# Exploring the Utilization of CBRS Spectrum through Crowdsourced Measurements

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***Abstract*—This paper presents a novel methodology to assess the effectiveness of the Citizens Broadband Radio Service (CBRS) spectrum-sharing framework. Using end-user crowdsourced measurements, we analyze the use and adoption of CBRS across various market stakeholders—including Mobile Network Operators (MNOs), Regional MNOs, Mobile Virtual Network Operators (MVNOs), Wireless Internet Service Providers (WISPs), Neutral Hosts, and Private Networks. We provide key insights into CBRS usage, with some MNOs leveraging the spectrum to enhance network capacity on a secondary basis and MVNOs affiliated with cable operators deploying their own infrastructure in high-traffic areas. Beyond the preliminary results, this study establishes a foundation for evaluating the effectiveness of CBRS in fostering competition, innovation, and efficient spectrum use, while offering a framework for further research as regulatory reforms and market dynamics evolve.**

***Index Terms*—CBRS, Spectrum sharing, Dynamic Spectrum Access, PAL, GAA, Crowdsourced measurements**

## I. Introduction

The Citizen Broadband Radio Service (CBRS) is a spectrum-sharing framework established in the United States for the shared use of the 3.5 GHz band (3550–3700 MHz) to enable more efficient use of spectrum that was formerly allocated for use by military radars, Fixed Satellite Services and other legacy fixed wireless broadband systems. CBRS introduces a dynamic three-tiered spectrum access model with three different user groups with varying priorities. Dynamic sharing is facilitated by automated Spectrum Access Systems (SASs), which coordinate the use of spectrum between incumbents, holders of Priority Access Licenses (PAL), acquired in spectrum auctions at the county level, and General Authorized Access (GAA) users.

This innovative spectrum-sharing framework has garnered global attention as a model for future spectrum management. However, limited empirical evidence exists regarding its adoption, operational effectiveness, economic relevance as a sharing model, and progress toward stated goals. The only publicly available empirical data is the recent reports by the National Telecommunications and Information Administration (NTIA) [1], which focus on longitudinal trends in device authorizations from Spectrum Access System (SAS) administrators. Although this is very useful data for understanding overall adoption trends, it provides limited insights into how and by whom the CBRS spectrum is being utilized.

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This research seeks to analyze CBRS use from a different vantage point by investigating CBRS adoption across different stakeholder groups, including Mobile Network Operators (MNOs), Mobile Virtual Network Operators (MVNOs), Wireless Internet Service Providers (WISPs), Neutral Hosts and Private Network integrators. Our analysis utilizes a novel approach based on crowdsourced measurements obtained from a mobile crowdsourcing data provider. We aggregate the data recorded by end-user terminals to identify Long-Term Evolution (LTE) and New Radio (NR) cells deployed. Specifically, we focus on LTE and NR cells operating in the 3550–3700 MHz spectrum band (b48 for LTE and n48 for NR), whether used as primary or secondary carrier. We utilize the Mobile Country Code (MCC) and Mobile Network Code (MNC) to classify operators by type associated with each cell.

We address the following research questions:

1) **Extent and type of use.** How extensively is the CBRS used, which stakeholders are utilizing this spectrum, and how is its use distributed spatially?
2) **Technologies.** What are the technological characteristics of cellular deployments utilizing the CBRS band across different stakeholders? Are these deployments predominantly LTE or NR? Do they function as Primary or Secondary Component Carriers, and do they serve public or private networks?
3) **Access Tiers.** How frequently is the CBRS spectrum utilized under PAL or GAA? Do usage patterns vary among different stakeholders? Have CBRS PAL licensees invested significantly more in infrastructure deployment compared to stakeholders using the GAA tier? Furthermore, is there a correlation between the cost of PALs and the volume of deployments?

In addition to complementing the existing knowledge base for how CBRS spectrum is being used from a novel vantage point, the work presented here will provide a baseline for assessing the impact of CBRS regulatory reforms currently underway, which are expected to expand commercial access to and use. Facilitating the assessment of the market impact of the CBRS and regulatory reforms will provide valuable insights for spectrum management policies more generally.

The remainder of the paper is organized as follows. Section II presents an overview of the CBRS regulatory framework and reviews related work. Section III outlines the methodology used to process and analyze the data. Section IV presents the results of our analysis, detailing the answers to the research questions stated above. Section V discusses these findings, interpreting their implications for spectrum policy development, and suggesting directions for future research.

## II. Background

### A. CBRS Regulatory Framework

Spectrum management in the United States has undergone significant evolution over the past three decades, transitioning from static allocation models to pioneering more dynamic and flexible frameworks, such as the CBRS. The novelty of CBRS lies in providing three tiers of dynamic interference protection: (1) Incumbents (principally, naval radar); and two tiers of commercial users, (2) PAL licensees; and (3) GAA licensees.[1] Active incumbents have priority access and are protected from interference by commercial users operating in the CBRS band. Commercial users are only authorized to transmit when such transmissions would not interfere with active incumbent users; and GAA users are authorized to transmit only when such transmissions would not interfere with either active incumbent or PAL users. GAA licensees are not protected from interference from other CBRS users.

