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On Reliability of CBRS Communications near U.S. Navy Installations in San Diego

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***Abstract*—This paper reports findings from two real-world unlicensed General Authorized Access (GAA) device installations in the recently released incumbent-dominated Citizens Broadband Radio Service (CBRS) shared spectrum in San Diego County, a region with a strong naval incumbent presence. We quantify the impact of the incumbents on GAA users by developing a one-step time-homogeneous Markov chain-based model to track the state of the systems, estimating the transition probabilities from measured data, and measuring the stationary distribution and expected values of hitting time and return time. Our measured datasets-based analyses show that the transmission rights of the deployed CBRS Devices (CBSDs) remain inactive for more than half the experiment duration. Also, the return time to get back the transmission rights is more than 13.5 hours for both locations. We also note that the cloud-based centralized Spectrum Access System (SAS) administrator of the CBRS shared spectrum often obfuscates the available spectrum information and revokes CBRS communication rights without prior information from the auctioned Primary Access License (PAL) users and unlicensed GAA users to protect the incumbents' location details and their movements. As a result, the communication reliability of the non-incumbents (i.e., PAL and GAA) gets affected by the current policy frameworks concerning only aggregate interference mitigation using the environmental sensing capability networks to protect the incumbents.**

***Index Terms*—CBRS, SAS, GAA, Markov chain, stationary distribution, hitting time, return time, communication reliability.**

I. Introduction

CITIZENS Broadband Radio Service (CBRS) is a newly released spectrum by the Federal Communications Commission (FCC), and it spans from 3550 MHz to 3700 MHz [1]. CBRS is originally owned by the incumbents, which include the United States military, in-band fixed satellite earth stations, and grandfathered wireless services. However, when not in use by the incumbents, the CBRS shared spectrum can be opportunistically accessed by the non-incumbent users, which include the Primary Access License (PAL) and General Authorized Access (GAA) users [1], [2]. Through spectrum auction, PAL users can opportunistically access 3550 MHz to 3650 MHz (i.e., the first ten channels each of 10 MHz). In contrast, GAA users can access the entire spectrum without disturbing the incumbent and PAL transmissions. Note that the CBRS shared spectrum access is centrally administered by the cloud-based Spectrum Access System (SAS) administrator, which is primarily responsible for protecting the incumbent transmissions and their actual locations (Dynamic Protection Areas (DPAs) throughout the United States territories) with the help of deployed Environmental Sensing Capability (ESC) networks. The SAS administrator allows the non-incumbents to transmit opportunistically when the shared spectrum is not utilized by the incumbents [2]–[4].

Although the primary reason behind releasing the CBRS shared spectrum is to increase wireless access bandwidth to meet the growing spectrum demands of end users, non-incumbent users often face challenges in acquiring communication rights on the CBRS and can be unknowingly suspended from accessing shared spectrum in incumbent-dominated regions, defeating the purpose of introducing the CBRS spectrum [5]. Note that as the GAA CBRS Devices (CBSDs) can be deployed with much lower cost (as no spectrum auction cost is involved), better communication reliabilities of GAA devices can help minimize the Capital Expenditure (CapEx) and Operational Expenditure (OpEx) costs for deploying next-generation telecommunication infrastructure [6]. However, GAA CBSDs should communicate reliably on the CBRS shared spectrum to achieve the above goals.

In this paper, we study the communication reliabilities of two installed GAA CBSDs positioned in nearby areas of Marine Corps Air Station (MCAS) Miramar [7], an incumbent establishment in San Diego County. In particular, we analyze the measured information communication log between the SAS administrator and the installed two GAA CBSDs for approximately two months (February 22, 2023 to April 14, 2023)[1] to model the SAS administrator's hidden state machine as a one-step time-homogeneous Markov chain that permits a GAA CBSD to communicate on the CBRS shared spectrum. Furthermore, we evaluate the long-term temporal characteristics of the two CBSDs by estimating the stationary distributions of all the process states and the expected return time to a specific process state.

A. Related Works

The authors of [8] demonstrated a GUI-based live CBSD deployment experiment on an LTE-A network in Finland. The authors in [9] designed co-channel and adjacent channel interference mitigation-based coexistence scenarios for incumbents and non-incumbents. In [4], [10], [11], the authors

[1]For the comparison purposes, we utilized the specified duration's information communication logs because of the availability of the SAS-CBSD communication log datasets for both deployed GAA CBSDs.

proposed various move list creation approaches to protect incumbents from communicating non-incumbents. Moreover, a few works dealt with the multiple coexistence scenarios of non-incumbents [12], [13].

To the best of our knowledge, no experimental evidence exists on realizing the communication reliabilities of GAA devices. