of the CBRS band, this most accurately captures the level difference between the adjusted CBRS price and the hypothetical unencumbered comparable. *See*, K.C. Halm, Van Bloys, and Heather Moelter, "FCC Adopts 3.5 GHz CBRS Auction Framework in Anticipation of Auction in 2020," Davis Wright Tremaine LLP, September 20, 2019, https://www.dwt.com/insights/2019/09/fcc-cbrs-auction-framework.

[106] Note that given C-Band and 3.45 GHz are similar frequency bands, its propagation characteristics must be quite similar under the similar power and clutter surrounding the tower. In our modelling, we use an estimated coverage area for a 3.6 GHz band which lies between C-Band and 3.45 GHz.

[107] We calculate the unencumbered value of the 3.45 GHz Band by using the price pf unencumbered licenses and scaling those up to a national price using relative geographic values of licenses. The average price including the encumbered licenses was $0.74/ MHz-pop (using 2010 population). See Sasha Javid, "Post-Auction Analysis for Auction 110 (3450 – 3550 MHz Band)," accessed December 2, 2022, https://www.sashajavid.com/FCC_Auction110.php.

[108] Calculation: The price difference between CBRS and unencumbered 3.45 GHz rounds to $0.57/MHz-pop ($0.79/MHz-Pop minus $0.22/ MHz-pop). The value from enhanced propagation rounds to $0.46/MHz-pop ($0.68/MHz-pop minus $0.22/MHz-pop). The ratio shows of these two differences ($0.46 /$0.57) yields 80%.

significant aggregated value of the shared spectrum. The reason spectrum can be shared amongst various users is the limited interference that a low-powered regime enables.[109] Without lower power limits, the band could not be used commercially at all, and thus would have realized zero dollars in commercial value. It is the lower power limits that allow services to be deployed in the CBRS band making it commercially valuable and maximizing the value of the band, compared to an exclusive licensed lower-powered regime.

While propagation can account for some differences in the auction spectrum value, auction value does not reflect the full value of the shared-licensed CBRS spectrum, as explained below [add cross-reference]. And even the remaining auction value difference between the CBRS Band and adjacent bands are generated by dimensions other than propagation. In the next step of our methodology, we quantify how much of this residual the presence of uncertainty can explain.

2. Disaggregation of Rights Regarding Uncertainty: Estimating the Impact of Uncertainty on Spectrum Value in the 3.45 GHz Band

Uncertainty surrounding spectrum use lowers the value of the spectrum. Empirically, untangling the impact of uncertainty is complex as there are many factors that are correlated with uncertainty which also affect spectrum value. This complexity is reflected in the residual that we have backed out in the section above. That residual is a combination of multiple interrelated dimensions, including factors such as uncertainty around coordination (in both bands) and the fact that what is being allocated in the CBRS Band is “priority access” and not exclusive use of a specific frequency. The measured residual is also impacted by other value drivers of the CBRS allocation, such as the added demand brought to the auction from bidders who value the smaller geographic licenses, lower power levels, or other value drivers. There is no way to disentangle the effect of uncertainty on spectrum value using the CBRS auction results, as the uncertainty does not vary along geographic or spectrum dimensions.

In order to assess the effect of uncertainty on spectrum value, we must keep all other factors constant while varying levels of uncertainty. This is exactly what we do in our analysis of the 3.45 GHz band, where different license areas had different levels of encumbrances, and hence different levels of the impact of uncertainty. By keeping our analysis “within” band, all band

[109] Kurt Schaubach, “Department of Defense (DoD) Spectrum and the Sharing Opportunity,” Federated Wireless, July 20, 2023, accessed August 29, 2023, https://www.federatedwireless.com/blog/defense-spectrum-and-the-sharing-opportunity/.

specific factors remain constant. Then we look across licenses within the band that have varying levels of uncertainty.

In the 3.45 GHz band, there were two types of areas that required coordination from flexible use: (i) 33 "Cooperative Planning Areas" where federal operations would continue to operate and new licensees would need to share the spectrum with the DoD uses; and (ii) 22 "Periodic Use Areas" that overlap with some Cooperative Planning Areas, in which the DoD would need periodic access to "all or a portion of the band in specific, limited geographic areas."[110] There were ten generic "Category 1" blocks that would be available in 334 PEAs (out of a total of 406 PEAs)—where access to all ten generic blocks were either unrestricted or subject to the same restrictions.[111] In 72 PEAs (out of a total of 406 PEAs) where the restrictions differed according to the frequency, there were two products—four Category 1 blocks (A-D) and six Category 2 blocks (E-J), based on the frequency block.[112] Regarding these PEAs, the FCC advised, "the coordination requirements on blocks in a given category in a given PEA may differ from the requirements on the same category of blocks in a different PEA. For example, the Cat1 blocks in one PEA may be unrestricted while the Cat1 blocks in another PEA may require some degree of coordination. Similarly, the restrictions on Cat2 blocks will likely vary from PEA to PEA."[113]

The varying level of measurable uncertainty in the 3.45 GHz band comes from the different number of CPAs and PUAs in each license. The 3.45 GHz auction was explicitly designed such that

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[110] Cooperative Planning Areas (CPA) are defined as:

"geographic locations in which non-federal operations shall coordinate with federal systems in the band to deploy non-federal operations in a manner that shall not cause harmful interference to federal systems operating in the band." See, Auction 110 Report and Order, ¶ 23.

Periodic Use Areas (PUA) are defined as:

"*geographic locations in which non-Federal operations in the band shall not cause harmful interference to Federal systems operating in the band for episodic periods*." *See*, Auction 110 Report and Order, ¶ 25.

Auction 110 PN, ¶ 5.

[111] Auction 110 PN, ¶¶ 176, 177.

[112] The coordination requirements on blocks in a given category in a given PEA could "differ from the requirements on the same category of blocks in a different PEA. For example, the Cat1 blocks in one PEA may be unrestricted while the Cat1 blocks in another PEA may require some degree of coordination." Similarly, the restrictions on Cat2 blocks could differ between PEAs. *See*, Auction 110 PN, ¶ 48. *See also*, "Updated Attachment A," September 10, 2021, https://www.fcc.gov/file/21845/download.

[113] FCC "Auction of Flexible-Use Service Licenses in the 3.45-3.55 GHz Band for Next-Generation Wireless Services, Notice and Filing Requirements, Minimum Opening Bids, Upfront Payments, and Other Procedures for Auction 110, Bidding in Auction 110 Scheduled to Begin October 5, 2021", WT Docket No. 19-348, Public Notice, DA 21-655, released June 9, 2021, ¶ 178, https://docs.fcc.gov/public/attachments/DA-21-655A1.pdf ("Auction 110 Procedures PN")

the winners of licenses work out the parameters of cooperation with federal incumbents operating in the designated CPAs and PUAs after the license was won.[114] Hence, licenses with more CPAs and PUAs have inherently more uncertainty around use than licenses with less CPAs and PUAs. We measure this by calculating the population in each PEA that are covered by the CPAs and PUAs and categorizing each license into encumbered population quartiles.

The table below reports our findings:

TABLE 3: UNCERTAINTY IMPACT ON SPECTRUM VALUE IN THE 3.45 GHZ BAND

Term		($/MHz-pop)
Average Price of Unencumbered License	[A]	0.79
Average Impact of Uncertainty Around License Use		
$/MHz-pop	[B]	-0.11
Percentage Difference from Unencumbered License	[C]	-13%

Sources and Notes:
[A]: Brattle estimated average price for unencumbered licenses in the 3.45 GHz band.
[C]: [B]/[A].
See Appendix B for more information.

This uncertainty effect is incremental to the impact of the population affected by the CPAs and PUAs, and is a proxy for the impact of uncertainty regarding coordination required in the shared areas. This uncertainty is similar to the uncertainty experienced in the CBRS Band because in both cases the cause of uncertainty is cooperation with incumbent federal government users and an unfavorable resolution of the uncertainty would make the licensed spectrum unusable. Our estimates therefore suggest that the presence of uncertainty caused by novelty of the sharing protocol accounted for approximately 13% of realized auction prices.[115] In the CBRS Band, there was uncertainty around how well the SAS based dynamic sharing protocol would work given how novel this technology was and that uncertainty applied to all licenses. However, now that the concept has been proven to be successful, we could reasonably anticipate that the uncertainty is

[114] Coordination was only allowed to be discussed once the auction had closed, which means that during bidding there would have been significant uncertainty around usage in CPAs and PUAs. *See*, Department of Defense, "DoD 3.45 GHz Workshop," April 19, 2022, https://www.ntia.doc.gov/files/ntia/publications/3.45_ghz_coordination_workshop_-_briefing_-_19_april_2022_final.pdf.

[115] From our regression coefficients, we find that the impact of uncertainty on license prices can range from a 0% to 44% decrease.

resolved, and the CBRS Band is at least 13% more valuable than it was when auctioned under uncertainty.

It is worth noting that the uncertainty that was present when the CBRS band was auctioned in 2020, the sharing mechanism through the SAS coordination system, was a novel approach to spectrum use that the Commission had implemented for the first time. Given this novel technology, it was unclear whether this would work well and whether winning bidders would actually be able to use the spectrum to deploy wireless services in this band due to interference concerns. Recently stakeholders have pointed to the success of the SAS-based sharing mechanism CBRS band and discussed how the expected uncertainty has not materialized.[116] For example, the CEO of Federated Wireless (a SAS) has stated that although there are almost 400,000 radios on this system, as the SAS operator, they receive "less than maybe 20 interference investigation requests a year and we handle all of them."[117] Thus the interference concerns, about PAL licensees not being able to use their spectrum due to interference appear not to have materialized. The NTIA points outs that during a 21-month period CBRS deployments have increased by 121%.[118] Therefore, going forward, spectrum subject to a similar sharing mechanism will not be subject to the same uncertainties.[119]

3. Re-Aggregating Usage Right: Deconstructing the Value of Spectrum and Estimating the Impact of Disaggregating Usage Rights

Table 4 below combines our calculations from above to back out the private value generated/lost due to the disaggregated rights offered in the CBRS Band.

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[116] WInnForum Standards, "Success Case Studies in the Citizens Broadband Radio Service (CBRS) Band," accessed August 28, 2023, https://cbrs.wirelessinnovation.org/cbrs-success-stories.

[117] Monica Allenven, "Federated CEO Refutes those CBRS Slams," Fierce Wireless, August 23, 2023, accessed August 28, 2023, https://www.fiercewireless.com/wireless/federated-ceo-refutes-those-cbrs-slams.

[118] NTIA, "An Analysis of Aggregate CBRS SAS Data from April 2021 to January 2023," May 01, 2023, accessed August 28, 2023, https://www.ntia.gov/report/2023/analysis-aggregate-cbrs-sas-data-april-2021-january-2023.

[119] There has been discussion on newer technologies that may be implemented for spectrum sharing in the future, and these technologies are already under testing. This paper is agnostic about the technology that enables sharing.

TABLE 4: DECOMPOSING THE PRICE DIFFERENTIAL BETWEEN CBRS AND ADJACENT BANDS

Power Limit/ Propagation Impact		
Realized CBRS Price	[1]	$0.22
Price with Improved Propagation	[2]	$0.68
Propagation Price Effect	[3] = [2] - [1]	$0.46
Uncertainty Impact		
Percentage Difference from Unencumbered Licenses	[4]	-13%
Price with Improved Certainty	[5] = [1] / (1 + [4])	$0.25
Uncertainty Price Effect (with CBRS Propagation)	[6] = [5] - [1]	$0.03
Price with Improved Certainty and Improved Propagation	[8] = [2] / (1 + [4])	$0.78
Estimated Average National Price of Unencumbered 3.45 GHz Band	[9]	$0.79
Effect of Disaggregating Usage Rights in CBRS	[10] = [8] - [9]	-$0.01

Sources and Notes:
[1]: Sasha Javid, "Auction 105 Summary," accessed September 14, 2023, https://sashajavid.com/FCC_Auction105.php.
[2]: See Table 2.
[4]: See Table 3.
[9]: Weighted average price of unencumbered licenses in Auction 110, scaled up based on historical license relative values. See FN 89.

After adjusting for the disaggregated propagation and uncertainty effect, we find that, if the CBRS spectrum did not have any incumbent operations such that the usage rights could be similar to, say, exclusively licensed mid-band spectrum, the aggregated certainty and propagation rights would imply that the CBRS auction could have reached $0.78/MHz-pop. This implies a residual of less than $0.01/MHz-pop, which implies a very small premium of 1.1% from the aggregated rights price (*i.e.*, unencumbered 3.45 GHz price). In other words, the private value, *i.e.*, the auction price, of the CBRS spectrum to bidders would be similar to the 3.45 GHz band controlling for power limits and uncertainty. Importantly, however, the 3.45 GHz usage rights were not an option for CBRS. Moreover, simplistically comparing auction revenues from the two bands not only ignores the similar value of both if CBRS did enjoy the same usage rights as the 3.45 GHz band, it also ignores the private and non-private value generated by the CBRS band that is only possible under a lower-powered sharing regime. The proper valuation of the configuration of usage rights under an exclusive versus sharing regime must account for the total value generated by the usage rights and not just auction revenues, which only reflects a sub-set of the spectrum value.

IV. Collection of Usage Rights that Maximize Spectrum Value

The empirical results from the previous sections show that market value depends on the collection of usage rights being evaluated, and that comprehensive spectrum valuation includes non-private as well a private value. It is not the sharing of spectrum that affects the value, but rather the specific rights associated with a band of spectrum, such as power limits and uncertainty surrounding specific sharing regimes. That uncertainty is expected to decrease as the CBRS Band deployments and the CBRS-style sharing regime becomes a more reliable model of success for potential licensees.[120] In this section, we discuss the principles that should guide sharing and show that we need to consider a more holistic view of the value generated by spectrum usage that goes beyond just auction receipts and private market values. For example, the disaggregation of usage rights may allow for smaller wireless carriers and WISPs to offer broadband in rural communities in a cost-effective way and expand the beneficial economic impact of connectivity.

Unlike with exclusive sharing where, by definition, only one user can operate the band, broader sharing regimes can generate values that are additive in nature and generated by all the shared users of the bands; those values are increased further by the costs saved from not requiring federal (or other) incumbents to clear or relocate. Spectrum policy is a continued sequence of incremental welfare improvements given a set of policy choices. Thus, when the FCC is deciding on spectrum reallocation for terrestrial flexible use licenses, given a set of feasible policy choices, the goal should be to maximize the total social and economic value of spectrum to all users, and accurately account for the costs of clearing versus not clearing, subject to the priorities set by policymaker. However, even when more value for society is created with sharing, often incumbents (especially federal spectrum users) are often opposed to relocating or sharing the

[120] In cases where the incumbent sharing partners are the federal government users, increased experience sharing in the CBRS and 3.45 GHz bands with these counter parties will hopefully also lead to reduced uncertainty about the possibility of sharing with these users in the future.

spectrum.[121] The costs to incumbents (of clearing the band for exclusive use or sharing) and benefits to new users of the shared band should be carefully estimated and combined with market value estimates before a decision is taken. The aggregate value of a shared band should be estimated by the equation below.

$$\begin{aligned}&Net\ Value\ of\ Shared\ Use\\ &\quad = [\text{Net Private Value from New Users}] + [\text{Net Private Value from Incumbents}] + \\ &\qquad [\text{Non} - \text{Private Value from Innovation}]\end{aligned}$$

Where:

$$Net\ Private\ Value\ from\ New\ Users\ or\ Incumbents =$$

$$[Usage\ Value\ of\ New\ Users\ or\ Incumbents] - [Sharing\ Costs]$$[122]

The **Principle of Spectrum Sharing** states that the ***Value of Spectrum will be Increased under Sharing if***:

$$[Net\ Value\ of\ Shared\ Use]$$

$$>$$

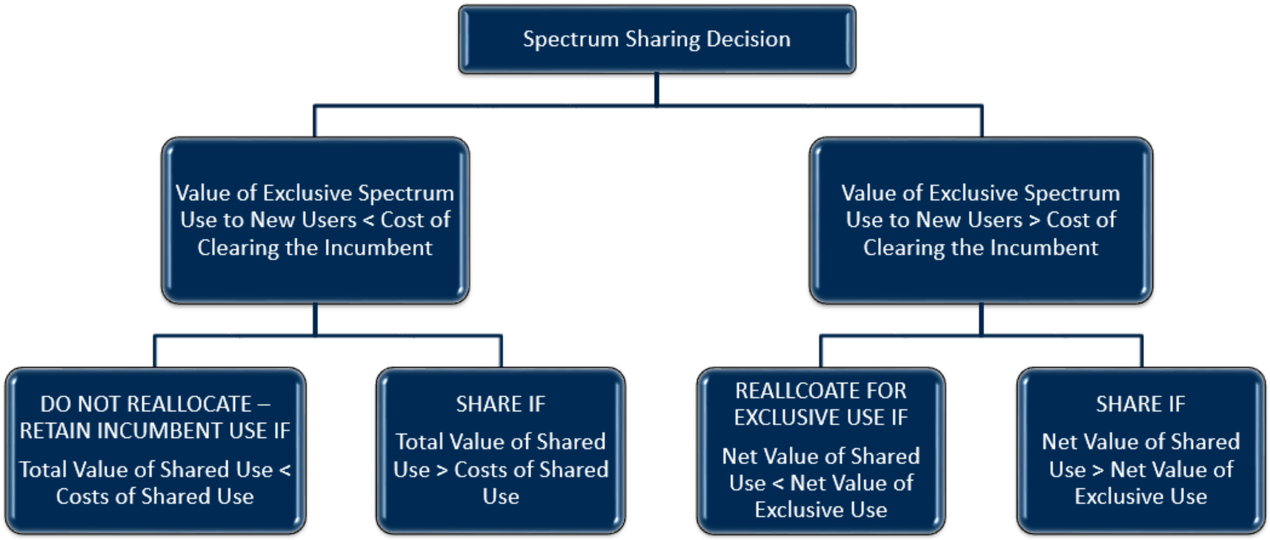
$$[Value\ of\ New\ (Exclusive)\ Users]\ - [Clearing\ Cost]$$

Based on this value calculation and an estimate of the costs of shared use, we provide a decision schematic below.

[121] Edward Graham, "FCC's Spectrum Sharing Proposal Draws Lawmaker Concerns," Nextgov, November 28, 2022, https://www.nextgov.com/policy/2022/11/fccs-spectrum-sharing-proposal-draws-lawmaker-concerns/380097/.

[122] In theory, the sharing costs for the new users and for the incumbents are likely different.

FIGURE 2: SPECTRUM SHARING DECISION TREE



A. Private Costs and Benefits of Aggregation and Disaggregation of Usage rights

As seen in the Spectrum Sharing Decision Tree above, there are four primary elements to consider when deciding which collection of usage rights will maximize private spectrum value. We list these below.

i. Net Private Value of New Users of Exclusive Licenses

- The *private value to new users* comes from their ability to control the quality of service.[123] For mobile providers operating nationwide networks, the aggregated usage rights under exclusive sharing are generally more valuable than shared access, as this is perceived by some as critical to ensuring service quality and improving spectral efficiency through technical innovations.[124]

- *Clearing Costs* are the primary *cost of granting exclusive licenses*, *i.e.*, aggregated usage rights (exclusive use rights) to new users. They are the cost of relocating

[123] Different Shades of Spectrum Sharing.

[124] CTIA, "Spectrum Considerations For 5G," accessed November 21, 2022, https://api.ctia.org/wp-content/uploads/2019/03/Spectrum-Considerations-for-5G.pdf.

the incumbents, or any loss of revenues suffered by incumbents due to interference from new uses. When there are federal incumbents in a band, especially those with mission critical services, the cost of clearing a band may be very large, and in many instances, clearing the band may not be a feasible option.

ii. *Net Private Value of New Users/Uses of Shared Licenses*

- The *private value to new users/uses of shared licenses* comes from their ability to access and use spectrum that they may not otherwise have been able to afford under an exclusive licensing regime, or from new uses of the shared spectrum by mobile providers. New and non-traditional spectrum users who want to deploy new services such as private wireless networks "that don't need to operate at a nationwide scale but need predictable and secure wireless connectivity across larger coverage footprints than Wi-Fi local area networks," such as Fixed Wireless Access ("FWA") from mobile providers or precision agriculture services, fall under this category.[125]

- *Sharing Costs* are the cost of sharing the band with other users, such as managing interference, implementing interference mitigation technologies, paying fees to a spectrum coordinator for managing the shared access, and so on.

iii. *Net Value to Incumbents*

- The *value to incumbents* of using the spectrum band under consideration preserved in a sharing regime as they do not have to (fully) vacate the band.

- *Sharing Costs or the costs in a coordinated sharing* regime are imposed to minimize interference, and any other costs associated with coordination.[126]

iv. *Non-Private Value from Innovation*

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[125] Different Shades of Spectrum Sharing. *See e.g.*, WiFi Forward, "Farms of the Future, Made Possible with CBRS," August 12, 2022, accessed December 19, 2022, http://wififorward.org/news/farms-of-the-future-made-possible-with-cbrs/. Jeff Epstein, "5G and CBRS Give Fresh Life to Fixed Wireless Access," Private LTE and 5G, Market Pulse, June 1, 2022, accessed December 19, 2022, https://www.privatelteand5g.com/5g-and-cbrs-give-fresh-life-to-fixed-wireless-access/.

[126] Deloitte, "The Impact of Licensed Shared Use of Spectrum," GSMA, p. 10, January 24, 2014, https://www.gsma.com/spectrum/wp-content/uploads/2014/02/The-Impacts-of-Licensed-Shared-Use-of-Spectrum.-Deloitte.-Feb-2014.pdf.

> The *benefits of disaggregated rights* mostly come from the expansion of consumer facing wireless services to new and innovative users/uses of the spectrum band. This is beyond the private value (price paid in the auction) generated, to say, John Deere, from deploying spectrum for precision agriculture. These are a form of positive externality.

We will use the three bands discussed earlier to illustrate the Principle of Spectrum Sharing. We will show how the comparative costs and benefits discussed above favor the aggregated use rights regime for some bands while for others disaggregated rights may be more valuable. We show how this Principle justifies the sharing of the 12 GHz band between different services and the exclusivity of the C-Band. We then discuss the 3.1-3.45 GHz band and compare the base case of aggregated rights against alternative collections of disaggregated rights.

1. 12 GHz Band (12.2-12.7 GHz)

In a given spectrum band, if the incumbents' uses can coexist without interference with new terrestrial mobile uses, or if the cost of allocating the spectrum to terrestrial mobile use has a limited monetary impact on incumbents, then sharing the band with other services (coexistence) while granting *aggregated complementary rights*, *i.e*., exclusive use licenses for the new 5G users, will likely maximize value.

If these conditions were true for the 12 GHz band, and the FCC followed the above Principle, then using the framework developed earlier, the benefits from sharing the band between the three services (licensed mobile services, DBS and NGSO services) would outweigh exclusive mobile access in the band, as the additive benefit from mobile services, DBS and NGSO services minus the small interference cost will be greater than the value of granting exclusivity to mobile services minus the relocation cost.[127] The aggregate value of the band will be the sum of values from the 5G services (proxied by the auction receipts), the value of DBS services in the band, and the value of NGSO services, minus the limited interference cost.[128] The Commission however, has opted

[127] The average value created is estimated at $40 billion and the costs are minimal. *See* Coleman Bazelon and Paroma Sanyal, "Valuing the 12 GHz Spectrum Band with Flexible Use Rights," Comments of RS Access: Appendix B – Brattle Group Economic Study, May 7, 2021, https://www.fcc.gov/ecfs/document/10508241713847/3, ("Valuing the 12 GHz Spectrum Band with Flexible Use Rights"). Our understanding is that engineering studies find minimal likelihood of harmful interference with the NGSO services in the 12.2 – 12.7 GHz portion of the band, and potential for limited harmful interference for a small subset of DBS customers, making the cost of sharing small relative to the benefits. *See* RKF, "Analysis of Starlink Submission Regarding the Effect of 5G Deployment on NGSO FSS," filed by RS Access, July 15, 2022, https://www.fcc.gov/ecfs/document/1071645443795/1.

[128] As part of the comments filed in the 12 GHz docket, we explored the costs and benefits of sharing the band between terrestrial mobile use, DBS and NGSO services and found that moving DBS out might be expensive, but

not to have high-powered two-way mobile services in the band, but is still interested in expanding fixed terrestrial use of the band, which would also be a type of shared use.[129]

2. C-Band (3.7-4.2 GHz)

For C-Band, the clearing costs (exclusive of accelerated clearing) were small (estimated at $3 billion) compared to potential auction revenue.[130] This is a clear case where incumbents would have to be moved before 5G services could be deployed in the band and the cost of clearing was small, making net private values from exclusive licensing high. With new satellites, all existing satellite based services provided in the C-Band would continue, so there were not losses in the incumbents' incomes.[131] Additionally, sharing with the satellite operators was not an option due to interference concerns, limiting the value from sharing.[132]

The commonality between the C-Band and the 12 GHz band is that there were no federal incumbents with mission critical services in these bands. For the 12 GHz band, this meant that in the absence of interference, the band could be shared by different services, and a small subset of incumbents would need to be compensated. For the C-Band, the low cost of clearing coupled with the existence of interference, implied that exclusive licensing could potentially maximize the value of the band. Below, we discuss the value proposition of the 3.1-3.45 GHz band using various disaggregated rights scenarios, as an illustration of the Principles of Spectrum Sharing and the decision framework that follows from it.

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allowing them to stay would only reduce value by a little. *See*, Valuing the 12 GHz Spectrum Band with Flexible Use Rights.

129 2023 12.7 GHz NPRM, ¶¶ 48-49.

130 Douglas Chun, "Overcoming C-Band Satellite Interference," Norsat International, October 23, 2017, accessed December 1, 2022, https://www.mpdigest.com/2017/10/23/overcoming-c-band-satellite-interference/.

131 Debra Warner, "C-band Bonanza Bails Out Sluggish Year for Satellite Orders," Spacenews, November 9, 2020, accessed January 23, 2023. https://spacenews.com/c-band-bonanza-bails-out-a-sluggish-year-for-satellite-orders/.

132 Mike Dano, "Life After the Andromeda Spectrum Auction is Looking Problematic," Light Reading, September 30, 2021, accessed November 23, 2022, https://www.lightreading.com/5g/life-after-andromeda-spectrum-auction-is-looking-problematic/d/d-id/772460, ("Life after the Andromeda Spectrum Auction is Looking Problematic").

3. 3.1-3.45 GHz Band

a. Comparing the Costs of Sharing versus Exclusive Licensing

Clearing Costs. Similar to the CBRS Band, the 3.1-3.45 GHz Band also has DOD radars with mission-critical services that cannot be easily moved. In fact, the "spectrum from 3.1 GHz-3.45 GHz is much more heavily utilized by government users than 3.45 GHz-3.55 GHz, making it more difficult to clear the spectrum for commercial users."[133] The Pentagon has recently stated that vacating the mid-band for commercial 5G would cost the DOD at least $120 billion.[134]

Sharing Costs.[135] In a CBRS-style sharing regime, as discussed earlier, the SAS is the spectrum coordinator, and this service comes with a cost. For example, Google charges $2.25 per household per month (for fixed wireless use) for its SAS product.[136] We use this as an estimate of the monthly cost for any service using the CBRS Band.[137] Assuming that CBRS-based spectrum sharing is used nationwide, we use the number of housing units in the contiguous U.S. to convert the $2.25 per month to a total cost per month of $0.29 billion.[138] This would imply an aggregate net present cost of approximately $4.7 billion, as shown in Table 5, below.

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133 Life After the Andromeda Spectrum Auction is Looking Problematic.

134 Congress May Sell Out National Security for 5G — There's a Better Way. *See also*, "Transcript of House Armed Services Subcommittee on Strategic Forces Hearing on Strategic Forces Posture," March 08, 2023, https://www.stratcom.mil/Media/Speeches/Article/3325743/hasc-sf-subcommittee-fiscal-year-2024-strategic-forces-posture-hearing/.

135 When discussing sharing cost, we are not considering the cost that is associated with the uncertainty regarding the sharing protocol, such as the risks associated with whether the dynamic sharing and the SAS coordinator regime would work well in the CBRS Band, as it was still untested at the time of the auction. This type of cost due to uncertainty of the sharing protocol is included in the value side of the equation, where it reduces the value of the band, as seen from the earlier discussion in Table 3.

136 Google, "Spectrum Access System (SAS): SAS Pricing," accessed December 2, 2022, https://www.google.com/get/spectrumdatabase/sas/, ("Spectrum Access System (SAS): SAS Pricing")

137 For example, for IoT or Private-LTE uses, Google proposes a per-Radio charge. *See*, Spectrum Access System (SAS): SAS Pricing.

138 We calculate 130,878,255 housing units in the contiguous US; *see,* United States Census Bureau, "National, State, and County Housing Unit Totals: 2010-2019," accessed December 2, 2022, https://www.census.gov/data/tables/time-series/demo/popest/2010s-total-housing-units.html.

b. Comparing the Value from Sharing versus Exclusive Licensing under Alternative Scenarios

As explained earlier, the 3.1-3.45 GHz Band is allocated to federal radiolocation on a primary basis and to Earth exploration-satellite and space research and radiolocation services on a secondary basis. Given the difficulty in moving federal operations, it stands to reason that the amount of spectrum available under exclusive licensing may be smaller than that available under a shared regime. To understand the comparative value of disaggregated and aggregated rights under various licensing regimes, we develop an example with the 3.1-3.45 GHz Band. We assume a base auction price of $0.22/MHz-pop for the 3.1-3.45 GHz Band if there is CBRS-style sharing with uncertainty similar to the CBRS auction and we also assume that 350 megahertz could be made available for exclusive licensing, but with significant clearing costs ($120 billion as estimated by DoD).[139] We then simulate re-aggregation of rights (*i.e.*, power limits) and alternative scenarios of bidders' certainty, to estimate the impact of value of the 3.1-3.45 GHz Band under shared versus exclusive licensing, using the estimates from Table 4, above.

Table 5, below, shows three hypothetical situations, where Column 1 shows a CBRS-style sharing regime with power limits and uncertainty surrounding the sharing regimes and Columns 2 and 3 show aggregated rights and no uncertainty scenario – *i.e.*, exclusive licensing – where all 350 megahertz can be cleared at two clearing cost scenarios.

[139] These significant clearing costs are for relocating, and thus preserving, the DoD's missions. Consequently, whether the incumbents remain in the band or are relocated, the value of their operations remains the same. Not relocating, however, avoids any risks associated with a transition to new frequencies and equipment.

TABLE 5: PRIVATE VALUE OF DISAGGREGATED USAGE RIGHTS IN THE 3.1-3.45 GHZ BAND

Licensing		**CBRS-Style Sharing**	**Exclusive**
Power		Low Power	Full Power
Risk		Uncertainty	Full Certainty
Clearing Cost		Zero	High
		[1]	[2]
Baseline			
Base Price (CBRS) ($ / MHz-Pop)	[a]	$0.22	$0.22
Total Population	[b]	306,675,006	306,675,006
Megahertz Available	[c]	350	350
Exclusive Revenues ($bn)	[d]	$23.28	$23.28
Propagation Increment			
Propagation Price Effect ($ / MHz-Pop)	[e]	$0.00	$0.46
Propagation Revenue Increase ($bn)	[f]	$0.00	$49.65
Uncertainty Increment			
Uncertainty Price Effect ($ / MHz-Pop)	[g]	>= $0.00	$0.03
Certainty Revenue Increase ($bn)	[h]	>= $0.00	$3.54
Private Value			
3.1 - 3.45 GHz Price ($ / MHz-Pop)	[i]	$0.22	$0.71
Premium for Frequency Assignment ($ / MHz-Pop)	[j]	$0.00	$0.02
Frequency Assignment Revenue Increase ($bn)	[k]	$0.00	$2.15
3.1 - 3.45 GHz Adjusted Price ($ / MHz-Pop)	[l]	>= $0.22	$0.73
Revenue from New Users	[m]	>= $23.28	$78.62
Costs			
Clearing Costs	[n]	$0.00	$120.00
SAS Cost per Household per Month	[o]	$2.25	$0.00
Estimated SAS Cost per Month ($bn)	[p]	$0.29	$0.00
Estimated Sharing Cost ($bn)	[q]	$4.67	$0.00
Total Costs ($bn)	[r]	$4.67	$120.00
Net Value			
Net Value to New Users ($bn)	[s]	**>= $18.61**	**-$41.38**

Sources and Notes:

[a]: Sahsa Javid, "Auction 105 Summary," accessed September 14, 2022, https://sashajavid.com/FCC_Auction105.php.

[b]: 2010 CONUS Population from Census Bureau.

[c]: Assumption.

[d]: [a] x [b] x [c].
[e]: See Table 4.
[f]: [e] x [b] x [c].
[g]: See Appendix B Table 1.
[h]: [g] x [b] x [c].
[i]: [a] + [e] + [g].
[j]: Assumption based on Auction 110 assignment phase premium.
[k]: [j] x [b] x [c].
[l]: [i] + [j].
[m]: [d] + [f] + [h].
[n]: The Pentagon has reported that vacating mid-band for commercial 5G would cost DOD at least $120 billion.
See, "Transcript of House Armed Services Subcommittee on Strategic Forces Hearing on Strategic Forces Posture," March 08, 2023, https://www.stratcom.mil/Media/Speeches/Article/3325743/hasc-sf-subcommittee-fiscal-year-2024-strategic-forces-posture-hearing/.
[p]: [o] x [Estimated US Households using the service], calculated as 100% of 2010 CONUS Households.
[q]: Google Fixed Wireless Monthly SAS Cost for 1 of households in the CONUS, discounted at a rate of 6.30% per Department of Revenue Washington State, "Cost of Capital Study," 2021, accessed September 14, 2023, https://dor.wa.gov/sites/default/files/2022-02/2021COCWireless.pdf.
[r]: [n] + [q].
[s]: [m] - [r].

The table above shows how disaggregated rights can affect the private value of spectrum using the 3.1-3.45 GHz Band as an example. We start with a very conservative baseline price, *i.e.*, the CBRS auction price, assuming that a CBRS-style sharing regimes would have the identical power limits and uncertainty as the CBRS regime. What makes the baseline conservative is that the 3.1-3.45 GHz is a lower frequency band than the 3.5 GHz Band and hence the same power limit as the 3.5 GHz Band will lead to better propagation and hence greater value of the band. In addition, we would expect there to be less uncertainty with a shared regime as users have more experience with implementing a shared regime with a SAS. To the extent any uncertainty around implementing a shared use regime has been resolved, the value in Column [1] would be higher.[140]

The analysis starts with the historically observed private market value of CBRS spectrum observed at auction of $0.22/MHz-pop. For the exclusively licensed scenarios in Column [2], we make three adjustments. We add back $0.46/MHz-pop for the greater propagation from higher power levels allowed in an exclusively licensed regime; $0.03/MHz-pop for eliminating any uncertainty that *might* continue to exist for a shared regime; and $0.02 as a premium for knowing which

[140] The values in cells [1][g] and [1][h] would be positive. In the table we indicate this possibility with a greater than equal to sign. If these numbers were positive, then the total value of the shared spectrum would also be greater than our estimated value and this is indicated in cell 1[s].

frequency a licensee will be assigned. This establishes a private market value of $0.73/MHz-pop for exclusively licensed spectrum (total private market value of 350 MHz of more than $78 billion) compared to $0.22/MHz-pop for a CBRS-style sharing regime (total private market value of 350 MHz of almost $24 billion).

Next, we address the costs of sharing versus the costs of exclusive licensing. The costs of sharing are the costs of implementing a SAS – estimated to be almost $5 billion. The costs of exclusive use are the costs of clearing the spectrum. We use the $120 billion estimated clearing cost that the DOD has stated, as discussed earlier. In row [s] of Table 5 we report the net private values to all new users which takes into account both the value of new uses and the costs of enabling those uses. We find that the value of a shared regime would be almost $19 billion (column [1], row [s]), whereas the value of exclusive use would be -$41 billion (column [2], row [s]) if the DOD's estimate of clearing costs are accurate. In general, we find that even if the clearing costs were significantly less that the DOD estimate, sharing would provide a better economic decision that exclusive licensing. Even when just comparing private values, in situations where the clearing costs are lower, sharing may still be the value maximizing option compared to exclusive licensing.[141]

This example however, gives a conservative value of sharing, as it does not capture any of the non-private values that a sharing scheme may generate, such as bringing new and non-traditional spectrum users to the market, increased service competition, expanding broadband coverage, increase innovation and bringing new spectrum-based services into the market. Below, we discuss some of these value generating streams that need to be considered when deciding between the collection of usage rights that maximize the value of the spectrum band, although quantifying these is often difficult.

B. Illustrative Non-Private Value from Innovation Generated by Disaggregation of Usage rights

Shared spectrum licensing often enables multiple categories of users, such as industrial, manufacturing, education, health care, agricultural, and regional and nationwide wireless carriers, to productively share the same frequency bands. Such non-traditional users can expand wireless service choice for consumers, engender innovative and new spectrum uses for both

[141] We find that if the clearing costs are anywhere above half (approximately) the DoD clearing cost estimate, then the private value from sharing will be greater than the private value from exclusive.

consumer and commercial users, and provide better connectivity to educational institutions and so on. Further research is necessary to quantify all the possible non-private value streams that can arise from a disaggregation of user rights. Below, we discuss two uses that have emerged out of the CBRS Band, when we can quantify the non-private values of sharing.

1. Expanding Wireless Service Choice for Consumers: Entry of Non-Traditional Entities into the Wireless Marketplace and Innovative Uses from MNOs May Expand Wireless Connectivity for Consumers and Foster Greater Competition

The CBRS auction provided a chance for many potential wireless competitors to enter the marketplace, including many Wireless Internet Service Providers (WISPs), cable operators, businesses such as Chevron and Deere & co., and a number of utilities, bringing additional value to the band and to the economy.[142] The top bidders in the CBRS auction included Verizon, DISH and cable providers and non-MNOs such as SAL Spectrum LLC, AMG Technology Investment Group (Nextlink), Windstream Services and XF Wireless Investment/Comcast. This result was unlike other spectrum auctions.[143] Bringing in these new demands for spectrum has the potential to increase competition in the wireless marketplace, decrease prices further, and increase quality of service.[144] Additionally, the price paid for spectrum by some entrants exceeded what traditional mobile carriers paid. For example, Sempra (San Diego Gas and Electric) and Southern California Edison paid $0.57/MHz-pop and $0.51/MHz-pop respectively, compared to Verizon's $0.30/MHz-pop.[145]

The disaggregation of usage rights afforded a way for smaller wireless carriers and WISPs to offer broadband in rural communities in a cost-effective way and expand the economic impact of

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[142] Monica Allenven, "Verizon, Dish & Cable Top List of CBRS Auction Winners," September 2, 2020, accessed November 20, 2022, https://www.fiercewireless.com/operators/verizon-dish-cable-top-list-cbrs-auction-winners.

[143] Mike Dano, "Verizon, Dish, Charter, Comcast: Here Are the 20 Biggest CBRS Auction Winners," September 2, 2020, https://www.lightreading.com/5g/verizon-dish-charter-comcast-here-are-20-biggest-cbrs-auction-winners/d/d-id/763633.

[144] Research has shown that competition between providers with quality-differentiated products increase the distribution of quality offered in a market. *See e.g.*, Justin P Johnson and David P. Myatt, "Multiproduct Quality Competition: Fighting Brands and Product Line Pruning," *American Economic Review* 93(3) (2003): 748-774.

[145] Monica Paolini, "Industry Voices — Paolini: Why Did Utilities Pay so Much for CBRS Licenses?" September 22, 2020, accessed November 20, 2022, https://www.fiercewireless.com/private-wireless/why-did-utilities-pay-so-much-for-cbrs-licenses, ("Why Did Utilities Pay so Much for CBRS Licenses?").

broadband.[146] In the current technical environment, beam-forming capabilities found in Massive MIMO radios can be used with the CBRS spectrum to provide rural broadband in places where there may not have been an economic incentive to deploy for traditional wireless providers.[147] For example, both Mercury Broadband, a regional internet provider and Avista Utilities, an energy company "debuted CBRS-based Fixed Wireless Access services to the communities they serve." The entry of these players in the spectrum space will foster greater innovation and novel uses, leading to increases in economic value and consumer welfare.

Fostering digital equity across rural and urban geographies is now one of the foremost policy goals of the FCC. Various subsidy programs by the FCC such as the ACP and the Rural Digital Opportunity Fund, along with the BEAD program from the IIJA under the Department of Commerce, are granting billions of dollars in broadband subsidies to deploy broadband to rural areas.[148] This speaks to the enormous value of connecting the rural population. If a CBRS-style spectrum sharing regime can incentivize more providers to enter the wireless space and offer FWA services, the benefits from this should be considered when computing the value generated by spectrum sharing.

Additionally, MNOs such as Verizon have been using the CBRS spectrum to boost their 4G and 5G speeds and to offer private LTE services.[149] An industry report shows that LTE network speed for Verizon saw an increase of up to 80% on average, after deploying CBRS.[150]

A 2020 study by the Federal Reserve Bank shows that the "local labor market effects, benefits accruing to consumers, benefits accruing to businesses and homeowners, and benefits accruing to participants in telemedicine and distance learning," from broadband connectivity ranges between $22 million to $192 million annually depending on the state and the numbers of

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[146] Bob O'Donnell, "CBRS Enables New Opportunities for Rural Broadband," Forbes, accessed November 201, 2022, https://www.forbes.com/sites/bobodonnell/2022/03/08/cbrs-enables-new-opportunities-for-rural-broadband/?sh=5170438a2edf, ("CBRS Enables New Opportunities for Rural Broadband").

[147] CBRS Enables New Opportunities for Rural Broadband.

[148] *See*, Broadband USA, "Broadband Equity, Access, and Deployment (BEAD) Program," accessed November 22, 2020, https://broadbandusa.ntia.doc.gov/broadband-equity-access-and-deployment-bead-program. *See also*, FCC, "Auction 904: Rural Digital Opportunity Fund," accessed November 22, 2022, https://www.fcc.gov/auction/904.

[149] Verdict, "Two Years After CBRS Auction, US Service Providers Start to Reap Benefits," March 17, 2022, accessed December 19, 2022, https://www.verdict.co.uk/cbrs-spectrum-auction-us-service-providers/.

[150] RCR Wireless News, "Verizon Expands CBRS Spectrum Use from 4G to 5G," June 15, 2022, accessed December 19, 2022, https://www.rcrwireless.com/20220615/5g/verizon-expands-cbrs-spectrum-use-from-4g-to-5g.

unserved population.[151] Using these numbers, we provide an initial illustrative estimate (detailed in Appendix C) of the benefit from expanding CBRS-based fixed wireless services as around $1.4 billion.[152] Future work on this segment of value will involve a deeper dive into this issue and a more detailed valuation rubric.

2. Fostering New Spectrum-Based Services for Industry: Entry of Non-Traditional Entities will Likely Generate New Wireless Uses

The disaggregated rights regime in the CBRS auction has not only attracted new users in the consumer wireless space, but has also fostered innovative uses. For example, it led to the growth of private LTE networks among utilities. Utilities require reliability and real-time operations and thus have a preference to "deploy and control their own private networks, and to minimize their dependency of mobile operators which cannot grant utilities the level of control they want."[153] The utilities who obtained access to the CBRS spectrum through PALs can now provide better services to their customers, for example to monitor and optimize energy consumption, but also "ensure mobile connectivity to their staff (*e.g.*, for remote assistance during service disruption or upgrades, to manage workflow), and to remotely control and manage their infrastructure and facilities."[154] A similar narrative also applied to companies such as Chevron and John Deere, where the PALs will "enable John Deere to accelerate the availability of 5G in its largest manufacturing facilities."[155]

The USDA estimates that bringing wireless connectivity to rural America will lead to enhanced agricultural management and technological progress, which in turn "could create approximately

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[151] Federal Reserve Bank of Richmond, "Bringing Broadband to Rural America," *Community Scope*, 8(1) (2020), p. 4, https://www.richmondfed.org/-/media/RichmondFedOrg/publications/community_development/community_scope/2020/community_scope_2020_no1.pdf.

[152] We used the average value creation and used the number of unserved population to estimate this.

[153] Why Did Utilities Pay so Much for CBRS Licenses.

[154] Why Did Utilities Pay so Much for CBRS Licenses.

[155] Gigi Wood and John Deere, "John Deere to Deploy 5G in Manufacturing Facilities," Construction, November 18, 2020, accessed November 21, 2022, https://www.forconstructionpros.com/construction-technology/article/21203330/john-deere-john-deere-to-deploy-5g-in-manufacturing-facilities.

$47–$65 billion annually in additional gross benefit for the U.S. economy."[156] Of this increase, "rural broadband connectivity is the driver of more than one-third of the value or $18 billion to $23 billion per year."[157] A portion of the value from these emerging services would be lost to society in the near-term but-for the CBRS auction with its shared spectrum paradigm. These new use cases will be further developed in future work.

C. Net Private Plus Non-Private Value Generated by Disaggregation of Usage Rights

Using the 3.1-3.45 GHz Band as an example, we find that the net private value of spectrum under an exclusive licensing regime is negative when clearing costs are accounted for, but using a CBRS-style sharing scenario that avoids the clearing costs can create almost $19 billion in net private values.[158] However, to arrive at the full economic and social value generated by the shared licensing regime, the non-private values have to be included in the spectrum value maximizing equation guiding the spectrum sharing decision.

[156] USDA, "A Case for Rural Broadband," April 2019, p. 23, https://www.usda.gov/sites/default/files/documents/case-for-rural-broadband.pdf, ("A Case for Rural Broadband").

[157] A Case for Rural Broadband, p. 23.

[158] *See,* Table 5.

V. Conclusion

This paper articulated the Principles of Spectrum Sharing and developed the framework to guide policy makers when faced with a sharing versus exclusivity decision. We estimate the impact of disaggregated usage rights on spectrum value and show that when auction receipts for shared spectrum are reduced it is not the 'sharing' regime that lowers private values (as proxied by auction receipts), but the usage rights that are included in the sharing regime.

What emerges from the above discussion are broad guidelines for implementing the Principle of Spectrum Sharing.

- *Exclusive Licensing is the Preferred Option*:
  - When the cost of clearing a band (*i.e.*, cost of exclusivity) is lower than the private value of the band under exclusive licensing, and the value from exclusivity is greater than the net shared value (private and non-private values), exclusive licensing maximizes the value of the spectrum
- *Sharing is the Preferred Option*:
  - In situations where the interference from new services to incumbents is minimal, and relocation of incumbents is not needed, sharing the band with incumbents maximizes the value of the spectrum.
  - If the net private value from sharing is less than the net private benefit from exclusive use, then the non-private values from sharing and from the exclusive regime should be accounted for before deciding to implement an exclusive versus shared license spectrum management regime. If the net non-private value from sharing is greater than the net non-private value from exclusive use, and the difference swamps the private value shortfall in sharing, then granting disaggregated rights in a shared regime will maximize spectrum value.
  - In our illustrative example, we find that a CBRS-style sharing in the 3.1-3.45 GHz band, with 350 megahertz of spectrum available for shared use, even with conservative estimates of clearing costs, maximizes the social net value of spectrum in the 3.1-3.45 GHz Band compared to an exclusive regime. The entry of non-traditional operators that is encouraged from shared licensing, as in the CBRS model, fosters greater innovation and novel uses, leading to increases in

economic value and consumer welfare that should be accounted for when assessing the full value of any spectrum proposal. For example, sharing is particularly useful for private networks being used for manufacturing, automotive, agriculture, energy, retail, commercial real estate, communications, media, and supply chain industries, as well as schools and libraries. These industries now have many more options for service as they look for innovative, purpose-built solutions to industrial needs, particularly in rural and remote areas that may not be served by traditional carriers. Bringing in these new demands for spectrum has the potential to increase competition in the wireless marketplace, decrease prices further, and increase quality of service – all of which add significant consumer value.

Thus, when deciding between a shared licensing versus an exclusive licensing regime careful attention should be paid to all the benefits and costs and then choose the set of rights – disaggregated or exclusive – depending on which has a higher overall net value. Exclusive licensing and sharing regimes are complementary strategies to make more 5G spectrum available in the U.S. The goal should be to maximize the total social and economic value of spectrum to all users, based on complete value and cost estimates.

Appendix A: CBRS Band Propagation Aggregation Model

To simulate a network buildout using publicly available data, we calculate the number of towers with C-Band GHz propagation characteristics required to build to individual census tracts such that the population in each tract is completely covered.[159] 2020 U.S. Census data is used for both tract area and population.[160] Each tract is classified into a morphology (Dense Urban, Urban, Suburban, or Rural) according to its population density.[161] Using a study that details site coverage areas by morphology and band frequency, the number of towers in each tract is estimated by dividing the tract's land area by its morphology's coverage area (from the study).[162] We use 2.6 GHz as a propagation proxy for C-Band or 3.45 GHz spectrum, since these bands' coverage area per site is expected to be roughly equivalent to that of 2.5 GHz as a result of transmit power levels and antenna gains, and 2.5 GHz is not a frequency considered in the study.[163] Henceforth we will refer to the C-Band and the 3.45 GHz Band as the 2.5 GHz Band. Next, we impose a population capacity constraint. We calculate the population that one tower can serve without a decrease in quality, which we determine based on the population that fits within one tower's coverage area in the least densely populated *urban* tract (*i.e.*, multiply the minimum population density of urban morphologies by the coverage area in urban morphologies). We then calculate an alternative number of towers in each tract (as opposed to our previous method that used

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[159] For greater accuracy in aggregate, we allow for fractional towers in a given tract.

[160] For tract areas, *see*, "Gazetteer Files," US Census, accessed November 15, 2022, https://www.census.gov/geographies/reference-files/time-series/geo/gazetteer-files.2020.html#list-tab-NA5D12ZK3VL5TF9C99. For tract populations, *see*, "Decennial Census P.L. 94-171 Redistricting Data," US Census, accessed December 5, 2022, https://www.census.gov/programs-surveys/decennial-census/about/rdo/summary-files.html.

[161] Dense Urban tracts have population density of at least 30,000 pops per sq. mi. *See*, David Wisely, Ning Wang, and Rahim Tafazolli, "Capacity and costs for 5G networks in dense urban areas," IET Communications, October 30, 2018, accessed November 15, 2022, https://ietresearch.onlinelibrary.wiley.com/doi/10.1049/iet-com.2018.5505. Urban tracts have a population density of 7,500 pops per sq. mi.; Suburban tracts have a population density of 600 pops per sq. mi.; and Rural tracts comprise the remainder. *See*, "U.S. Technology and 5G Update," American Tower, April 2018, accessed December 7, 2022, https://www.americantower.com/Assets/uploads/files/PDFs/vendor-relations/investor-relations/2018/us-technology-and-5g-update-april-2018.pdf.

[162] "APT 700 MHz: Best Choice for Nationwide Coverage," ZTE Corporation, https://www.gsma.com/spectrum/wp-content/uploads/2013/07/ZTE-LTE-APT-700MHz-Network-White-Paper-ZTE-June-2013.pdf, ("APT 700 MHz: Best Choice for Nationwide Coverage").

[163] Bevin Fletcher, "Verizon Defends C-Band Plans," Fierce Wireless, March 29, 2021, accessed November 15, 2022, https://www.fiercewireless.com/operators/verizon-defends-c-band-plans.

area) based on population by dividing the tract's population by the population constraint. We then calculate the towers required in a tract as the maximum of the towers required to cover the tract's area and its population.

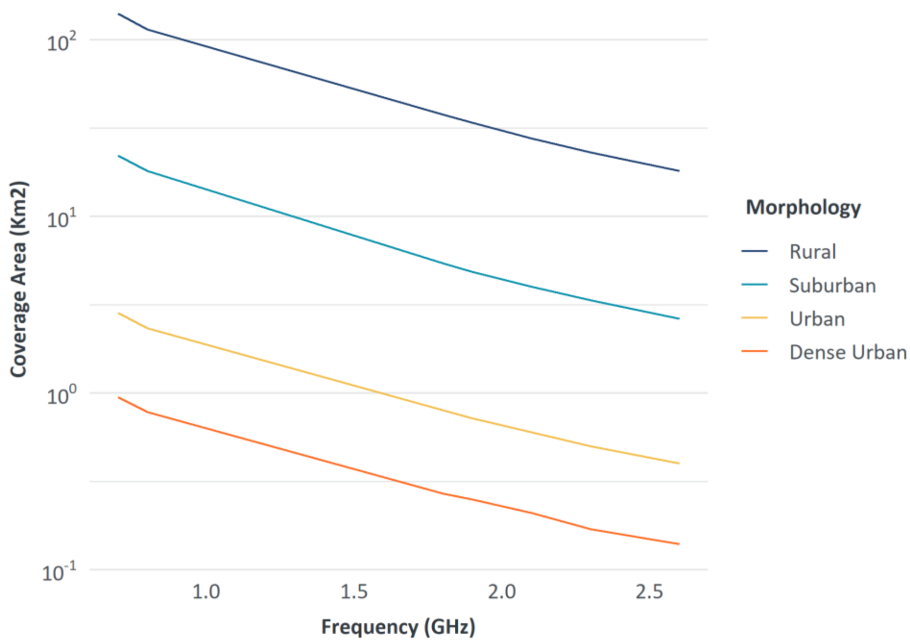
Having calculated the number of towers in each tract, we then determine which tracts are to be included in the buildout. We optimize a buildout for population density. As a proxy for a contiguous buildout, we rank each tract in the contiguous United States from the most densely populated to the least. Starting with the most densely populated tract, we then rank each tract within the *county* of this tract from the most densely populated to the least. The buildout then begins within the county: the most densely populated tract is included first, followed by the second most densely populated tract within the county. This process continues until the entire county is included in the buildout; once the county is finished, the process is repeated for the next most densely populated tract in the contiguous United States. Tracts are included in the buildout until a 99.5% coverage threshold (in terms of total population) in the contiguous United States is satisfied.[164]

Since the highest frequency included in the study is 2.6 GHz, we must estimate coverage areas for the CBRS Band (3.5 GHz) using the coverage areas of the frequencies that are included in the study.[165] We estimate a logarithmic relationship between frequency and coverage area and use this to estimate the coverage areas for CBRS spectrum under the four morphologies and apply them to the buildout.

[164] We use 99.5% to reflect the maximum coverage of any of the four major national wireless carriers. *See*, "2020 Communications Marketplace Report," FCC, December 31, 2020, accessed August 18, 2022, https://docs.fcc.gov/public/attachments/FCC-20-188A1.pdf.

[165] CBRS spectrum falls in the range of 3550 MHz to 3700 MHz, thus 3600 MHz (3.6 GHz) is used as an approximation for CBRS. *See*, Linda Hardesty, "What is CBRS?" Fierce Wireless, June 23, 2020, accessed November 16, 2022, https://www.fiercewireless.com/private-wireless/what-cbrs.

0 FIGURE 1: COVERAGE AREA VS. FREQUENCY



Sources and Notes:
See, APT 700 MHz: Best Choice for Nationwide Coverage.

Using the estimated CBRS Band coverage areas, we compare the coverage of the CBRS Band to that of the 2.5 GHz Band. In each tract included in the buildout, we multiply the number of 2.5 GHz (fractional) towers by the CBRS Band coverage area per tower and, separately, by the CBRS Band maximum population capacity per tower (calculated in the same fashion as it was for 2.5 GHz Band). This yields the area and population covered by the CBRS Band in each tract if it were built with the same infrastructure as the 2.5 GHz Band. From these two measures, we estimate the share of area and the share of population that would feasibly be covered by a CBRS network in each tract. We then calculate the CBRS population covered as the tract's total population multiplied by the minimum of these two shares. In doing so, we fix the costs associated with using CBRS or 2.5 GHz spectrum and estimate the difference in revenue gained from the two.[166] The populations covered by these two bands, and the ratio of this coverage, are detailed in 0 Table 1.

[166] We assume that a provider such as Verizon already has the infrastructure in place for the C-Band and CBRS is deployed on the existing infrastructure. Therefore the deployment cost is similar (maybe be some negligible difference in the cost of radios), and the revenue differs based on the number of pops covered.

0 TABLE 1: TOWER BUILDOUT POPULATION COVERAGES

Covered Population: C-Band	[A]		327,614,099
Covered Population: CBRS on Existing C-Band	[B]		104,588,480
Expected Coverage Ratio	[C]	[B]/[A]	32%

Appendix B: 3.45 GHz Uncertainty Regression

Having accounted for the effect of propagation on the price of CBRS spectrum at auction, we need to turn to another auction to more directly explain the value of spectrum sharing's uncertainty. Every license in the CBRS auction was sold with the same spectrum sharing scheme, so every license holder was equally uncertain about their usage rights. In contrast, as described above in Section **Error! Reference source not found.**, the FCC's 3.45 GHz auction included sharing requirements that varied across licenses. Each license had its own combination of CPA and PUA encumbrances, and any license holders whose spectrum would interfere the incumbents in these areas would need to individually coordinate and negotiate usage rights.[167] Therefore, the reduction in the price of an impaired license beyond its reduction in effective population is likely a result of bidders' uncertainty about their usage rights.