Spectrum access to the CBRS band is administered by Spectrum Access Service (SAS) providers. Although multiple SAS operators have been approved, currently, only Google and Federated Wireless provide SAS services. To transmit in the CBRS band, a commercial CBRS Device (CBSD) needs to obtain a county-level, time-limited transmission authorization from a SAS operator. Those authorizations are for 10MHz channels [2] and for location-specific (latitude/longitude), power-level-limited authorizations. The most common type of CBSD is a Category-B device that is authorized for outdoor (higher-power) transmissions, with lower-power Category-A devices to be used most often indoors.[3]

SAS operators manage CBSDs authorizations dynamically, consistent with the interference protection rules above. For each type of device that is protected, a SAS operator has to compute a Dynamic Protection Area (DPA). Before granting new CBSD authorizations, the SAS operator has to assure that the aggregate power authorized within each DPA is below the protection threshold. When a PAL licensee wishes to transmit, it requests an authorization from the SAS operator, and assuming that the granting of the license would not interfere with any incumbent, it is granted an authorization for transmission in an assigned channel in the relevant PAL territory. For each active PAL, a DPA is set up to ensure non-interfering co-existence with other active PAL and GAA devices. If no channel is available for the PAL licensee because GAA devices have been authorized, then GAA authorizations are cancelled to clear a DPA for the PAL licensee. If an incumbent goes active then an Environmental Sensing Capability (ESC) system notifies the SAS and it rescinds the authorizations of a sufficient number of PAL and GAA licensees to ensure the incumbent's DPA power limits are not exceeded. When a GAA seeks an authorization, the SAS checks whether the GAA is seeking authorization inside a DPA. If not, then the GAA authorization is granted. If the GAA is seeking authorization within a DPA, the SAS checks if granting the authorization would result in aggregate power within the DPA being exceeded, and if not, then the authorization is granted.

For the DPAs to be updated based on aggregate interference across the entire footprint of active CBRS devices, all of the commercial devices have to maintain a "heartbeat" to regularly check with their authorizing SAS in case their authorization needs to be rescinded. Additionally, once every 24 hours, the SAS operators (Google and Federated Wireless) have to share information about all of the active authorized devices so that each may compute aggregate interference levels and DPAs for all interference-protected users.

In July 2024, the Federal Communications Commission (FCC) approved new CBRS operating rules that greatly expanded commercial access to CBRS spectrum by shrinking the DPAs. The focus of the rule changes was to update the interference propagation models used to compute DPAs to more realistically take account of environmental and technical features that limit the interference that commercial devices may cause for protected users. Notably, these rules have been proposed for modification in 2024 to enable further spectrum sharing [2], a change projected to expand CBRS coverage to an additional 72 million people.

### B. Related work

There is extensive qualitative research examining emerging spectrum-sharing frameworks and focusing on the trade-offs that may arise when balancing innovation, flexibility, competition and incumbent protection. Several researchers have conducted analyses of both Europe's Licenced Shared Access (LSA) and the U.S. CBRS spectrum-sharing frameworks. In [3], the authors compare both frameworks across four key spectrum management dimensions: frequency harmonization, technology standardization, usage rights, and assignment procedure, highlighting that, despite their conceptual similarities, CBRS has progressed more rapidly in implementation compared to LSA, and suggesting that this disparity may stem from differing institutional contexts and enforcement capabilities between the U.S. and European regulatory bodies. In [4], the

[1]For the regulatory rules for access to the CBRS band, see https://www.ecfr.gov/current/title-47/chapter-I/subchapter-D/part-96.

[2]CBSDs may request additional 10MHz channels if they need additional bandwidth.

[3]The maximum EIRP (10-MHz channel) for Category-A devices is 30 dBm (1 W) and for Category-B devices it is 47 dBm (50 W). End-user Devices (EUs) (e.g., CBRS-capable handsets) are not considered CBSDs and are limited to 23 dBm (200 mW). See https://www.ecfr.gov/current/title-47/chapter-I/subchapter-D/part-96/subpart-E/section-96.41

authors analyze the reasons behind the stalled implementation of LSA and advocate for the adoption of evolutionary regulatory frameworks, highlighting mitigating factors. In [5], the authors examine the impacts of CBRS, focusing primarily on economic and policy perspectives, including efficiencies achieved and challenges encountered, based on the assignment procedures for PALs and the auction results.

This qualitative research provides nuanced insights into the challenges policymakers, regulators, and industry stakeholders face as they navigate the new frameworks that govern shared spectrum access. However, despite growing calls [6] for robust metrics and methodologies to capture how spectrum is actually used — and to provide policymakers with empirical data such as throughput measurements and other Quality-of-Service (QoS) indicators — widely accepted standards and practices for collecting and reporting those measurements remain elusive.

Most of the measurement work on CBRS focuses on assessing interference, aiming to ensure coexistence among incumbents, PAL holders and GAA users. Several studies focused on the limited interference protection for GAA end users within the CBRS regulatory framework. Researchers [7] have analyzed how the presence of incumbents adversely affected the reliability of unlicensed GAA devices by deploying two CBRS devices near U.S. Navy installations in San Diego. Their findings indicate that the transmission rights of the two deployed CBRS devices remained inactive for more than half of the experiment's duration.

Other works have analyzed the impact of interference between adjacent bands allocated to mobile uses. In [8] researchers highlighted the challenges CBRS connections face compared to the C-band (detail frequencies, review) due to stricter emission power regulations in CBRS. They examine the impact of such interference on end-user QoS in real-world scenarios, showing that relocating channels further from the C-Band improves key network performance metrics, including throughput and latency. [9] extends this analysis to interference caused by other GAA deployments. Therefore, a significant portion of the research community's efforts has focused on developing algorithms to mitigate such interference, which is particularly crucial for ensuring seamless coexistence among diverse air interfaces (see, e.g. [10]).

Related to the assessment of CBRS rules, in [11], the authors conduct drive-test measurements on real-world networks to demonstrate the discrepancies in propagation models currently used to determine the Equivalent Isotropic Radiated Power (EIRP) limits for CBSDs. Their work emphasizes the need for alternative approaches to adapt existing rules and policies.

Despite the growing interest in CBRS, deployments have not been thoroughly measured or assessed in existing research. The NTIA reports cited earlier [1] rely on the data of authorizations granted by the SAS operators to track CBRS usage. However, the SAS operators base their authorizations and computations of CBRS usage (and power limits) on the power requested by the CBSDs and other relevant transmission details. The SAS operators do not observe whether CBSDs actually utilize their authorizations and the NTIA does not provide information on the types of operators or users that are requesting CBRS authorizations for their CBSDs.

The goal of this study is to provide a step toward establishing a baseline assessment of actual CBRS usage, utilizing a different approach (Crowdsourced mobile device measurements) and a different data provider than the SAS operators. Previous studies have demonstrated the potential of mobile crowdsourced measurements to evaluate how spectrum distributions and portfolios influence the MNOs' deployment strategies [12]. These novel methodologies, based on end-user measurements, can also offer valuable insights into spectrum-sharing frameworks and inform related policies, as we show in this paper. This diversity of perspective is advantageous in that it provides information not available to the SAS operators, although its partial coverage means that it complements, but does not replace what may be learned from the SAS. It also supports evidence-based policy-making, as, in the absence of multiple reliable unbiased measurements, different stakeholders may have strategic interests in distorting measurements or influencing policies to serve their own agendas [13]–[15].

## III. Methodology

In this Section, we describe the methodology used to address the research questions introduced earlier. Section III-A details the variables used from crowdsourced network measurements. Then, Section III-B outlines the methods employed for counting cell deployments depending on their use as Primary Component Carriers (PCC) or Secondary Component Carriers (SCC). Finally, Section III-C describes the processing of the FCC Auction 105 results and their integration with the crowdsourced data to classify deployments by CBRS access tiers (PAL or GAA).

### *A. Variables used from network measurements*

Crowdsourced measurements give valuable insights about the performance and configuration of cellular networks. In our study, these measurements are provided by the company Weplan Analytics. Measurements correspond to a 4-month period between mid-August and mid-December of 2024 across the Contiguous U.S. counties. Each measurement consists of a number of variables. For this study, we only work with the following variables, related to cell identity:

- PLMN (Public Land Mobile Network): identifies the mobile network operator using a combination of the Mobile Country Code (MCC) and Mobile Network Code (MNC).
- Network technology: indicates the Radio Access Technology (RAT) used by the detected cell. For this study, it is either 4G LTE or 5G NR.
- ARFCN (Absolute Radio Frequency Channel Number): encodes the carrier frequency on which the cell operates. In each technology it uses different conversion formulas, with different ranges for each frequency band. In our

study, it allows us to identify measurements in the CBRS band, b48 for LTE and n48 for NR.

- ECI/NCI (Evolved Cell Identifier/New radio Cell Identifier): uniquely identifies a cell within an LTE (ECI) or NR (NCI) PLMN.
- PCI (Physical Cell Identifier): this variable facilitates distinction between neighboring cells that operate on the same frequency. Unlike ECI/NCI, it is not a unique cell identity.
- Type of cell: labels the cell depending on whether it is acting as PCC or SCC. If a cell is serving the User Equipment (UE) as PCC, the cell manages all procedures to allocate radio resources to the UE. If it is serving as SCC, it is used in Carrier Aggregation scenarios, to increase the bandwidth allocated to the connection with the UE.
- Geohash of level 5 [16]: encodes the geographic coordinates of the registered measurement into a string of 5 characters. For the contiguous U.S. land, each level-5 geohash represents an approximately rectangular area of around $18\ \mathrm{km}^2$, with $3.7$ km by $4.88$ km and a diagonal of $6.12$ km. For each geohash we use its geographical center with longitude and latitude in geographic coordinates to assign the measurement to a specific county.

### B. Method for cell detection

Two different crowdsourced **datasets** are used, which contain measurements related to cells acting as PCC or SCC respectively. In each base, some basic **filtering** is applied to clean the data. Firstly, we consider that a cell has been detected if it is found (using the method described below) on at least two separate days. This helps prevent errors caused by synchronization problems in the data collection, which can result in inconsistencies across different variables of the same measurement event. Secondly, the PCI value $0$ in crowdsourced measurements is not reliable, because, in addition to being a true PCI value, it is sometimes used as a "fill" value during the measurement when the PCI is unknown. Therefore, it has to be discarded from the analysis.

Each data measurement includes the **identity of the cell** to which the UE is attached. The method for detecting deployed cells is conditioned by the information available from the operating system of the end-user terminals. This information is different depending on the relation between the cell and the UE. Unique cell identifiers, i.e. ECI or NCI, can only be obtained through PCC measurements, whereas the PCI is always accessible.

**Detecting a cell acting as PCC** is straightforward. In this case, the cell is uniquely identified by its PLMN (i.e. MNC and MCC) and ECI/NCI. These parameters are available for cells serving as PCC.

**Detecting a cell used as SCC** is more difficult. In this case, the ECI/NCI information is not available in the measurements, and therefore a different method must be used. In addition, a given cell in the CBRS band does not always use the same ARFCN, as the spectrum use is dynamic by definition.

A cell can typically be assumed to always use the same PCI during the time span of the measurements. However, since the amount of different PCI values is limited (there are $504$ possible PCI values in LTE and $1008$ in NR), there will necessarily be different cells in the same PLMN that use the same PCI. This reuse distance will be large, given the relatively large amount of PCI values available. An operator has a strong incentive to maximize the PCI reuse distance; otherwise, mobile terminals will not be able to differentiate between nearby cells with the same PCI.

It is thus safe to assume that nearby occurrences of the same (PLMN, PCI) pair correspond to the same cell, whereas distant observations of the same tuple correspond to different cells that use the same PCI. Consequently, cells acting as SCC correspond to spatial "clusters" of nearby points with the same (PLMN, PCI). A key question is what distance threshold to use in order to identify those clusters. Ideally, intra-cluster distances should be distinctly smaller than inter-cluster distances, which would allow reliable identification of the cells.

Figure $1$ shows a histogram of distances between pairs of points with the same (PLMN, PCI), obtained from the SCC dataset. A random sampling of $10^8$ such pairs is used, all pairs being equally likely. For each pair, the decimal logarithm of the distance is computed, and the histogram of the resulting values is plotted. Two regions can be clearly identified in the graph, corresponding to distances in the ranges $0.001$-$4$ km and $10$-$4000$ km approximately, with a clear gap in between, where almost no values occur.

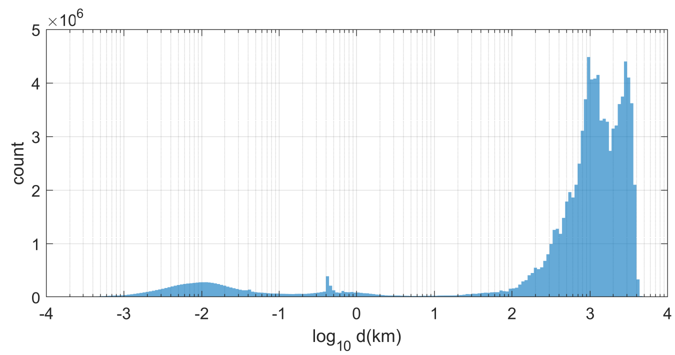


Fig. 1. Histogram of pairwise distances between points with the same PLMN and PCI for SCC cells

The results in Figure $1$ confirm that it is possible to identify cells using a distance threshold between $4$ and $10$ km. Thus in principle, given a set of measurements, for each (PLMN, PCI) all pairwise distances between points should be computed, and two points belong to the same cell if their distance is less than the threshold. This defines a graph, such that each of its connected components corresponds to a cell. However, computing all pairwise distances is not feasible for large datasets, because the computational load increases quadratically with the number of points (this is also the reason why a random sampling of pairs was used to generate the histogram in Figure 1, instead of all pairs). Therefore an approximate, simpler method must be employed that avoids computing all pairwise distances.

The chosen method is based on using geohashes: for a given (PLMN, PCI), two points are declared to belong to the same cell/to different cells respectively if they are in the same geohash/in different geohashes. A limitation of this method is that an actual cell can be seen in more than one geohash, if it is located near a geohash border, which will artificially increase the cell count. To minimize the probability of this, the geohash size should be as large as possible. On the other hand, the geohash size should be less than the minimum PCI reuse distance, to avoid incorrectly considering different cells as the same cell. Level-5 geohash is a good choice, because its size (3.7 km by 4.88 km) conveniently lies in the gap between the two regions observed in the histogram.

### *C. Mapping FCC Auction 105 Data with Crowdsourced*

To determine whether a specific cell is operating under the PAL or GAA tier, we map the FCC Auction 105 data to the detected cells, as detailed. We assume that a cell operates under the PAL tier if its owner holds a PAL license for the county where the cell is deployed. If no such license is held, the cell is assumed to be operating under the GAA tier. For that, we use the results of the FCC Auction 105, which is available on the FCC Public Reporting System [17]. The spectrum is auctioned at the county administrative level, allowing for a maximum of 7 distinct 10 MHz PALs per county. It contains the following information:

- County: Contains the abbreviated name of the state and its unique three-digit code.
- License: A unique identifier for each of the 7 PALs in each county.
- Bidder: Name of the company that acquired the PAL.
- Net payment per license: Final price paid by the licensee.

This data is processed to obtain aggregated tables by bidder and county with the total number of acquired licenses and the total payment made for those licenses. Then, this information is combined with the results of the crowdsourced data analysis. A label is assigned based on whether or not a company holds licenses in a given county. The PAL label is applied when a company holds at least one license in a county where its cells are detected. Conversely, if the company does not hold any licenses but has cells detected in that county, it is labeled as GAA. Unlike the NTIA report [1], our method does not account for mixed license use.

## IV. Results

CBRS is utilized by a broad range of stakeholders, each with distinct motivations and use cases for this shared spectrum. Based on our preliminary analysis, we have identified six different stakeholder categories: Mobile Network Operators (MNOs), Regional MNOs, Mobile Virtual Network Operators (MVNOs), Wireless ISPs (WISPs), Neutral Hosts, and Private Networks. Using the crowdsourced dataset described in Section III we have identified 11 PLMNs with a relevant number of measurements in the CBRS. To determine the company associated with each PLMN, we used [18]. Each company was then mapped to one of the six categories described above, as shown in Table I. Note that a single company can operate under multiple PLMNs.

TABLE I
Stakeholder Categories and Corresponding PLMNs

| Category | Stakeholders | PLMN |
|---|---|---|
| MNO | 4 | 310-260, 310-410, 311-480, 311-580, 312-680 |
| Regional MNO | 5 | 310-20, 310-580, 311-30, 311-650, 311-840, 311-850 |
| MVNO | 3 | 313-810, 314-20, 314-200 |
| Neutral host | 4 | 313-640, 314-30, 314-280, 314-330 |
| Private networks | 4 | 311-98, 311-530, 313-540, 313-650, 315-1, 315-10 |
| WISP | 3 | 311-740, 313-240, 313-420 |

One of the most prominent uses for CBRS is to expand the coverage and capacity of mobile broadband services. Participants in that category include the MNOs (i.e., Verizon, T-Mobile, AT&T and US Cellular). MNOs leverage CBRS spectrum to enhance network capacity, particularly in areas with high traffic demand, integrating it into their spectrum portfolios. The CBRS spectrum is especially valuable mid-band spectrum, but different MNOs have different portfolios and strategies for addressing their spectrum needs. The heterogeneity in business models among MNOs and other participants in CBRS was evident in the 2020 CBRS PAL auction. For example, whereas Verizon acquired PALs in numerous counties, primarily urban areas, AT&T did not acquire any licenses.[4] Similarly, Regional MNOs and smaller operators may find CBRS appealing as a cost-effective solution for network expansion without requiring large spectrum investments.

In contrast, other stakeholders see other benefits in CBRS spectrum. MVNOs, led by cable operators such as Comcast, Charter, and Cox, see CBRS spectrum as offering an opportunity to reduce their roaming payments to MNOs. Additionally, CBRS offers the opportunity for new kinds of mobile operator business models. Dish, known for its direct satellite broadcast services but interested in entering terrestrial mobile broadband, spent over $913m acquiring PALs. It explored partnering with Helium, the decentralized, blockchain-based WiFi network operator.[5]

The other stakeholders leverage the CBRS spectrum for a mix of business uses. In rural areas, WISPs use CBRS for Fixed Wireless Access (FWA), expanding broadband coverage in underserved regions. Similarly, neutral hosts, which provide

[4]Nonetheless, the value of 3.5GHz spectrum for meeting MNO needs was demonstrated by the over $80B raised for the 280 MHz of 3.7GHz C-Band spectrum auctioned in 2021 (see https://www.fcc.gov/auction/107), in which T-Mobile, Verizon, and AT&T were prominent auction winners (see https://www.lightreading.com/5g/c-band-auction-maps-and-charts-who-won-what-where-and-how-much). CBRS PAL auction raised $4.5B for 70MHz.

[5]See https://www.prnewswire.com/news-releases/dish-partners-with-helium-to-leverage-the-helium-networks-blockchain-model-using-cbrs-spectrum-301408662.html.

shared mobile infrastructure in venues such as stadiums, malls, or airports, are also reportedly interested in CBRS for local private 5G or LTE and shared spectrum infrastructure.

Finally, the emerging use cases for private networks, ranging from enterprise campus networks to industrial IoT deployments, may benefit from CBRS by enabling quick and cost-effective deployments using standardized cellular technologies without necessarily requiring a license. For instance, utility companies such as Southern California Edison Company are seeking to use CBRS spectrum to build out private 5G networks to support their smart-electric power grid initiatives.

Other utilities, large enterprises and venues have also acquired PALs to build out private 5G networks; however, most enterprise networks are expected to rely on GAA.

In the following subsections, we provide our results to answer research question.

In the following subsections, we address the research questions outlined above. Section IV-A focuses on exploring the extent and type of CBRS use as well as the technologies deployed (research questions 1 and 2). Section IV-B examines the use of CBRS access tiers (PAL and GAA) across stakeholders (research question 3).

### A. Cell deployments per stakeholder category

Table II summarizes the distribution of identified cells operating as PCC. Our findings indicate that deployments of MNOs account for 14.9% of the total identified primary cells; Regional MNOs, for 1.7%; MVNOs, for 77.8%; Neutral Hosts, for 1.5%; Private Networks, for 3.9% and WISPs, for 0.2%.

TABLE II
NUMBER OF PCCS BY STAKEHOLDER CATEGORY

| Category | Stakeholder | States | Counties | PCC |
|---|---|---|---|---|
| MNO | 4 | 27 | 172 | 557 |
| Regional MNO | 5 | 6 | 16 | 57 |
| MVNO | 3 | 11 | 20 | 2,913 |
| Neutral host | 4 | 20 | 45 | 63 |
| Private networks | 4 | 21 | 35 | 148 |
| WISP | 3 | 3 | 4 | 7 |

This contrasts with and complements the data reported by the NTIA [1] in several key ways. First, crowdsourced data tend to have a bias toward urban areas, as the data collection relies on end-user devices, which are more prevalent in densely populated regions with higher smartphone penetration and active usage. Although we believe the impact of crowdsourcing is relatively limited in this analysis [6], it may have led to an underrepresentation of stakeholders that primarily operate in rural areas (e.g., WISPs).

Second, our measurements only detect cellular technologies (LTE or NR). As a result, if CBRS is being used for FWA in rural areas with other technologies, such as proprietary solutions or non-cellular air interfaces, it remains undetected in our dataset. According to the NTIA, more than half of CBSDs operate with air interfaces other than NR or LTE (E-UTRA), highlighting this limitation. Furthermore, even if FWA networks were using cellular technologies, we would still not detect them because end-user devices typically connect to WiFi, which is what the device would report rather than the underlying cellular network. This explains why our data identifies so few cells deployed by WISPs, whose primary applications often involve FWA in rural areas.

On the other hand, despite these limitations, our analysis provides remarkable insights not previously reported. First, it is worth noting that among cellular operators, those with the most extensive infrastructure deployed in CBRS are MVNOs, particularly those affiliated with large cable operators. All cells detected as PCCs for these operators are NR cells, belonging to Spectrum Mobile and XFinity Mobile, as shown in Table III. These two operators account for 42% and 57% of the PCCs within their category, respectively, and 33% and 45% of the total number of PCCs detected across all categories. The high volume of cells serving as PCCs, compared to other stakeholders, suggests that their CBRS networks rely heavily on small cell deployments in urban areas. This observation aligns with NTIA data, which report the presence of NR cells starting in 2022, with sustained growth reaching approximately 10% of active CBSDs by July 2024.

TABLE III
NUMBER OF NR CELL DEPLOYMENTS BY STAKEHOLDER

| Category | Stakeholder | States | Counties | PCC |
|---|---|---|---|---|
| MVNO | Spectrum Mobile | 2 | 5 | 1,241 |
| MVNO | XFinity Mobile | 8 | 13 | 1,669 |

Regarding private networks, we are likely underestimating the amount of infrastructure deployed using CBRS spectrum. By design, our methodology likely captures only private networks that provide Internet access, such as campus networks, while overlooking private industrial networks that do not interact with public infrastructure in the same way. Nevertheless, the data indicates a notable use of CBRS-based campus networks to enhance localized connectivity. Another interesting observation is that all these networks are based on Private LTE; we did not detect any private 5G networks.

Finally, we were surprised by the low utilization of CBRS by MNOs, which prompted us to investigate further. In [9], based on data from a measurement campaign in South Bend, IN, evidence is presented suggesting that some MNOs are using CBRS frequency cells primarily as a secondary resource (SCC), adding network capacity through Carrier Aggregation techniques. Thus, we analyzed the spectrum bands reported as SCC, resulting in a dramatic increase in the number of detected cells. Interestingly, a single MNO accounts for 99% of all deployments detected as SCC. The results are presented in Table IV. Detected cells in all categories other than MNOs are likely outliers and should be interpreted with caution.

[6]In many geographic areas, we observed a high volume of measurements in other spectrum bands, such as the C-band, suggesting that the absence of measurements in CBRS is not due to the crowdsourcing effect. Further checks are underway to quantify this impact.

TABLE IV
NUMBER OF SCCS BY STAKEHOLDER CATEGORY

| Category | Stakeholder | States | Counties | SCC |
|---|---|---|---|---|
| MNO | 4 | 49 | 1354 | 63,956 |
| Regional MNO | 1 | 1 | 1 | 4 |
| Neutral host | 1 | 1 | 1 | 1 |
| Private networks | 1 | 1 | 1 | 1 |

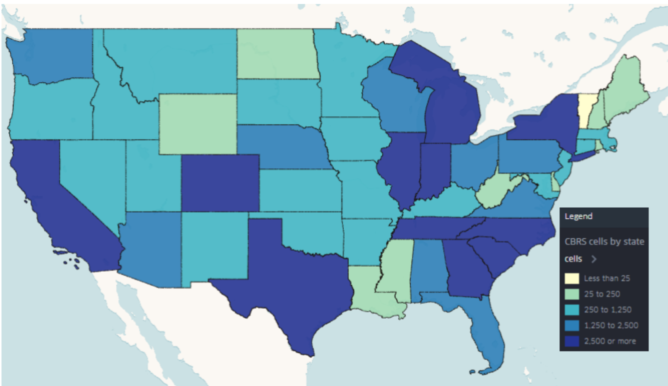


Fig. 2. Number of cell deployments by state in Contiguous US.

Figure 2 shows the geographic distribution of the total number of detected cells by state. The total cell count includes the sum of PCCs and SCCs and is provided solely for illustrative purposes. States with the highest total number of cells ($> 2,500$) consistently feature the presence of Verizon, driven by its extensive use of cells serving as SCCs. Additionally, many of these states also have MVNOs with NR deployments, contributing significantly to the number of cells serving as PCCs. In states without MVNO activity — such as those in California, Colorado, and Michigan — neutral host deployments play a prominent role. Notably, all these states contain major cities, which likely contribute to the high concentration of detected cells.

### B. Cell deployments per access tier

Finally, this section addresses the third research question by examining the use of the access tiers (PAL or GAA) associated with each stakeholder and their deployment patterns. The analysis seeks to uncover potential relationships between PAL license acquisition and the infrastructure deployed within the CBRS spectrum.

Before presenting the results on PAL and GAA cell deployments, it is essential to introduce the outcomes of the CBRS auction. The focus is on the categories of bidders with detected CBRS cellular networks, as shown in

Table V summarizes the CBRS PAL auction results focusing on the categories of bidders with detected CBRS cellular networks. Verizon stands out as the leading MNO, making the highest payment of $1,893 million. Among MVNOs, Spectrum Mobile (Charter) and Xfinity Mobile (Comcast) follow, each contributing approximately $450 million. In terms of licenses, Xfinity Mobile leads with 830 PALs, followed by Verizon with 557 and Spectrum Mobile with 210. US Cellular holds nearly all the remaining PALs acquired by MNOs. The auction results show variability in license pricing, as reflected in the payments and the geographic distribution of licenses acquired by Regional MNOs. Finally, "OTHER" includes 218 distinct bidders, accounting for 37.2% of the total auction expenditure.

TABLE V
RESULTS OF FCC AUCTION 105 BY CATEGORY*

| Category | Bidders | Counties | Licenses | Payment ($M) |
|---|---|---|---|---|
| MNO | 3 | 239 | 808 | 1,912.91 |
| Regional MNO | 4 | 98 | 264 | 6.86 |
| MVNO | 3 | 587 | 1557 | 933.92 |
| OTHER | 218 | 3,220 | 17,996 | 1,689.54 |

*We do not take into account M&A operations between PALs holders or abids due to FCC Consent Decrees after the FCC results from 2020.

Building on this analysis, Table VI presents CBRS usage data by category and tier, detailing the breakdown of deployments across the six groups of stakeholders, states, and counties, along with the number of cells operating as PCC and SCC.

Overall, the number of cells deployed by MNOs using GAA is larger than those using PAL access. Specifically for PCC usage, the number of GAA deployments is 4 times higher than PAL deployments, with GAA detected in 1,262 counties compared to just 178 counties for PAL access —a sevenfold difference. However, when analyzing SCC results, the ratio between PAL and GAA shifts, with GAA deployments being only about 1.5 times higher than PAL deployments. This translates to a ratio of SCCs per county of nearly 138 for PAL compared to 31 for GAA, suggesting that when MNOs acquire a license, the density of deployed cells per county is significantly higher. This disparity is likely due to PALs being concentrated in the most urban areas. However, the findings on GAA access tier deployments suggest that crowdsourced data remains a valuable approach for analysis, as the results are not overly biased toward urban areas or PAL deployments, enabling a broader understanding of CBRS utilization.

The aggregate results for the MNO category are mixed, as different MNOs have pursued varying strategies regarding CBRS spectrum, as previously mentioned. Conversely, Regional MNOs and MVNOs show more PAL activity than GAA, aligning with their strategy to prioritize deployments in areas where they have secured licenses. Finally, Neutral Hosts and private networks, which did not acquire PALs, rely exclusively on GAA for their deployed infrastructure.

Figure 3 presents a scatter plot showing the number of SCCs per county against the total payment made by Verizon for its PALs. The distribution indicates a moderate positive correlation of $0.54$, suggesting that Verizon has deployed more cells in counties where it paid more for the PALs. The large number of cells deployed and the extensive number of PALs held by Verizon enable us to test this relationship with high reliability. This finding highlights how the CBRS auction may incentivize deployments for PAL holders. However, the moderate correlation also implies that other factors, beyond the

TABLE VI
SUMMARY OF CBRS DATA BY CATEGORY AND TIER

| Category | Tier | Counties | PCC | SCC |
|---|---|---|---|---|
| MNO | PAL | 178 | 103 | 24,581 |
| MNO | GAA | 1,262 | 454 | 39,375 |
| Regional MNO | PAL | 11 | 51 | 4 |
| Regional MNO | GAA | 5 | 6 | 0 |
| MVNO | PAL | 18 | 2,863 | 0 |
| MVNO | GAA | 2 | 50 | 0 |
| Neutral host | GAA | 46 | 63 | 1 |
| Private networks | GAA | 35 | 148 | 1 |
| WISP | GAA | 4 | 7 | 0 |

payment amount, likely influence the number of deployments. Notably, the counties with the highest number of deployments correspond to major cities, such as Phoenix, Los Angeles, and Chicago.

