Evaluating the CBRS Experiment

Randall Berry
Northwestern Univ.
rberry@northwestern.edu

Thomas Hazlett
Clemson Univ.
hazlett@clemson.edu

Michael Honig
Northwestern Univ.
mhonig@northwestern.edu

J. Nicholas Laneman
Univ. of Notre Dame
jnl@nd.edu

Abstract:

In 2015, the FCC established the Citizens Broadband Radio Service (CBRS) for sharing the 3.5 GHz Band (3550-3700 MHz) among federal and non-federal users in the United States. This rulemaking created an experiment in a novel three-tier rights structure: strong protections for incumbents, including government radar systems; Priority Access Licenses (PALs) granting exclusive rights to high bidders in an FCC auction, in part of the band and subject to avoiding interference with incumbents; and Generalized Authorized Access (GAA) for unlicensed users, subject to avoiding interference with both PALs and incumbents. The first commercial deployments in this band were approved in 2019 for GAA devices, and an auction of PALs completed in 2020 generated $4.5 billion in revenues.

It is now timely to evaluate this experiment and glean lessons for applications to other spectrum bands, such as the neighboring 3.1-3.45 GHz band or portions of the upper mid-band spectrum 7-24 GHz. In fact, a number of perspectives on CBRS have been recently published. In this paper we review these developments and suggest related policy questions that should be considered when evaluating the use of CBRS-style allocation rules in future bands.

The CBRS policy involves several different innovations, seeking to accomplish multiple objectives. One can evaluate this approach from a technical point of view, as an experiment to show that dynamic sharing can provide multiple tiers of commercial access to a band of spectrum while protecting incumbent users. The approach involves coordinated access via a cloud-based Spectrum Access System (SAS) and an Environmental Sensing Capability (ESC) to monitor incumbent users of the band, with requirements standardized through the Wireless Innovation Forum (WInnForum) and implementations certified by the FCC. From an economic and policy

point of view, this type of dynamic sharing is asserted to reduce the costs and delays involved in making additional spectrum available for commercial use, as it seeks to avoid relocating incumbents. Of course, costs and benefits should be observed, not simply assumed, and the process undertaken should be compared to those associated with the relevant policy alternatives.

CBRS adopted the PAL and GAA tiers for commercial access in an attempt to provide spectrum that could not only support deployments by traditional wireless providers, but also enable new uses of the spectrum by non-traditional entities. How well the spectrum can support these uses, and whether this type of approach leads to an economically efficient mix of uses, provides another economic and policy lens through which this system can be evaluated. This paper explores the technical implementation of the CBRS spectrum sharing approach, and then attempts to appraise the economic welfare results of the novel allocation policy.

1. Introduction:

In 2015, the FCC established Citizens Broadband Radio Service (CBRS) for sharing the 3.5 GHz Band (3550-3700 MHz) among federal and non-federal users (FCC 2015).[1] Further requirements for this service were adopted in 2016 and in (FCC 2018). This rulemaking created an experiment in a novel three-tier rights structure: strong protections for incumbents including government radar systems; Priority Access Licenses (PALs) granting exclusive rights to high bidders in an FCC auction; and Generalized Authorized Access (GAA) for unlicensed users. Standards for using this spectrum have been developed by the Wireless Innovation Forum (WInnForum), a multi-stakeholder group which includes commercial companies, government representatives, nonprofits, and academic institutions. The development and commercialization of LTE and 5G solutions for this band is also being promoted by the OnGo Alliance, a trade association formed in 2016. The first commercial deployments in this band were approved in 2019, and an auction of PALs completed in 2020 generated $4.5 billion in revenues. It is now timely to evaluate this experiment and glean lessons for applications to other spectrum bands, such as the neighboring 3.1-3.45 GHz band or portions of the upper mid-band spectrum 8.4-24 GHz.

There have been a number of recent examinations of CBRS, including: (NTIA 2022), a report published by NTIA that analyzes operational data related to CBRS deployments from April 1, 2021 to January 1, 2023 and concludes that there has been "significant growth in band utilization"; (CTIA 2022), a critical report published by CTIA, the cellular operators' trade association; largely supportive statements from commercial organizations including Wireless Internet Service Providers (WISPs), the National Cable and Telecommunications Association (NCTA) and

[1] This band was first identified by NTIA in a 2010 Fast track report as a candidate for shared use between federal and non-federal users (NTIA 2010). The FCC published the first notice of proposed rule-making for CBRS in December 2012 (FCC 2012).

Federated Wireless; and (TAC 2022), a recent FCC TAC report. There is also a five-year project being conducted through the government's National Advanced Spectrum and Communications Test Network (NASCTN) to collect data and provide insights on the CBRS sharing ecosystem's effectiveness as well as track changes in the spectrum environment over time.

In this paper we review recently available studies and pose related policy questions that should be considered when evaluating the use of CBRS-style allocation rules in other bands that are being considered for repurposing. The CBRS policy involves several different innovations, seeking to accomplish multiple objectives. One can evaluate this approach from a technical point of view, as an experiment to show that dynamic sharing can provide multiple tiers of commercial access to a band of spectrum while protecting incumbent users. The approach involves coordinated access via a cloud-based Spectrum Access System (SAS) and an Environmental Sensing Capability (ESC) to monitor incumbent users of the band, with requirements standardized through WinnForum and implementations certified by the FCC. A question is then, how well has this approach worked in both protecting incumbents and in enabling commercial access.

From an economic and policy point of view, this type of dynamic sharing is asserted to reduce the costs and delays involved in making additional spectrum available for commercial use, as it seeks to avoid relocating incumbents. Of course, costs and benefits should be observed, not simply assumed, and the process undertaken should be compared to those associated with the relevant policy alternatives.

CBRS adopted the PAL and GAA tiers for commercial access in an attempt to provide spectrum that could not only support deployments by traditional wireless providers, but also enable new uses of the spectrum by non-traditional entities. How well the spectrum can support these uses, and whether this type of approach leads to an economically efficient mix of uses, provides another economic and policy lens through which this system can be evaluated.

This paper reviews CBRS through each of the previous views. Before doing this, we first review the historical context of this policy and give and overview of the CBRS technical rules..

1.1 Historical Context of CBRS Policy

As noted earlier, the CBRS policy was a project undertaken in the U.S. over roughly the 2010 – 2020 decade. The effort followed, however, the earlier allocation of 50 MHz (3650-3700 MHz) in 2004-2005, when the Federal Communications Commission set aside frequencies for use by wireless Internet Service Providers (WISPs) using "a streamlined licensing approach… that combines the beneficial aspects of both an unlicensed and licensed regimes [sic]" (FCC 2005, Par. 92). Access rights to frequencies were non-exclusive, but users were required to register the location of their operations. In addition, such systems were regulated by "equipment certification provisions to ensure that both fixed and mobile stations incorporate the requisite contention-based technologies" (FCC 2005, Par. 49). The FCC predicted that "this Order for the 3650 MHz band should facilitate the rapid deployment of advanced telecommunications services and technologies to all Americans" (FCC 2005, Par. 18).[2]

While that spectrum allocation was ostensibly designed to advance competition in the broadband access market, the fixed wireless product it favored saw little growth over the ensuing years relative to the explosive growth generated in the adjacent mobile sector. That is seen in FCC data charting the growth in wireless data subscribers from two sources, mobile networks and fixed wireless, in the decade following the FCC proceeding. See Figure 1. While the FCC's count of nationwide Fixed Wireless subscribers grew from about 200,000 in 2005 to approximately 1.2 million in 2016, mobile broadband subscribers (receiving service via licensed spectrum over cellular networks) grew from zero to about 270 million.

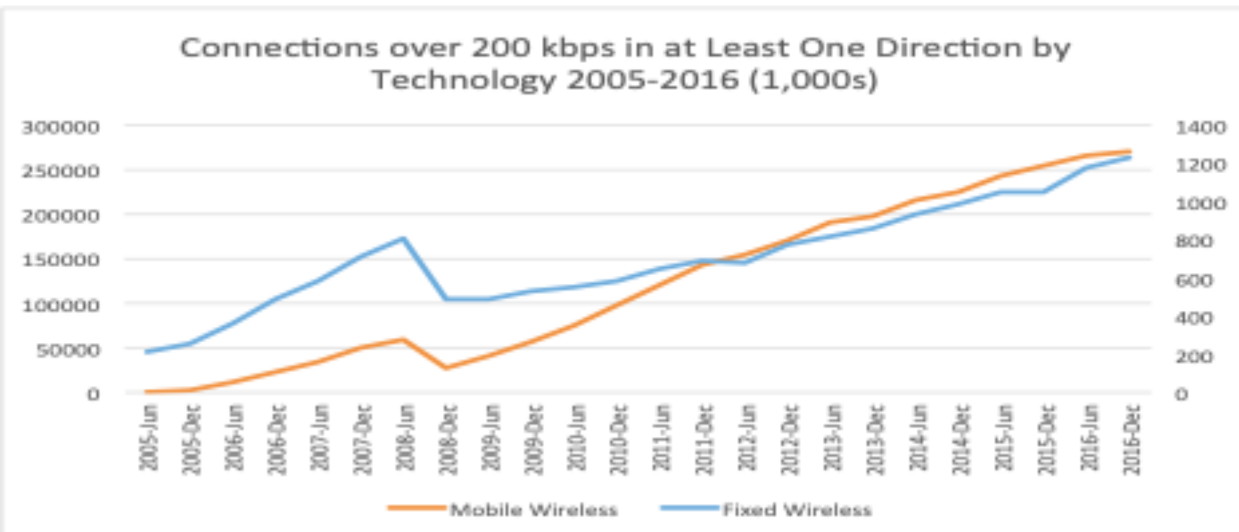


FIG. 1. MOBILE DATA SUBSCRIBERS (L) AND FIXED WIRELESS SUBSCRIBERS (R) (FCC DATA)

The CBRS allocation of 3550 - 3700 MHz ended up encompassing the swatch of 50 MHz allocated for fixed wireless broadband service in 2005. Regulators, in the National Broadband Plan (NBP) written in 2009 and 2010 (and funded by the "stimulus bill" enacted shortly after Pres. Barack Obama's inauguration), were engaged on the issue of U.S. competitiveness in broadband (hence, the project's name). The NBP report, unveiled in March 2010, focused heavily on the importance of making more spectrum available for wireless access to the Internet. In particular, the NBP

[2] The conclusion was energetically disputed in the FCC proceeding by Intel and Alvarion, two firms heavily invested in supplying carriers using both licensed and unlicensed spectrum. Both argued that the FCC 3650 MHz rules should have allowed for exclusive rights (using licensed spectrum) for at least the top 50 U.S. markets. See discussion in Hazlett & Leo (2011), 1048, 1079; and Brito (2007).

found that long spectrum allocation delays were stifling productive gains[3] and that regulators should employ superior tools for shifting under-utilized bandwidth into more efficient service.[4] The finding that allocations had taken from 6-13 years for administrative processing (see Table 1, taken from the NBP), was the predicate for the report to recommend greater urgency. To enhance U.S. economic performance, and to improve access to world-class, high-speed Internet services, such delays needed to be overcome. Hence, a spectrum allocation target was given to policy makers: "The FCC should make 500 megahertz newly available for broadband use within the next 10 years, of which 300 MHz between 225 MHz and 3.7 GHz should be made newly available for mobile use within five years" (FCC 2010, 84).