To measure this effect, we use clock phase results from the 3.45 GHz auction and the encumbrance data supplied to bidders by the DOD ahead of the auction.[168] In the 3.45 GHz auction, licenses were sold at the PEA – Category level, where each PEA had a different number of Category 1 and Category 2 licenses. For example, out of a total of 406 PEAs, in 72 PEAs, the four licenses classified as blocks A through D were sold as Category 1, while the six licenses classified as E through J were sold as Category 2.[169] The DOD provided information on which specific bands all relevant CPAs and PUAs interfered with, and in a separate KML file, they also provided the locations of these CPAs and PUAs. We use this KML file to identify the census blocks touched by each CPA or PUA, designating all of the population in any of these census blocks as impaired. We then use the DOD encumbrance data at the 100 meter level to identify which licenses would be impaired in those locations. Then, we aggregate these impairments at the census block – frequency level to the PEA – category level. For each PEA – category combination, we calculate the share of the population under any impairment and the weighted average number of CPAs and PUAs covering the population. We add this data set to the clock phase round 151 results, which were supplied at the PEA – category level.

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[167] The uncertainty in this case is *ex post* – as the auction winner does not know *ex ante*, the collection of disaggregated rights they will have after the negotiation.

[168] *See*, "Results (zipped)," FCC Public Reporting System, accessed November 18, 2022. https://auctiondata.fcc.gov/public/projects/auction110/static_files/clock_results.zip. *See also*, "3450-3550 MHz," NTIA, September 14, 2022, accessed November 18, 2022, https://www.ntia.doc.gov/category/3450-3550-mhz.

[169] "Auction 110: 3.45 GHz Service: Licenses Offered," FCC, accessed November 18, 2022, https://www.fcc.gov/auction/110/factsheet#licenses_offered.

With these data, we run a regression model to measure the effect of encumbered population on the final price of each license, controlling for other major drivers of license value. More specifically, our model takes the following regression specification:

$$\$\,per\ MHz\ POP = Intercept + \sum_{q=1}^{4} \beta_q\, Encumbrances_q + \beta_5 Population + \beta_6 Population^2 + \beta_7 Avg.Pop.Density + \beta_8 Category_2$$

In this specification, $\$\,per\ MHz\ POP$ denotes the average price for the license in each PEA. $Encumbrances_q$ is a dummy variable that takes the value 1 if the license is in the q^{th} quartile of population-weighted average encumbrances.[170] These dummy variables can be interpreted as the incremental impact of uncertainty on the license prices relative to the prices of licenses without uncertainty. The metric of population-weighted average encumbrances incorporates the share of population in the market that is encumbered and also reflects the number of encumbrance areas covering the encumbered populations. We also control for the following drivers of license value:

- Total Population (in millions): included as a first-order and square term, this captures the size of the market as a whole.
- Average Population Density: this captures the relative cost to deploy a network in the market.
- Category 2: this is a dummy variable indicating whether the license is a Category 2 license, capturing the additional effect of the auction-specific category designations on bidders' behavior.

[170] These quartiles exclude an encumbrance value of 0, implying no encumbrance. Likewise, the coefficients for these quartile variables reflect the adjustment to the "Zero Encumbrance" intercept associated with each quartile.

TABLE 1: REGRESSION COEFFICIENTS

Term	Estimate	Standard Error
Intercept (no encumbrances)	0.2808***	0.0184
Encumbrance Quartile 1	-0.0252	0.0545
Encumbrance Quartile 2	-0.1347**	0.0552
Encumbrance Quartile 3	-0.2668***	0.0557
Encumbrance Quartile 4	-0.4425***	0.0566
Total Population	0.0743***	0.0176
Total Population^2	-0.0026***	0.0007
Population Density	0.0004***	0.0001
Category 2	0.2917***	0.0379
R-Squared	0.351	

Sources and Notes:
[1]: *p<0.1; **p<0.05; ***p<0.01
[2]: Licenses where $ per MHz POP is equal to or greater than $2 are dropped (these account for 2.72% of licenses).
[3]: Encumbrance variables are in quartiles for non-zero encumbrances. Zero encumbrances is considered the baseline group.

Table 1 shows the results of our regression. Relative to zero encumbrances in a given license, as the value of the population-weighted average encumbrances in a license increases (*i.e.*, moves into a higher quartile), so too does the magnitude of the *decrease* in price per MHz-pop. Using the estimates for the coefficients of these quartiles and the population associated with each quartile (including that for zero encumbrances), as well as the average price of an unencumbered license, we estimate the average impact of uncertainty around license use in Appendix B Table 2.

APPENDIX B TABLE 2: UNCERTAINTY IMPACT

Term		($/MHz-pop)
Average Price of Unencumbered License	[A]	0.792
Price Difference for Licenses in the…		
Bottom 25% of Encumbered Licenses	[B]	-0.025
25%-50% Encumbered Licenses	[C]	-0.135
50%-75% Encumbered Licenses	[D]	-0.267
Top 25% Encumbered Licenses	[E]	-0.443
Average Impact of Uncertainty Around License Use		
$/MHz-pop	[F]	-0.105
Percentage Difference from Unencumbered Licenses	[G]	-13.3%

Notes:
[F]: Population weighted average of [B] through [E] (includes licenses with zero encumbrances).
[G]: [F]/[A].

Appendix C: Illustrative Non-Private Value

The table below demonstrates the calculations supporting our illustrative estimates of non-private value associated with a CBRS-style spectrum sharing regime.

APPENDIX C TABLE 1: ILLUSTRATIVE NON-PRIVATE VALUE CALCULATIONS

Expanding Wireless Service Choice for Consumers		
Estimated Minimum Report Annual Broadband Benefit ($mm)	[a]	$507.65
Corresponding State Households	[b]	13,090,881
National Households	[c]	130,878,255
Extrapolated National Annual Broadband Benefit ($mm)	[d]	$5,075
Net Present National Broadband Benefit ($bn)	[e]	$80.56
Fixed Wireless Residential Connections, 2019 (mm)	[f]	1.49
Non-DSL Residential Connections, 2019 (mm)	[g]	87.11
Wireless Percent of Broadband	[h]	1.71%
Value from New Wireless Broadband Services ($bn)	[i]	$1.38
New Spectrum-Based Services for Industry		
Estimated Rural Broadband Connectivity Value per Year ($bn)	[j]	$18
Percent of Value from Mobile Wireless Access	[k]	5.00%
Wireless Access Value per Year ($bn)	[l]	$0.90
Value from New Wireless Uses ($bn)	[m]	$14.29

Sources and Notes:

[a]: Calculated as sum of individual states' average of 50% adoption value and 20% adoption value from Federal Reserve Bank of Richmond, "Community Scope," December 2020, https://www.richmondfed.org/publications/community_development/community_scope/2020/comm_scope_vol8_no1.

[b]: Households in Maryland, North Carolina, South Carolina, Virginia, and West Virginia, per source of [a], from United States Census Bureau, "National, State, and County Housing Unit Totals: 2010-

2019," accessed December 2, 2022, https://www.census.gov/data/tables/time-series/demo/popest/2010s-total-housing-units.html.

[c]: United States Census Bureau, "National, State, and County Housing Unit Totals: 2010-2019," accessed December 2, 2022, https://www.census.gov/data/tables/time-series/demo/popest/2010s-total-housing-units.html.

[d]: [a] x [c] / [b].

[e]: [d] discounted at rate of 6.30%.

[f], [g]: FCC 2020 Communications Marketplace Report.

[h]: [f] / [g].

[i]: [e] x [h].

[j]: USDA, "A Case for Rural Broadband," April 2019, https://www.usda.gov/sites/default/files/documents/case-for-rural-broadband.pdf.

[k]: Assumption that half of connectivity value is wireless and 10% of wireless value is from CBRS-style sharing.

[l]: [j] x [k].

[m]: [l] discounted at rate of 6.30%.