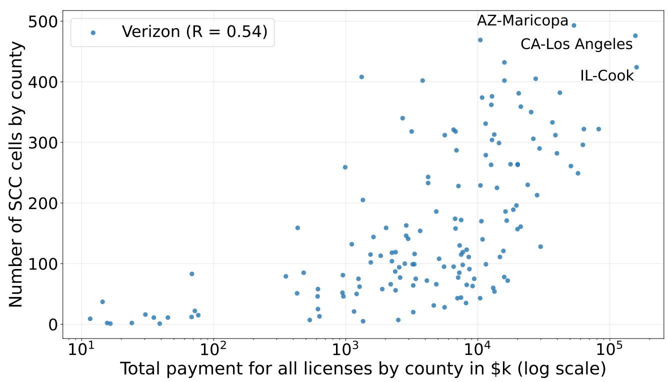


Fig. 3. Distribution of SCCs deployed against total payment in PALs by counties for Verizon.

## V. CONCLUSIONS

In this study, we presented a novel methodology for evaluating the effectiveness of new spectrum-sharing frameworks, such as CBRS. By analyzing real-world data, we gained valuable insights into the deployment and utilization of CBRS spectrum across six different stakeholder categories.

First, while MNOs do not primarily rely on CBRS to deliver their services, our findings demonstrate that CBRS serves as an important strategic tool for expanding competitive options in mobile broadband service provision. For instance, Verizon has deployed a significant number of cells in the CBRS spectrum as secondary carriers, enhancing network capacity, particularly in urban areas and in counties where the company invested heavily in PAL licenses. Additionally, we identified intensive use of CBRS by MVNOs affiliated with large cable operators, such as Spectrum Mobile and Xfinity Mobile, as they build out their mobile broadband services, which are primarily WiFi-based. This demonstrates how CBRS enables these operators to extend their networks and reduce dependence on traditional MNOs. Although mobile broadband service represents only one of the potential uses of CBRS, it currently accounts for the majority of deployments. Insights into MNOs' use of CBRS are particularly valuable for understanding competitive dynamics in the mobile broadband market. Furthermore, CBRS is creating opportunities for new types of providers, such as Helium, highlighting the critical role of spectrum management reform in fostering robust competition in the mobile broadband sector.

On the other hand, we faced challenges in assessing CBRS use by WISPs, as many FWA deployments do not rely on standardized cellular technologies. Similarly, while we detected significant use of CBRS by private networks, our methodology likely captures only a fraction of these networks, particularly those that provide broadband access, leaving industrial private networks underrepresented.

Though incomplete, the analysis presented here provides a valuable and novel perspective on how CBRS spectrum is being used. Given the importance of the midband spectrum allocated to CBRS and the importance of the framework for advancing regulatory models to enable more flexible, dynamic spectrum resource management, enhancing market intelligence regarding the success of CBRS is especially valuable. Whereas the NTIA data provides a census overview of all of the authorization activity of the CBRS SASs over time, it does not break that usage down by type of user, does not allow one to map the CBRS authorizations to actual traffic, and is available only with a lag. In contrast, the crowdsourced data analyzed here offers insights into how end users are actually making use of CBRS for PCC or SCC to utilize services offered by particular mobile broadband service providers and the distribution of such usage across the nation.

This preliminary study has opened the door to exploring new dynamics in spectrum sharing through crowdsourcing. There are several promising directions that we will explore in future research. Crowdsourced data includes additional QoS performance metrics that have not been utilized in this study. When fully integrated with additional information about CBRS usage, these data will provide a more comprehensive understanding of how CBRS fits within the broader context of spectrum management. Such integration will bring us closer to estimating the economic value of CBRS and its market implications for mobile broadband and other wireless services, including competition and innovation dynamics.

Finally, while the dynamism of CBRS spectrum usage, as evidenced in our data and NTIA reports, highlights its importance for commercial wireless services, the reforms adopted in CBRS rules have the potential to significantly enhance its role. This further amplifies our interest in building on this initial work to evaluate how CBRS usage is changing over time and in conjunction with the shifting strategies of CBRS market participants.[7]

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[7]For example, in the FCC proceeding underway, AT&T has been outspoken in calling for refarming CBRS spectrum after having elected not to participate in the earlier PAL auctions, whereas WISPs and the cable operators have been outspoken in supporting expanding commercial access to the CBRS spectrum. In an earlier footnote, we noted how Helium and DISH have adapted their strategic business models in tune to developments elsewhere. For example, Helium appears to have shifted away from exploring CBRS in favor of relying more on MVNO roaming under what media reports suggest are more favorable roaming agreements – which attests to the potential for how access to CBRS as a viable option can render access to scarce spectrum more contestable.