TABLE 1. "TIME REQUIRED HISTORICALLY TO REALLOCATE SPECTRUM" (FCC 2010, 79)

Band	*First Step*	*Available for Use*	*Approx. Time Lag*
Cellular (1G)	1970	1981	11 years
PCS (2G)	1989	1995	6 years
Educational Broadband Service (EBS)/Broadband Radio Service (BRS)	1996	2006	10 years
700 MHz	1996	2009	13 years
AWS-1	2000	2006	6 years

This initiative led the Department of Commerce, through its National Telecommunications and Information Administration (NTIA), to formally begin the process of once again re-allocating 3.5 GHz bandwidth. This occurred in a Oct. 2010 report issued by NTIA, which "conducted the Fast Track Evaluation… to jump-start the effort to make 500 megahertz of spectrum available for wireless broadband use…" (NTIA 2010, iv). We thus reference this as the NTIA's "Fast Track Report." The Report recommended adding 100 MHz of spectrum adjacent to the existing 3650-3700 broadband allocation (with rules established in 2005): "NTIA … recommends reallocating 100 megahertz of the 3500-3650 band (3550-3650 MHz) for wireless broadband use within five years…" (Ibid., v).

As discussed previously, the FCC's reallocation took years longer. Access was first permitted for unlicensed, GAA devices in 2019; PALs were auctioned in 2020; PAL licenses began to be issued

[3] The social losses were summarized: "the cost of not securing enough spectrum may be higher prices, poorer service, lost productivity, loss of competitive advantage and untapped innovation" (FCC 2010, 85).

[4] For instance: "In general, a voluntary approach that minimizes delays is preferable to an antagonistic approach that stretches on for years. However, the government's ability to reclaim, clear and re-auction spectrum (with flexible use) is the ultimate backstop against market failure and is an appropriate tool when a voluntary process stalls entirely" (FCC 2010, 79).

(pursuant to the auction assignments) in March 2021 (and are, as of this paper's writing, mostly but not entirely complete). See Figure 2 and Table 2.

The allocation process was contentious and involved a substantial debate over policy. The total size of the allocation appears to have been decided fairly early, adding 100 MHz to the existing 50 MHz in use since 2005 (as seen in the NTIA Fast Track Report). The structure of the 3 tiers was also decided early, as was the split of frequency space – up to 70 MHz allocated to PALs. But other licensing features became matters of intense debate. The 2015 Report & Order established the first specific set of rules for the allocation, and set forth a band plan that included over 500,000 PAL licenses – seven per Census Tract (of which there are over 74,000). This map featured a level of license fragmentation that was orders of magnitude higher than used previously. Moreover, the standard FCC approach – to auction initial licenses with 10-year or 15-year terms that then included expectancy of (zero-priced) renewals, resulting in indefinite terms – was replaced by a three-year term that denied incumbents renewals.[5]

This approach was sharply criticized by various interests, most notably T-Mobile. The mobile carrier which was then climbing past Sprint to become the nation's third largest network was particularly interested in obtaining additional bandwidth with which to challenge the two (much) larger networks, Verizon and AT&T. T-Mobile told the Commission that the extremely large number of PALs being issued would create excessive interference issues. This was based on the simple logic of spillovers, which occur across boundaries. With vastly more, much smaller, license areas, the boundaries were dramatically elevated in scope. In a Comment filed with the FCC, T-Mobile (2018, Slide 8) estimated the following differences, assuming the assignment of PALs across 73,800 Census Tracts:

TABLE 2. BOUNDARIES ACROSS DIFFERING NATIONAL LICENSE GRIDS

Political Boundary	*Aggregate Border Length (miles)*
Census Tract	1,465,038
County	536,857
Partial Economic Areas (PEAs)	221,956

5 The initial FCC proposal, floated by the FCC in 2013, had been even sharper: one-year license terms with no renewals for incumbents. "PALs would have a one year, non-renewable, term but licenses would be able to aggregate multiple consecutive PALs to obtain multi-year rights to spectrum within a given geographic region. PALs would automatically terminate after one year and would not be renewed. While shorter than the 10- or 15-year terms typically associated with area-licensed wireless services, a 1-year term would be more appropriate in this case." FCC 2013, Par. 13. The 2015 Report & Order (Par. 105) changed this structure to a three-year term and offered to extend initial terms from three to six years (upon bids for the extra length), a nod to investment incentive effects.

The argument proved largely persuasive, and the FCC adopted a more conventional approach, using county-sized licenses and granting 10-year terms with the expectation of renewal.

The FCC conducted Auction 105 to take bids for CBRS PALs. The sale was conducted July 23, 2020 - August 25, 2020. Some $4.543 billion in net bids were collected in the sale of 20,625 authorizations, with about ten percent (2006) unsold (and remaining with the FCC). These licenses began to be awarded to winning bidders in March 2021, and the awards process was about 98% complete as of July 29, 2023.

1.2 Overview of CBRS Access Rules

We next give a brief overview of the CBRS approach. A recent survey of work related to CBRS along with a description of technical challenges is given in (Agarwal 2022). See also (FCC 2023), (FCC 2018), (Mun 2017), (NTIA 2022), and (Massaaro and Bertran 2020) for additional background.

CBRS is based on a three-tier approach to spectrum access, in which users at higher tiers receive protection from interference due to users at lower tiers. The highest tier represents incumbent users of the band which includes federal users, fixed satellite services (FSS), and Grandfathered Wireless Protection Zones (GWPZ). The main federal users of the band are military radars, including ship-borne naval radars that operate offshore and within certain harbors as well as ground-based radars that operate at specific sites. The two lower tiers are used for commercial access to the spectrum and consist of PAL users and the GAA tier.

As noted previously, PALs are 10 year renewable licenses that give the licensee exclusive access to 10 MHz of CBRS spectrum within a given county. PAL users must accept interference from incumbent users and also not interfere with them. In any given county, up to seven PALs may be licensed and a given entity can own up to four of these. These licenses are restricted to the lower 100 MHz of the band.

The GAA tier is licensed-by-rule so that it essentially operates like unlicensed spectrum. GAA users can operate over the entire band subject to not causing interference to either the incumbent or the PAL users. They are not given any interference protection from other tiers, or from each other. The 3.5 GHz band consists of 15 channels, each with 10 MHz of bandwidth. Since at most 7 of these are allocated to PALs, there will be at least 8 channels in every county that are not allocated to PALs and therefore available for GAA use.

Every commercial user of CBRS spectrum is required to register with a SAS administrator. The SAS dynamically controls access to the spectrum. For example, when incumbent users need access to the spectrum in a given area, the SAS will inform lower tier users that they cannot operate in that portion of the spectrum. SAS administrators are certified by the FCC. The first group of certified SAS providers includes Google, CommScope, Federated Wireless and Sony.[6] A SAS provider can also utilize a ESC, which refers to a network of sensors deployed to detect Naval radar systems, primarily along the coast. When an ESC detects an incumbent, it informs the SAS, which then activates a dynamic protection zone in the given area.[7]

The CBRS rulemaking and standards defines two classes of base stations, also called *Citizens Broadband Radio Service Devices (CBSDs)*: category A and category B. Category A CBSDs have a lower power limit and are targeted at indoor small cell usage. Category B CBSDs have a higher power limit and are targeted at outdoor usage.[8] During the FCC proceeding some commenters had requested even higher power limits than those decided for Category B base stations.[9] It has been noted that the specified limits are significantly lower than the limits in neighboring commercial bands such as the C-Band. The FCC noted that the choice of power limits is a trade-off between the advantages of higher power for "reducing deployment costs" and the lower power advantages of "greater spatial reuse" and "reduced coexistence challenges" (FCC 2015, par. 214). The CBRS specifications favor the latter lower power benefits more than the policy in neighboring bands, in part due to focus on small cell deployments and in part because of the greater coexistence challenges due to the three-tier sharing model.

2. Evaluating CBRS

As we have noted, the policy adopted by CBRS involved several different innovations and was trying to accomplish multiple things, creating several different ways in which this experiment can be evaluated. We discuss several of these in this section following a brief description of prior work aimed at evaluating CBRS.

2.1 Disputes Over Pros and Cons

CBRS is relatively new, so performance evaluations thus far have been limited. We mention a few studies and data sets that are publicly available in order to motivate and contrast with our current study. The NTIA has recently published a study on the growth of CBRS deployments and services (Boulware et al 2023). The study is based on operational data obtained from SAS administrators

[6] As of May 31, 2022, Commscope announced that it was no longer offering a SAS service (Dano 2022).
[7] If an ESC is not used in an area where federal incumbents operate, then this area would become an exclusion zone and enforced as such by the SAS.
[8] Category B CBSDs can also utilize high-gain antennas, are required to be installed professionally, and are required to provide additional information to a SAS due to their higher transmission powers.
[9] The FCC reports that "Commenters supporting higher power CBSDs typically express interest in using such devices for outdoor backhaul, coverage, or capacity for managed networks." and notes that "some commenters, including Alcatel-Lucent, AT&T, BLiNQ, CTIA, and Verizon requested higher maximum power levels for outdoor operations than we adopt" (FCC 2015, par. 211)

on a quarterly basis from April 1, 2021 to Jan 1, 2023. Specifically, the number of CBSDs are provided, divided into categories according to power (Category A or B), installation type (indoor/outdoor), license type (PAL or GAA), air interface, and location type (urban/rural). That data set shows the steady growth in CBSDs (121% over the 21 month period), and that the dominant mode of access has been GAA, as opposed to PALs. Also, more than 70% of CBRS deployments have been in rural census blocks.

The NTIA report provides an encouraging view of CBRS: "With CBRS, the FCC established a ground-breaking spectrum-sharing paradigm that enabled commercial access to mid-band spectrum, demonstrating the success of a collaborative partnership among stakeholders in government and industry." Although the number of CBSDs is an indication of band utilization that may support this view, it does not show broader aspects of utilization in terms of, for example, coverage and data rates provided, user devices connected, and aggregate traffic conveyed. The latter aspects are more difficult to obtain, of course, and may be subject to proprietary restrictions, but together would be a more compelling indicator of the demand for that spectrum. Also, the NTIA study does not attempt to compare the value generated by the spectrum in economic terms with other access methods across different markets.

The NTIA study provides one counter-response to a CTIA-sponsored report (CTIA 2022) which claims that CBRS has had relatively low utilization. The CTIA report argues against using CBRS as a model for sharing in other bands based on the observations that CBRS is mostly used for traditional wireless access for broadband services, and that the demand for shared spectrum by non-traditional service providers is relatively small. Additional arguments are that intermittent availability of spectrum, depending on the incumbent's behavior, may rule out some applications, and the lower power restrictions associated with CBRS increase costs for cellular providers seeking wide-area coverage. We examine some of these claims by comparing auction prices for PALs across locations within and outside dynamic protection areas, and with other recent auctions (see Appendix). Missing from the analysis in (CTIA 2022), as well as other studies that favor CBRS, is an estimate for the savings in cost associated with clearing the band (that is, moving the incumbents including naval radar to another band).

Another response to (CTIA 2022) is provided by Federated Wireless (FW 2023) as part of comments in response to an FCC Notice of Inquiry regarding possibilities for repurposing 12.7-13.25 GHz. Those comments cite deployments of Dynamic Spectrum Management System (DSMS) tools in other bands (including CBRS and 6 GHz), number of PAL and GAA deployments as quantified in the NTIA report, and the diversity of licensees "improve connectivity for a variety of critical infrastructure, educational, and industrial projects. The CBRS shared licensing framework, which includes smaller license areas and the ability for users to combine PAL and GAA spectrum, has made these myriad deployments possible, demonstrating another meaningful measurement of the success of the CBRS shared licensing framework." Missing, however, is an estimate of opportunity costs associated with exclusive-use and high-power access.

The FCC Technical Advisory Committee (TAC) has recently issued a report on CBRS with recommendations regarding the design and implementation of sharing schemes that may be considered for other bands (TAC 2022). From the report, "The consensus is that centralized spectrum sharing in CBRS has been effectively demonstrated, but enhancements to the CBRS framework would improve the utility of spectrum in future shared bands." The report is mainly concerned with technical aspects of CBRS and makes recommendations such as incorporation of improved propagation models for interference detection, de-emphasizing sensing for interference detection and shifting to incumbent informing capability (IIC), and taking into account interference from adjacent bands, in addition to improving upon regulator clarity in advertising the sharing rules.

Other recent work (Malandra 2022) describes challenges in deploying CBRS for local community networks. Those challenges include variable propagation characteristics and network congestion, in particular, for GAA access. Alternative access methods are mentioned that could also be used for such applications, although there is no detailed cost-benefit comparison. Earlier papers such as (Mun 2017) and (Massaaro 2020) discuss potential use-case scenarios for CBRS such as enterprise coverage and neutral hosting; however, cost-benefit comparisons with alternative access methods are not considered.

In this paper we initiate a more comprehensive evaluation of CBRS that takes into account both the economic value generated from CBRS along with opportunity costs associated with excluding alternative access methods. We use available data sets to provide some insight into the following questions:

- To what extent has secondary access (intermittent availability) of CBRS spectrum affected the value placed on the spectrum?
- How has the introduction of CBRS sharing rules affected the overall market for cellular services?

Specifically, in addition to the data set in (NTIA 2022), we rely on auction prices provided by the FCC and across countries along with the data set in (WinnForum 2020) specifying Dynamic Protection Areas (DPAs). The association of auction prices with service providers was presented in (Javid 2020) and (Dano 2020), shortly after the PAL auctions concluded. Although it is difficult to reach definitive conclusions based on the available data and analysis so far, one of the purposes of the paper is to indicate what additional data is needed in order to enhance the analysis and provide evidence for possible narratives in response to the preceding questions.

2.2 CBRS as a technology proof-of-concept

Though spectrum sharing had been employed in other bands, such as the TV white spaces, CBRS pushed the boundaries of this approach and to date has been much more widely deployed. In particular, the privacy concerns of federal incumbents such as naval radar, raised new issues that needed to be addressed. In terms of protecting incumbents, this experiment appears to have been a success. For example, Federated Wireless reported that "in its first few years post-launch, incumbent DoD operations have reported zero instances of interference." The FCC TAC report reports a similar statistic (FCC 2022).[10] However, the FCC TAC also notes that this protection was achieved at a cost in that very conservative assumptions were used for propagation modeling and interference margins. Further, the assignments over PALs and GAA users to date under CBRS have been "semi-static" and so does not serve as a proof of true "real-time" spectrum sharing that may be required to share other bands (Rysavy 2022).

Related to this success, the CBRS deployments have shown the feasibility of using a cloud-based SAS infrastructure for managing spectrum access. This infrastructure has been successfully deployed by multiple SAS vendors and used by a variety of different customers. However, as CTIA points out, achieving this success was "more complex than anticipated" and in particular multiple commenters have highlighted the difficulty in using ESCs to monitor incumbent activity. The FCC TAC mentions that "while ESCs are capable of detecting incumbent activity, they have a substantial downside of negatively impacting CBRS use with[in] up to 80 km from the sensors." (FCC 2022) This is due in part to the need to also protect the ESC sensors from interference generated by CBRS base stations, resulting in CBRS devices near the sensor having to reduce their power or not operate at all. The FCC TAC further suggests that relying solely on such sensors should be avoided in future spectrum sharing scenarios. An alternative to ESCs has been proposed by NTIA called the Incumbent Informing Capability (IIC), which would be a portal in which federal users could notify the SAS about their operation, removing the need for sensors (DiFrancisco, et al 2020).[11]

Although there have been GAA deployments, the technical performance of the GAA approach appears to have fallen short. An issue in this case is coexistence among different GAA tier users. The CBRS policy specifies that GAA users "shall have no expectation of interference protection from other (GAA) users" (47 CFR 96.35). The standard does indicate that GAA users operating the higher power Category B CBSDs "must make every effort to cooperate … to minimize the potential for interference" (47 CFR 96.35). GAA has similar characteristics to unlicensed spectrum where technologies such as WiFi are deployed. Coexistence in unlicensed bands has typically been accomplished in part by users adopting a listen-before-talk protocol. For GAA spectrum, listen-before talk is not required and instead the common approach is for interfering

[10] Echoing a point made earlier, these reports are not accompanied with data on how often a SAS has needed to protect an incumbent user. Knowing this would enable a more meaningful assessment of this outcome.

[11] Approaches like the IIC were discussed in the 2015 proceeding at which point the FCC and NTIA favored a sensing based approach so as to require a SAS provider to maintain any sensitive federal data (FCC 2015).

operators to work with their SAS providers to divide the available GAA spectrum among them. One motivation for this approach is that in a given band of spectrum, not requiring listen-before-talk leads to better utilization of the spectrum by a single operator. However, with multiple operators, this approach has several short-comings including that it can be inefficient in using the available spectrum (as the assignment of spectrum to operators is relatively static), it can take time to agree and implement, and it needs to be updated whenever there is a new operator deploying in the area (including when a PAL holder may switch its traffic to GAA because its PAL spectrum is not available) (Woodley 2022). There has been work by the OnGo Alliance and WinnForum to develop better coexistence mechanisms.[12] Operators have been slow to adopt these, but perhaps over time these mechanisms will be adopted. We also note that compared to WiFi deployments, CBRS GAA deployments offer the advantage of providing larger coverage areas (especially outdoors), but this advantage also makes coexistence more challenging as networks are more likely to interfere with each other over longer distances.

2.3 CBRS as a new way to transition spectrum

One of the main reasons often put forward for adopting sharing in a band is that clearing and reallocating that band can take a very long time and be prohibitively expensive - sharing is often presented as a way to enable access to spectrum in a faster manner with lower costs in that it does not require the incumbent to relocate. Of course, when comparing sharing with clearing, a fair comparison should not include just the cost of clearing and assume that there are no costs for sharing. Sharing also incurs costs which we discuss next.

One component is the cost of deploying and operating the infrastructure for sharing. In the case of CBRS, this includes the cost of deploying SAS's as well as deploying ESCs. SASs are mainly software that can be deployed in the cloud, which can leverage existing cloud infrastructure and the ever-decreasing costs of deploying software services in the cloud. Multiple CBRS network customers can leverage this infrastructure, and there is competition among multiple SAS providers. Hence, it seems reasonable that this cost would be small relative to any costs for clearing spectrum. ESCs on the other hand require deploying (and maintaining) a network of spectrum sensors within a given geographic area, which incurs a cost that is not insignificant and as we noted previously, ESC sensors also impact the performance of nearby CBRS users. The alternative IIC approach, similar to a SAS, could leverage cloud based infrastructure and once developed would likely lead to lower deployment costs for future sharing systems.[13] There are also incremental costs added to CBRS base stations to enable them to follow the sharing protocol as well as nominal SAS registration fees that need to be paid by network operators to a SAS provider (which are used in

[12] For example, the OnGo Alliance has developed an approach based on "Coexistence managers" (OnGo Alliance 2022) and WinnForum has published several different GAA spectrum coordination approaches such as (Wireless Innovation forum 2019).

[13] The IIC approach would also incur a personnel cost in that federal employees would need to be trained and used to input the required data.

part to cover the costs of the SAS infrastructure as well as generate profits for the SAS providers, but again these costs would be small relative to the costs of clearing spectrum.[14]

More significant than the deployment and operating costs for CBRS is the opportunity cost incurred for sharing the spectrum compared to clearing the band. In other words what additional economic value could have been obtained if the band was cleared? There are several factors that should be accounted for to evaluate the opportunity costs of this sharing approach.

Costs of temporal sharing.

Temporal sharing as is done in CBRS, means that an entrant using the band with a lower priority will have the possibility of not being able to use the spectrum for a period of time. Clearly, this will lower the value of the band of spectrum to a commercial provider, i.e., having 10 MHz of spectrum with exclusive access is worth more than having the same 10 MHz of spectrum available only 90% of the time. This difference in value represents an opportunity cost from adopting sharing and is related to a comment in the CTIA sponsored report that "Federal preemption of commercial spectrum rights are a barrier to applications that require guaranteed levels of service" (CTIA 2023). Although it is clear that preemption would lower the value of spectrum, it is not clear to what degree it would be a barrier to adoption as this would depend on a number of factors. For example, as most providers utilize multiple bands of spectrum, when preempted, they could offload the traffic from the shared spectrum to other bands of spectrum so that their customers would maintain connectivity but experience a lower quality of service during these times. In wireless, quality of service varies over time due to other factors such as mobility, propagation effects, and the number of users per cell. A provider would need to understand how the additional variance in service quality due to temporal sharing affects a users' value for service to determine if it would be profitable to deploy a service on a shared band.

(Berry et al., 2020) presents a stylized model for such a situation to capture the opportunity cost for a given commercial deployment due to temporal sharing. In particular, this analysis shows that given a band for exclusive use, the incremental value to a service provider created by adding a band of W MHz of spectrum available for 50% of the time will be less than the value of adding W/2 MHz of spectrum available 100% of the time. This suggests that if one could clear and repack a given band of spectrum, there would be a gain in value compared to sharing the spectrum temporally. This analysis also shows that the value of such intermittent spectrum could depend on the other spectrum holding of a service provider as a firm with more additional spectrum could better absorb the offloaded traffic when the shared band is not available.

[14] For example, Google's pricing for SAS service used for fixed wireless is $2.25 per residence per month (Google 2023).

Does such a reduction in value appear in the case of CBRS? The CBSD data reported in (Boulware 2023) provides some insight. Statistics on active CBSDs are provided for "impacted" and "non-impacted" counties, where impacted counties are those in which part of the county is in a dynamic protection area. It is shown that the average number of base stations in non-impacted counties exceed that in impacted counties over the period analyzed (see Figure 2). In the most recent period the mean number of base stations in non-impacted counties is about 12% and there appears to be a similar growth rate of active base stations in the two cases. However this difference may not be due to intermittency but rather from the fact that until an ESC network was deployed for a DPA, portions of the spectrum were not able to be used in those areas, leading to later deployments in those counties. We note also that this data does not provide a measure of the difference in value between different CBSD deployments. For example, it could be that the CBSDs deployed in non-impacted counties on average generate more value than those deployed in impacted counties.

The PAL auction data analyzed in the Appendix provides another way to examine the impact of intermittency due to sharing. The regression analysis shown there provides no statistical evidence that PAL prices (in $/MHz-pop) are higher in DPA impacted counties than in non-impacted counties. Indeed the only statistically significant variable related to DPA impact predicts slightly higher prices in "large" counties that are impacted. This suggests that at least at the stage of bidding for PALs that intermittency did not have a significant impact on bidders' valuations. A possible explanation for this is that bidders expected low incumbent activity in most DPA impacted counties and so this did not affect their bids. More refined data that indicated the level of impact in each county would help to understand this better.

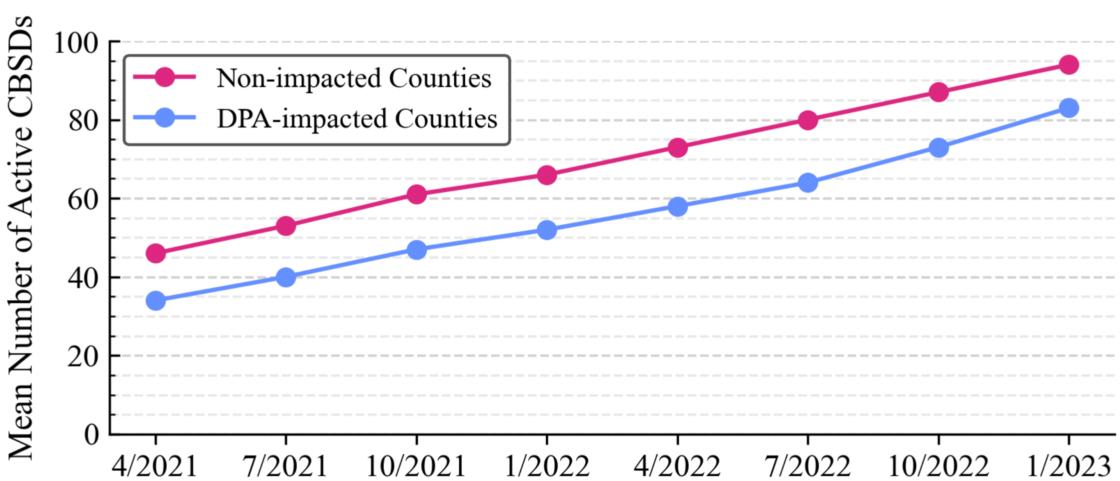


Figure 2: Mean CBSDs per county for DPA-impacted and non-impacted counties. [from (Boulware 2023)]

Even if bidders expect a low level of activity from federal users, within the CBRS framework, there is no guarantee given that this expectation would be met, adding another degree of uncertainty for an entrant when valuing the spectrum. One could envision other sharing frameworks, in which incumbent users had to commit to a given level of availability or perhaps negotiate this with entrants giving more predictability to the service being offered. Taking this further - such sharing arrangements could be enhanced if the entrants could also negotiate with an incumbent users around when they would access the spectrum. If an incumbent could commit to not preempting during certain high traffic times for an entrant, this would clearly make the shared spectrum more valuable.

In addition to intermittency, sharing is one reason for adopting lower power limits in CBRS compared to neighboring bands.[15] As lower power limits increase the cost of deploying infrastructure, this also reduces the value of the spectrum to providers that seek to provide wide-area coverage and so can be viewed as another opportunity cost. Some evidence of this can be seen in the PAL auction data shown in Figures 1 and 2. These figures show the closing prices for PALs in each county in $/MHz-POP versus the population of the counties. Figure 1 shows this data for counties with populations smaller than 200,000, while Figure 2 shows this for counties with populations greater than 200,000. In counties with populations greater than ~220,000 the average price for a PAL license is greater than $0.5/MHz-POP, while for smaller counties the average is closer to $0.1/MHz-POP. A possible explanation for this is that in larger counties, large commercial providers placed a high value on deploying small cells to augment their existing capacity, while in smaller counties, the lower power limits made PAL licenses less attractive.[16, 17]

[15] As discussed later, the main driver for lower power limits were a desire to target small cells deployments. However, lower power limits also help with coexistence by for example constraining the size of dynamic protection areas.

[16] There are other factors that also could impact these differences as will be discussed later. For example the presence of GAA spectrum might also suppress the bids for PALs in rural settings, where potential users might assume that this spectrum would be adequate for their needs.

[17] We also note that for very small counties, there is a much higher variance in the resulting prices compared to larger counties, suggesting that the prices in those counties may depend strongly on underlying factors such as the presence of certain industries.

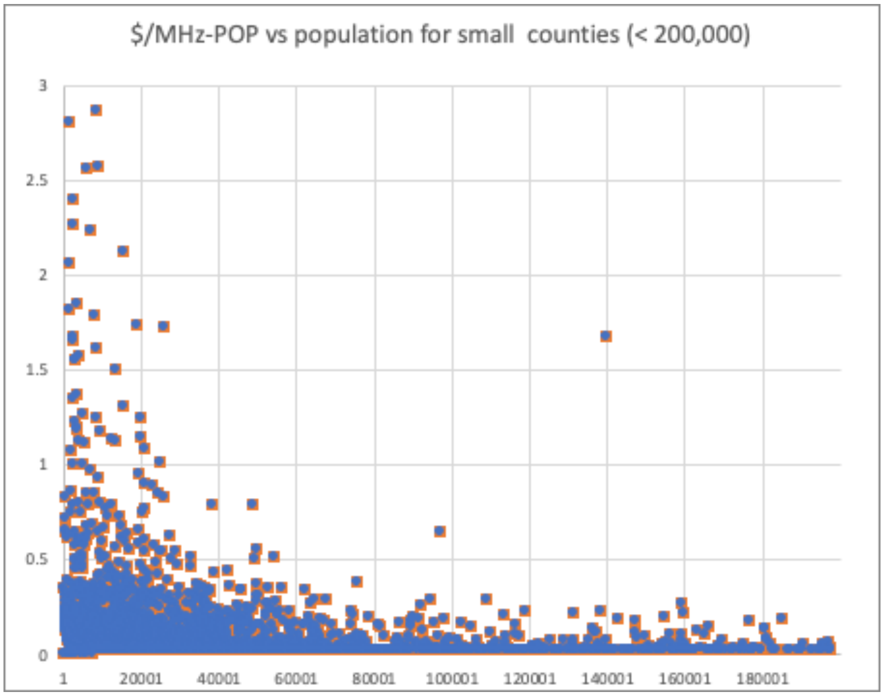


Figure 3: Closing auction prices for PALs versus county population for small counties (population less than 200,000).

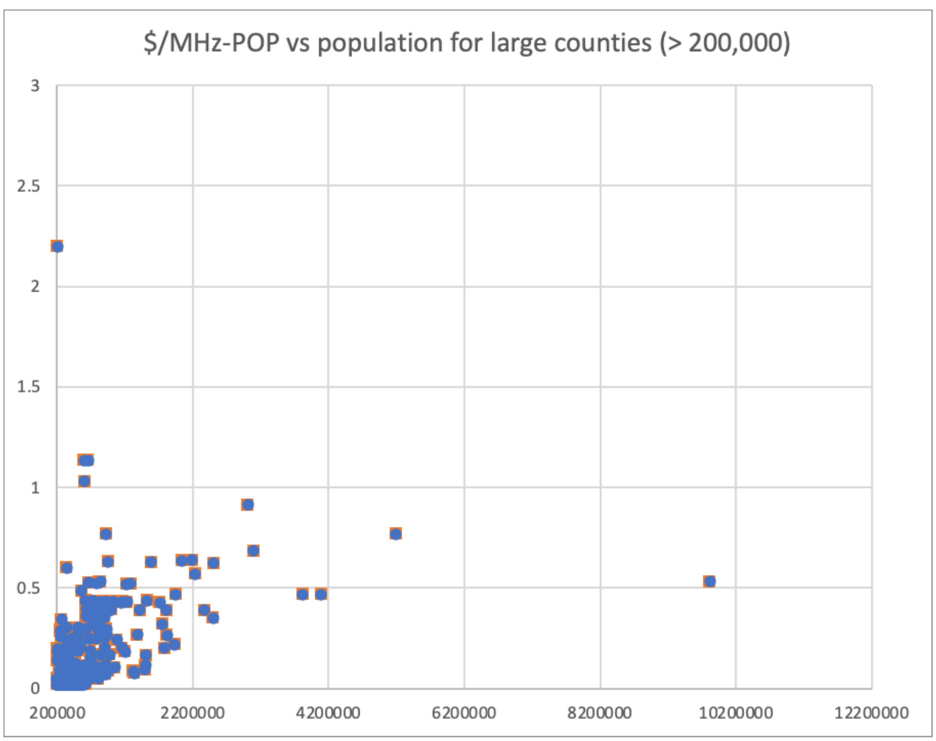


Figure 4: Closing auction prices for PALs versus county population for large counties (population at least 200,000).

Time to market:

Another form of opportunity costs in sharing (or clearing) is the time before a new service can be deployed. Sharing has been put forward as a way to enable quicker access to a band of spectrum and thus a way of reducing this opportunity cost. Indeed, when the NTIA first selected 3500-3650 MHz as a candidate for sharing in 2010, it was part of the "Fast Track" spectrum to be repurposed within five years. But actual reallocation of the entire 150 MHz has not yet been achieved; the allocation proceeding took through 2018; further administrative process (including certification of SAS databases and planning for Auction 105 to take bids for PALs) consumed another two years; the auction was held July-August of 2020; awards of licenses then took place over 2021 and 2022 and is now nearly, but not entirely, complete. See the basic timeline for the CBRS allocation in Figure 2.

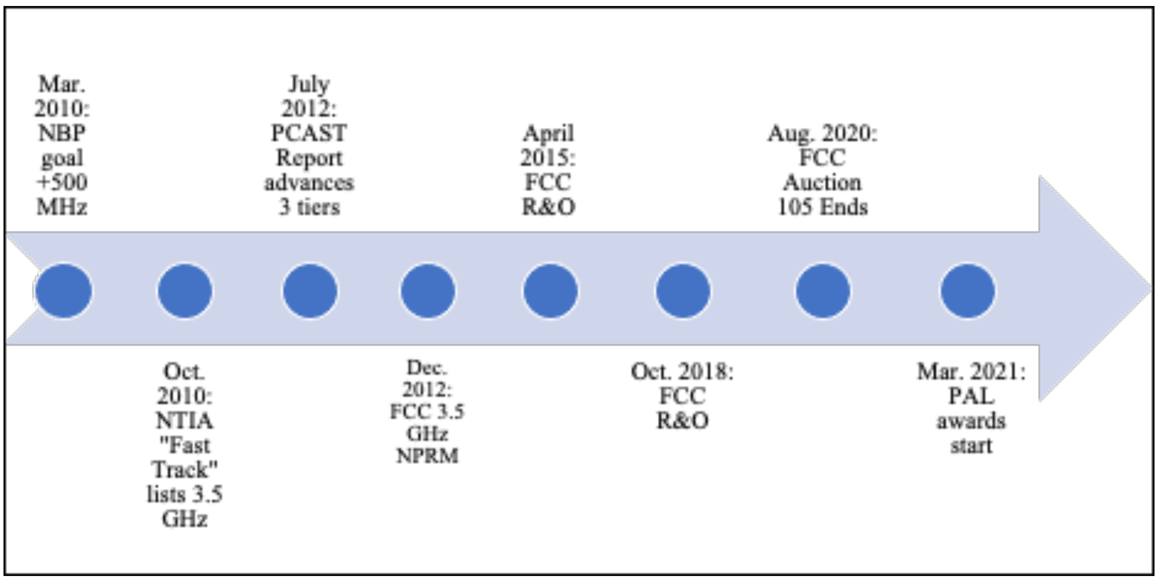


FIG. 5. CBRS SPECTRUM REALLOCATION TIMELINE

Hence, the CBRS consumed at least 11 years; and that estimate involves generous accounting for the endpoints. The National Broadband Plan began its inquiry in Spring 2009, and it was in these deliberations that the idea for the "Fast Track" allocation list that NTIA put forward in October 2010 was born. We count the policy creation only from publication of the NBP in March 2010. On the completion end, the. actual distribution of licenses to use Priority License rights was still incomplete (although close) as of July 2023. See Table 3. Yet, the March 2021 date noted in Figure 2 was at least ten years from "start to finish," double the projected "Fast Track." Indeed, this performance fails to better the historical average of 6-13 years, as calculated by the FCC.

This levies a grade on the policy endeavor. The spectrum sharing approach adopted for CBRS is largely undertaken to side-step the difficult and often delay-ridden outcome seen when a strong incumbent (in this instance, the U.S. military) is the object of a one-way transfer, losing frequency access without compensation. (Such public agency compensations are challenging to arrange, requiring special authorizations that typically strain political dealmaking processes and, in any event, involve terms of trade that are difficult to calibrate and highly complex to monitor. Beyond this, the incentives embedded in such private transfers are generally lacking given the constraints imposed on public sector agents, precisely because monitoring of behavior is challenging within agencies not controlled by residual claimants.) The three-tier CBRS regime consciously avoids attempting such rights transfers, and hence the complications of bargains to arrange them and oversight to enforce them, seeking to avoid the attendant delays and transaction costs thereby imposed. Yet, the administrative processes that are used to replace the avoided coordination mechanisms (or substitutes for regulation in the form of overlays or related incentive schemes enacted in several recent FCC reallocation[18]]) are themselves costly. A reform that ostensibly results in no economizing via delay-reduction measures a disappointing result.

TABLE 3. PAL ASSIGNMENTS ISSUED BY THE FCC

	No. of PALs	*Issue Date*
	17450	3.12.21
	125	4.30.21
	26	7.12.21
	102	12.9.2021
	2431	7.26.22
	42	10.12.22
PALs assigned as of 7.29.23	20176	
PALs sold in Auction 105	20625	
PALs unsold (held by FCC)	2006	
PALs sold but unassigned as of 7.29.23	449	

Source:https://www.fcc.gov/search/#q=Auction%20105%20Priority%20Access%20Licenses&t=edocs.

Looking forward, some of the delays incurred by CBRS might be reduced if this framework was used for other bands provided that much of the framework can be re-used and would not need to

[18] Overlays used in the PCS band helped break a political stalemate, paving the way for the 1994-95 auction (Auction 4) that assigned licenses for 2G services. Cramton, Kwerel & Williams (1998). Similarly, the FCC's AWS-1 auction in 2006 (Auction 66), the "Incentive Auction" in 2016-17 (Auction 1002), the satellite C-Band Auction (Auction 107), and the 2.5 GHz overlay auction (Auction 108) all utilized key aspects of the overlay concept. For a general explanation, see Hazlett (2014).

be re-developed from scratch (however given that different bands/incumbents have different characteristics some modification to this framework would likely be needed). We also note that other forms of clearing, such as the overlay approach used in the C-Band provide evidence that the time to clear spectrum can be sped up by adopting a framework in which entrants can contribute money to speed up this transition.

Sharing versus clearing?

The policy choice of sharing versus clearing a band of spectrum would in-part depend on observing if the cost saving from sharing exceeds the opportunity costs lost due to sharing. Depending on these costs one can envision cases where CBRS-style sharing is the best solution. However, it may be difficult for a regulator to make this judgment. One alternative might again be to adopt an overlay-like approach, where an entrant with overlay right could negotiate with an incumbent to decide on if the spectrum is best shared or cleared.

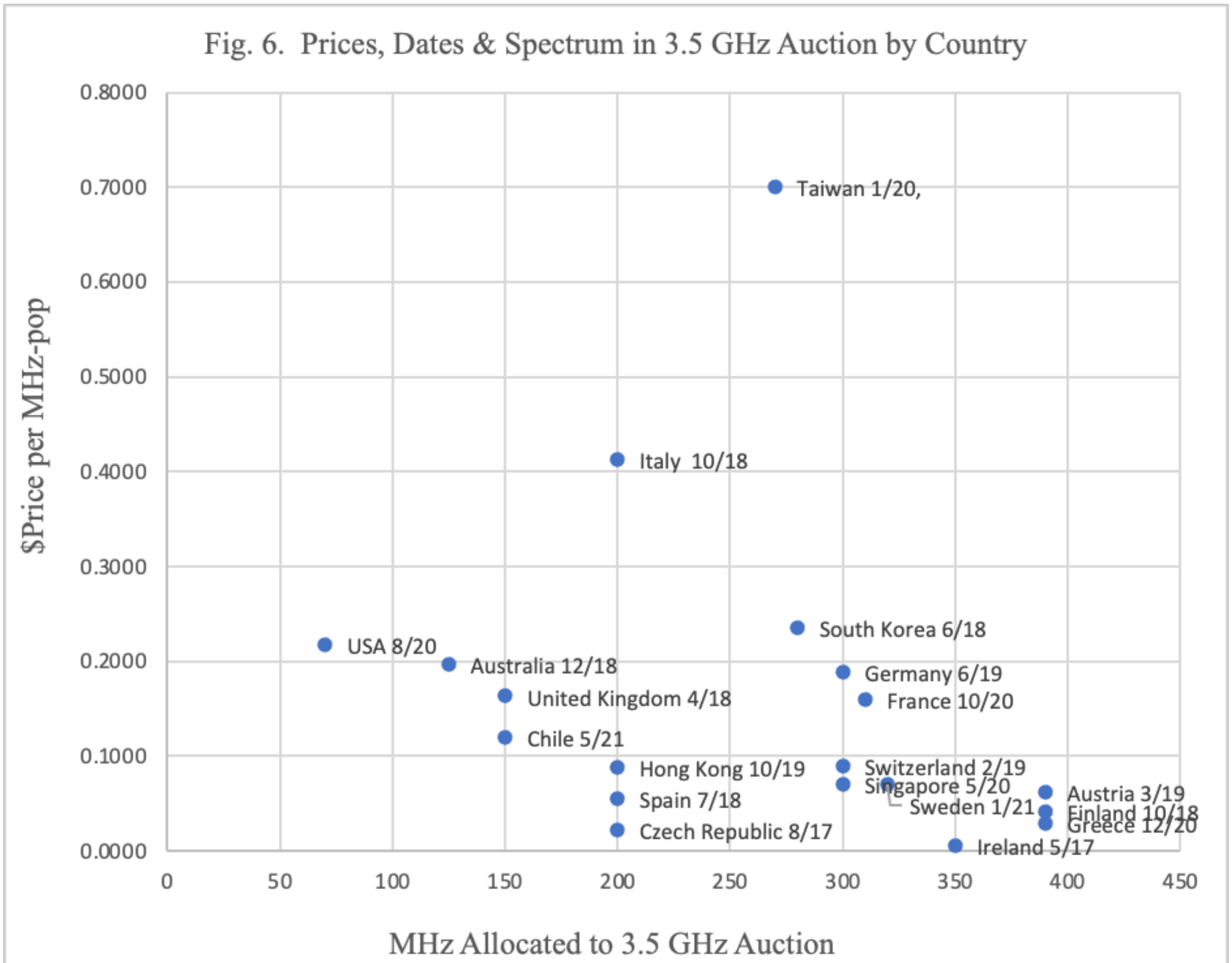
2.3 CBRS as a way to unlock more spectrum

How much spectrum did the FCC successfully push into more productive use? This is, of course, a key outcome variable. The Commission, despite having already allocated 50 MHz for wireless broadband a decade earlier (namely, 3650-3700), managed only to pull a total of 150 MHz into the newly reallocated CBRS Band. This included just 70 MHz of licensed spectrum which, as the FCC's NBP noted, forms the key input into mobile networks. Among twenty countries that have auctioned licenses in the 3.5 GHz frequencies, the U.S. received fairly high prices (adjusted for allocated MHz and population covered), but was not a leader (lagged in its allocation behind many countries) and allocated easily less spectrum to licenses. See Figure 3.[19] Eleven of the 20 countries allocated 270 MHz or more to licenses auctioned, and no other country allotted less than 150 MHz.

The suggestion is that the U.S. was late in distributing its 3.5 GHz licenses, and parsimonious in its allocation. There are multiple complicating factors that can be brought into this discussion, including the nature of the impairments (military radar) in the U.S. context and the substantive mitigating factor that, following the 2020 CBRS auction (Auction 105), the U.S. FCC held two more capacious license auctions: Auction 107, assigning licenses allocated 280 MHz in 2021, and Auction 110, assigning licenses allocated 100 MHz in 2022. In fact, both of these later sales granted rights to mid-band spectrum immediately adjacent (on either side) of the 3550-3700 Band. These incremental improvements in market supply pushed U.S. wireless markets forward decisively, bringing the total bandwidth available to mobile carriers to 1,123 MHz (not counting the mmW bands).[20] This allocation compares favorably with peer countries; the U.S. ranks at the

[19] Canada conducted an auction for 3.5 GHz licenses in August 2021. It collected a stunning price per MHz-pop of US$1.83, about nine times the U.S. level. Because the amount is so high, it is omitted from Figure 3.
[20] FCC (2021, Par. 20) gives a total allocation equal to 1,023 MHz. But in 2022, Auction 110 assigned licenses allocated 100 MHz, which is added to the total. As of year-end 2023 the U.S. will have 450 MHz of mid-band

top of peer countries for low- and high-band spectrum allocations, and middling for mid-band, as per a recent study (Stewart et al., 2022).



In the U.S. and elsewhere, antitrust authorities do not consider unlicensed spectrum to serve as a reasonable substitute to licensed spectrum. While aggregating more than about one-third of total licensed spectrum suitable for mobile communications explicitly triggers heightened antitrust scrutiny to investigate competitive effects, the existence of unlicensed bands is not a factor in evaluating whether the holdings of a given wireless carrier have the potential to foreclose competition. This suggests that the 80 MHz set aside for GAA operations in the CBRS Band is an input supply that exists in a separate market, and that the spectrum inputs that regulators (from the NBP through countless other policy documents) have identified as crucial to network growth are to be evaluated by focusing on licensed spectrum.

allocations, however, which is above those in Germany, Spain and Italy, while trailing Japan, the U.K. and South Korea.

It is also revealing that the U.S. regulatory system was able to identify additional 3 GHz spectrum to allocate to licenses in the immediate aftermath of the CBRS auction. There were no extraordinary obstacles to reallocating 3.45-3.55 GHz, or 3.7-3.98 GHz frequencies, as proven by the recent reallocations. The largest increment, the 280 MHz allocated to the licenses sold in Auction 107, constituted the largest U.S. spectrum refarming in both MHz (below mmW frequencies) and in value (at any frequency) – and this allocation was *not listed* in the NTIA's "Fast Track" catalogue of potential prospects for timely turnaround. Indeed, the process used to identify the band in question, satellite C-Band frequencies, was not top-down, but bottom-up: the proposal was submitted to the FCC by a 5G chipmaker and an incumbent satellite operator, firms seeking to capture gains from (a) economizing on the current consumption of bandwidth, and (b) selling the excess capacity thereby created to bidders in a private auction.[21] In the event, the FCC adopted a reasonable facsimile of the mechanism, but appropriated the lion's share of the rents. The submitted proposal requested that the incumbent licensees be allowed to organize a private spectrum auction and capture the revenues. Instead, the FCC organized the auction and awarded incumbent satellite licensees $13 billion, about 14% of the approximately $94 billion bid in total for licenses covering 280 MHz, labeling the payments "relocation costs and incentives."

While the split of revenues would likely impact incentives for future such bottom-up reallocations, the important point in evaluating the CBRS allocation is that the formal reallocation process occurred, start to finish, in less than four years. The Intelsat-Intel petition was filed Oct. 2, 2017, and the close of bidding in Auction 107 occurred on Feb. 17, 2021. The incumbents began vacating the 280 MHz reallocated in the auction almost immediately, and the winning licensees are reportedly able to access the entire band by year-end 2023. (As bidders were allowed to compete for frequency access with earlier opening dates, the most pressing demands were satisfied first, mitigating the wait to obtain use of the additional frequency spaces to come available in subsequent months.) Even with the most distant end points plausible, the reallocation will consume only 75 months, starting the clock with the filing of the idea and ending it with the December 2025 vacate deadline necessary to receive "incentive payments." This timeline easily economizes on the time invested in allocated the CBRS band – and for four times the bandwidth.

The impediments to expanding the CBRS Band, to at least rival the 3.5 GHz allotments licensed and auctioned across Europe, Asia and elsewhere was due to standard spectrum allocation lags. These lags proved crucial in restructuring the competitive landscape in the U.S. mobile market.

U.S. spectrum allocations were frozen during much of the period when the CBRS three-tier allocation policy garnered regulators' attention. After Auction 97, which closed in January 97 (and sold licenses allocated 65 MHz at 1.7/2.1 GHz), and Auction 105 (which was to sell the CBRS PAL licenses allocated 70 MHz of 3.5 GHz airwaves), the only FCC license sales were for mmW

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[21] The Oct. 2, 2017 submission to the FCC was jointly written by Intelsat and Intel. Caleb Henry, *Intelsat, with Intel, proposes way for 5G to use satellite's C-band spectrum*, SPACE NEWS (Oct. 3, 2017).

frequencies. U.S. carriers, particularly Verizon, attempted to deploy these spectrum resources to roll-out 5G, but the effort proved costly and ultimately counter-productive. The deployments were technically impressive but proved extremely limited in geographic scope given that the 24 GHz to 39 GHz frequencies fade rapidly (and are easily by blocked by walls, leaves, and even rain). AT&T, also constrained by the FCC's closed mid-band spectrum window, upgraded its 4G services as a substitute for 5G – bringing a rash of criticism for over-selling the tweak.[22] T-Mobile was better positioned, having been the largest license winner in the FCC's 2017 auction of 600 MHz licenses, and these low-band frequencies constituted a short-term gap-filler. T-Mobile's deeper strategy, however, was to acquire the generous, under-utilized 2.5 GHz (mid-band) spectrum held by Sprint. T-Mobile proposed to buy the No. 4 mobile operator for $26.5 billion in April 2018 (Crandall & Hazlett 2023).

The combination was contentious. While the merger was approved by the Department of Justice Antitrust Division and the FCC, it was opposed by a coalition of state Attorneys General. A trial on their claims was held; in Feb. 2020 a federal district court held that the states had not proven their case that the transaction would harm consumers, and T-Mobile acquired Sprint on April 1, 2020. Two aspects of the merger are of interest in our analysis of CBRS.

1. *A spectrum bargain*. T-Mobile offered to buy Sprint for $26.5 billion; the transaction was consummated for $40.2 billion. (The price difference was due to the fact that the offer involved the transfer of T-Mobile stock shares, which had appreciated over the two year period between initial offer and final purchase.) Sprint held licenses allocated 174.3 MHz nationwide (with local licenses weighted by population). At the lower price for Sprint, T-Mobile was effectively paying 39.7¢ per MHz-pop for just the bandwidth held by Sprint – it assumes that Sprint's nationwide network of cellular base stations, its thousands of small cells, and its 53 million subscribers were worthless. At the higher purchase price, T-Mobile paid 60.2¢ per MHz-pop. In comparison, the price of CBRS licenses (Auction 105, ending August 2020) averaged 21.7¢ and the mean price for the satellite C-Band spectrum (Auction 107, ending Feb. 2021) was $1.095.[23]

2. *Delayed gratification implies dissipation of consumer gains*. Had regulators concentrated on moving an additional 200 or 400 MHz pre-merger into the mobile marketplace, expanding the 3.5 GHz allocation to match or exceed those of many countries, great new capacity would have been on sale. The Sprint merger would no longer have been the one (retail) price-constraining option for T-Mobile. And the elimination of a fourth network may not have occurred.

A prominent industry analyst, Jonathan Chaplin with New Street Research, wrote about T-Mobile's options (Mar. 21, 2019):

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[22] And marketing reversals in the face of lawsuits. Clare Duffy, *AT&T will stop using '5G Evolution' marketing phrases to refer to its 4G LTE network*, CNN BUSINESS (May 20, 2020).
[23] Auction 105 and 107 prices from Sasha Javid's website: https://www.sashajavid.com/

T-Mobile has used excess capacity to take… market share over the last five years; however, they now face a capacity shortfall… T-Mobile has a choice: they can increase capacity and continue to take share, or they can increase price and slow sub growth. If the Sprint deal is approved, they will have the capacity to continue taking share with aggressive pricing.

This is, in fact, what happened. The merger went through, T-Mobile expanded market share and earned capital gains, providing a competitive threat to the previously top two industry leaders. From the April 2020 merger through June 2023, T-Mobile earned excess returns equal to 59% (adjusting for the S&P500 Index); Verizon -47.5%; AT&T - 53.2%. This ribald rivalry, shaking up incumbents and rewarding innovative competitors, was consummated when a "transition" was made to a reallocation: Sprint took a large payment, and vacated its bandwidth to T-Mobile. That seemingly less novel innovation produced striking results. To the extent that regulators shaped the CBRS reallocation with administrative delays, artificially scarce spectrum increments, and overhead for coordination mechanisms that reduce the flexibility of private initiative (through power limits, technology restrictions, and a lack of clear ownership which undercuts incentives for parties to explore possible win-win solutions as might be possible between entrants and incumbents) these side effects are rightly the subject of inquiry in evaluating policy effect.

2.4 CBRS as an "innovation band"

One goal of the CBRS regulations was to encourage innovative uses of the spectrum band. Examples of policy choices towards this end include the use of both PAL and GAA access, the use of relatively small (county-sized) license areas and the choice of lower power levels. As discussed previously all of these choices make the band less suitable for traditional cellular coverage. Have they spurred newer services? Potential uses discussed for this band include private wireless networks, fixed wireless access, and supplemental coverage for traditional service providers. A recent report from Del'Orro group, reported in (Dano 2022b) indicates the CBRS equipment sales are not meeting their expectations in private wireless networking and capacity augmentation. Reasons for this may include the availability of other mid-band spectrum for these purposes as discussed in the previous section. With regard to fixed wireless, another reported claim relates to the complexity of setting up a CBRS service (Dano 2022b). Though over time, this may become less of a barrier if easier to deploy products are made available.

Fixed wireless access is the one area of CBRS sales meeting Del'Orro's expectations.[24] Indeed the overall fixed wireless market has been growing significantly in recent years, with a 76% growth reported between 2020 and 2022 (FCC 2022). However, the largest growth in fixed wireless is coming from T-Mobile (FCC 2022), who is not using CBRS spectrum. This suggests that though CBRS is helping to grow the fixed wireless market, it is not the leading cause for this growth.

[24] Fixed wireless companies such as Windstream and Mediacom, were among the top bidders in the PAL auction, as well as cable companies such as Cox and Comcast that may consider fixed wireless offerings.

Many of the non-traditional uses of CBRS are likely using GAA spectrum, this makes assessing the market value of these services more difficult as values are not revealed in auction prices. Indeed, the presence of GAA spectrum also makes the values reported from PAL auctions less clear as a firm's marginal value for a PAL may be lower, given that without the PAL it can still access the GAA spectrum.

3. Conclusions

The CBRS policy was intended to side-step the transaction costs of existing FCC allocation policy, improving upon time to market, increasing efficient use of resources, and implementing newly developed tools – with widespread applicability to numerous other bands – that would allow productive wireless applications to emerge. It is now appropriate to subject the evolving experiment to an appraisal. At this preliminary stage, as useful data on usage and welfare gains are being created in real time and will, hopefully, soon become available to researchers, it is appropriate to being sifting through the market outcomes. The U.S. experience in the CBRS band has not evinced efficiencies in reducing delays, or in enhancing the flow of large amounts of bandwidth to higher valued uses. In terms of what rival nations have accomplished in their 3.5 GHz allocations, which uniformly rely primarily on awarding flexible, exclusive rights and which do not include the U.S.'s approximately 50-50 split between licensed and unlicensed, substantially more spectrum has been put into play. The lags and parsimoniousness of the time-consuming mid-band allocation, moreover, provided incentives for mobile carriers to merge.

References:

P. Agarwal, M. Manekiya, T. Ahmad, A. Yadav, A. Kumar, M. Donelli, S. T. Mishra. 2022. "A Survey on Citizens Broadband Radio Service (CBRS)," *Electronics* 2022, 11, 3985 (Dec.).

R. Berry, M. Honig, T. Nguyen, V. Subramanian, and R. Vohra. "The value of sharing intermittent spectrum." *Management Science* 66, no. 11 (2020): 5242-5264.

D. Boulware, A. Romaniello, R. L. Dorch, M. G. Cotton. 2023. *An Analysis of Aggregate CBRS SAS Data from April 2021 to January 2023*, NTIA Report 23-567, May 2023.

Brito, Jerry. 2007. *The Spectrum Commons in Theory and Practice*, 2007 STANFORD TECHNOLOGY LAW REVIEW 1.

Cramton, Peter, Evan Kwerel, and John M. Williams. 1998. *Efficient Relocation of Spectrum Incumbents*, 41 JOURNAL OF LAW & ECONOMICS (Oct.): 647-675.

Crandall, Robert W., and Thomas W. Hazlett. 2023. *Competitive Effects of the T-Mobile/Sprint Merger: Analysis of a "4-to-3" Combination*, Working Paper (June 27).

Dano, M. 2020. "CBRS spectrum auction maps: Who won what, and where", *Light Reading*, Sept. https://www.lightreading.com/5g/cbrs-spectrum-auction-maps-who-won-what-and-where/d/d-id/763837

Dano, M., 2022b. "CBRS isn't living up to expectations – Dell'Oro Group," *Light Reading*, January, 27. https://www.lightreading.com/5g/cbrs-isnt-living-up-to-expectations---delloro-group/d/d-id/774899

Dano, M. 2022. "CommScope ditches SAS business in 3.5 GHz CBRS Band," *Light Reading,* March 31. https://www.lightreading.com/5g/commscope-ditches-sas-business-in-35ghz-cbrs-band/d/d-id/776471

DiFrancisco, M. Drocella, E. Ransom, P. and Cooper, C. 2020. "Incumbent Informing Capability (IIC) for TIme-bansed Spectrum Sharing," *TPRC 48: The 48th Research Conference on Communication, Information, and Internet Policy*, Dec.

FCC. 2005. Federal Communications Commission, *In the Matter of Wireless Operations in the 3650-3700 MHz Band: Report and Order*, ET Docket No. 04-151 (Rel. Mar. 16).

FCC. 2010. Federal Communications Commission, NATIONAL BROADBAND PLAN (Mar. 10).

FCC. 2012. Federal CommunicationsCommission, *In the Matter of Amendment of the Commission's Rules with regard to Commercial Operations in the 3550-3650 MHz Band*, Notice of Proposed Rule Making and Order, GN Docket No. 12-354, Dec. 12.

FCC. 2013. Federal Communications Commission, *Commission Seeks Comment on Licensing Models and Technical Requirements in the 3550-3650 MHz Band*, GN Docket No. 12-354 (Nov. 1).

FCC. 2015. *Amendment of the Commission's Rules with Regard to Commercial Operation in the 3550-3650 MHz Band*, GN Docket No. 12-354, April 2015, amended May 2016.

FCC. 2018. Federal Communications Commission, *In the Matter of Promoting Investment in the 3550-3700 MHz Band: Report and Order,* GN Docket No. 17-258 (Rel. Oct. 24).

FCC. 2021. Federal Communications Commission, *In the Matter of T-Mobile LLC, Cellco Partnership, Applications for 3.7-3.98 GHz Band Licenses, Auction 107, Memorandum Opinion and Order,* ULS File No. 0009446137 (Rel. July 23).

FCC. 2022. Federal Communications Commission, *2022 COMMUNICATIONS MARKETPLACE REPORT,* GN Docket No. 22-203, Dec. 30.

FCC. 2023. Federal Communications Commission, *3.5 GHz Band Overview*, https://www.fcc.gov/wireless/bureau-divisions/mobility-division/35-ghz-band/35-ghz-band-overview

FCC Technological Advisory Council (TAC 2022), "Recommendations to the Federal Communications Commission Based on Lessons Learned from CBRS", Dec. 2022. https://www.fcc.gov/sites/default/files/recommendations_to_the_federal_communications_commission_based_on_lessons_learned_from_cbrs.pdf

Federated Wireless (FW 2023), "Expanding Use of the 12.7-13.25 GHz Band for Mobile Broadband or Other Expanded use", Reply Comments to FCC, GN Docket No. 22-352, 2023.

Google 2023. https://www.google.com/get/spectrumdatabase/sas/

Hazlett, Thomas W. 2014. *Efficient Spectrum Reallocation With and Without Nirvana*, George Mason Law & Economics Research Paper No. 14-16 (June 11).

Hazlett and Evan Leo. 2011. *The Case for Liberal Spectrum Licenses: A Technical and Economic Analysis*, 26 BERKELEY TECHNOLOGY LAW JOURNAL (Spring): 1037-1101.

S. Javid, "Spectrum Sharing Demonstrates its Potential Value as the FCC's CBRS Auction Closes with $4.59 Billion in Gross Proceeds", Aug. 2020. https://www.linkedin.com/pulse/spectrum-sharing-demonstrates-its-potential-value-fccs-sasha-javid/

F. Malandra, M. Silbey, R. Alvarez, B. Cacace and T. Hege, "Community CBRS Networks - What You Need to Know," 2022 IEEE Future Networks World Forum (FNWF), Montreal, QC, Canada, 2022, pp. 228-231.
WinnForum. CBRS standards online at https://cbrs.wirelessinnovation.org/

M. Massaaro and F. Bertran, “Will 5G lead to more spectrum sharing? Discussing recent developments of the LSA and the CBRS spectrum sharing frameworks”, Telecommunications Policy, 44 (2020).

K. Mun, "CBRS: New Shared Spectrum Enables Flexible Indoor and Outdoor Mobile Solutions and New Business Models", white paper, Mobile Experts LLC, March 2017. https://federatedwireless.com/wp-content/uploads/2017/09/Mobile-Experts-CBRS-Overview.pdf

NAB. 2021. In the Matter of Unlicensed White Space Device Operations in the Television Bands, Reply Comments of the National Association of Broadcasters, ET Docket No. 20-36, Federal Communications Commission (April 26).

NTIA. 2010. U.S. Department of Commerce, National Telecommunications & Information Administration, *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, 4380-400 MHz Bands* (Oct.).

OnGo Alliance. 2022. *OnGo Coexistence Technical Specifications,* ONGO-TS-2001, v.4.1.0, March 8.

PCAST. 2012. President’s Council of Advisors on Science and Technology, *Report to the President: Realizing the Full Potential of Government-Held Spectrum to Spur Economic Growth* (July 20).

Rysavy, P. 2022. “Lessons learned for the CBRS spectrum experiment,” *Fierce Wireless,* April 28. https://www.fiercewireless.com/tech/lessons-learned-cbrs-spectrum-experiment-rysavy

Stewart, Jennette, Chris Nickerson, and Juliette Wellham. 2022. *Comparison of Total Mobile Spectrum in Different Markets*, Analysys Mason White Paper for CTIA (Sept.)

T-Mobile. 2018. *Ex Parte Notification* to the Federal Communications Commission in GN Docket No. 17-258, GN Docket No. 17-183, and GN Docket No. 14-177 (Feb. 8).

RECON Analytics (CTIA 2022), “CBRS: An Unproven Spectrum Sharing Framework”, white paper, Nov. 2022.

Wireless Innovation Forum 2019, *Operations for Citizens Broadband Radio Service (CBRS); GAA Spectrum Coordination-Approach 1 Technical Report,* Document WINNF-TR-2003, May 31.

Wireless Innovation Forum (WinnForum 2020), "CBRS Incumbent Protections and Encumbrances Overview", Document WINNF-TR-5003, April 2020.

Woodley, M. 2022. *Is CBRS for everybody? - growing pains and progress towards a practical solution,* Ericsson Blog, Sept. 7. https://www.ericsson.com/en/blog/6/2022/cbrs-growing-pains-and-progress

APPENDIX

In this appendix we describe the regression analysis performed on the 2020 auction data for PAL (Auction 105). This auction resulted in 3332 counties having at least one PAL license sold. For each county we determined the normalized price in $/MHz-POP, where the price of of any unsold license was set to be zero. We did not include 12 counties in which no licenses were sold.

A histogram of the resulting prices is shown in Figure X below, which shows that nearly ½ of the counties had a price of less than $0.1/MHz-pop, while there were a few counties with very high prices - the largest being Loving county in Texas with a price of $141.46/MHz-pop, which was due in part to it having a population of only 82.

We then performed a regression of the normalized price in a county against the following quantities:

- The population of the county
- Dummy variables indicating if the county is within 0-200 Km, 200-300 Km or 300-400 Km of a DPA.
- The price in $/MHz-Pop for licenses covering that county in Auction 107 (The 'C-Band' Auction). [25]

The data for the DPA-impacted dummy variables is based on data from WinnForum (WinnForum 2020). Some counties may be in more than one DPA protection area, in which case we used the closest one to determine the dummy variable used. Note that Auction 107 assigned licenses based on the larger PEA boundaries. We determined the price in $/MHz-pop for each PEA and assigned that to each county within the PEA. Also we note that Auction 107 was confined to the continental U.S. and so included fewer counties than Auction 105. We removed any counties not in both auctions, leaving 3107 remaining counties.

[25] We also considered the prices from Auction 101 (28GHz), which is also based on counties, but found that adding that data into the regression did not generate statistically significant results.

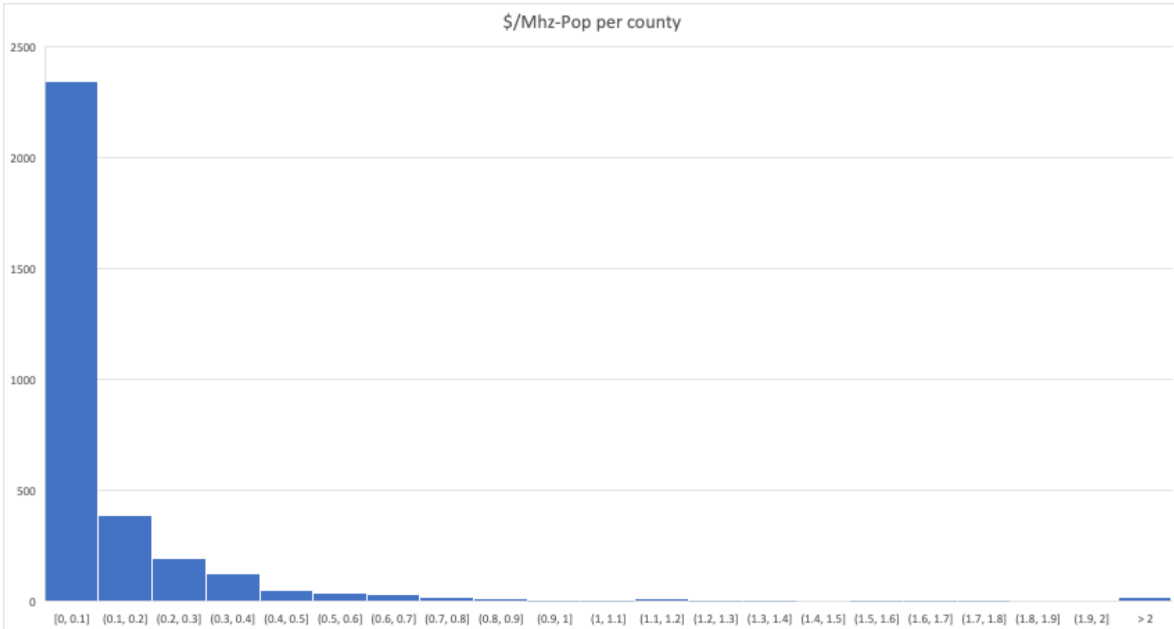

Figure 7: Histogram of prices ($/MHz-pop) over all counties.

We performed regressions for the following three cases:

1. All 3107 counties in both auctions.
2. The 311 "large" counties with a population of at least 200,000.
3. The 2796 "small" counties with a population less than 200,000.

For the first and the third case none of the regression coefficients were statistically meaningful and so we do not report those results here. For the large county case we have the following results:

	Coefficients	*P-value*
Intercept	0.05122047	0.49590227
population	7.1063E-08	8.8131E-05
DPA-200	-0.0641004	0.10465823
DPA-300	0.09171923	0.28492708
DPA-400	0.33264884	0.00798886
Auction 107	0.15739439	0.01009433

The regression results show that the population, the DPA-400 dummy variable, and the Auction 107 price are statistically meaningful (P-values less than 0.05). All three of these regression coefficients are positive, showing that the predicted Auction 105 price increased with larger population sizes, larger auctions 107 prices and larger values of the DPA-400 dummy variable. The positive coefficient for the DPA-400 variable means that counties within 300-400 km of a

DPA site tend to have higher prices. The other DPA dummy variables were not statistically significant.

We also report the correlation in prices between Auction 105 and 107. The correlation of the prices over all counties is -0.012, while the correlation of the prices in just the large counties is 0.32. A scatter plot of these prices for all counties is shown below. This is consistent with the regression results in that in smaller counties, prices in auction 107 are not predictive of those in the other.

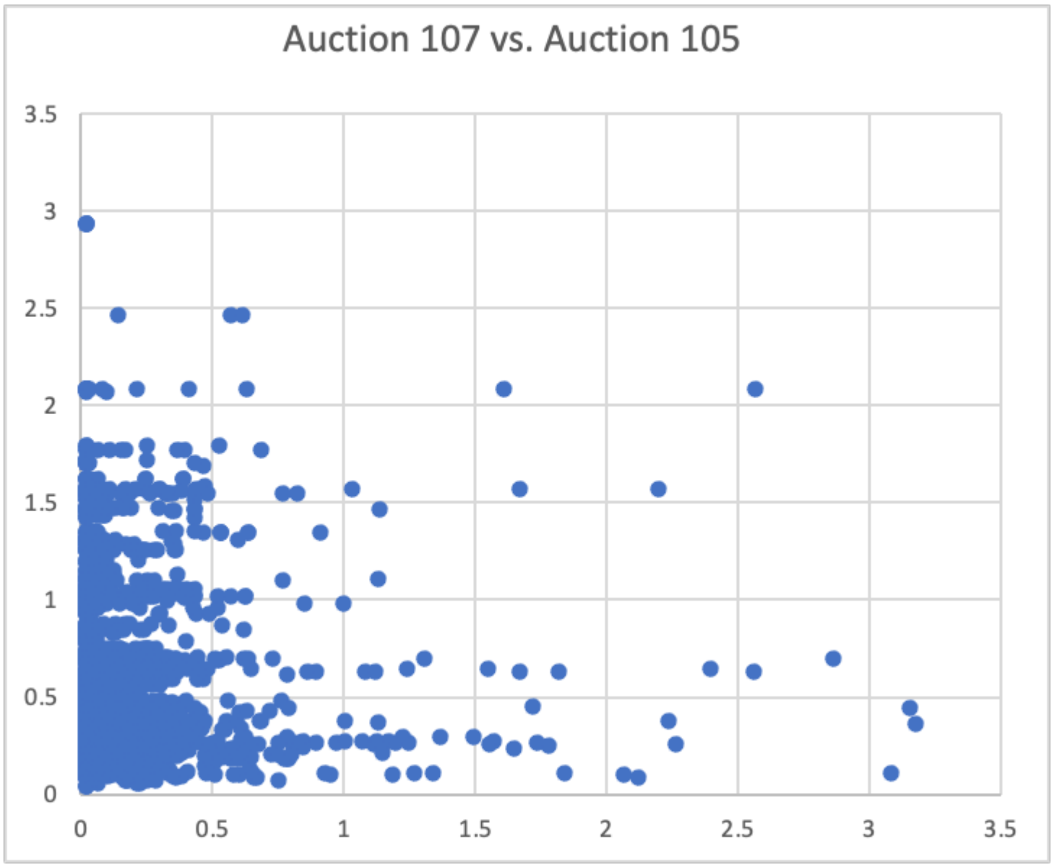

Figure 8: Prices in Auction 107 compared to those in Auction 105 in $/MHz-pop.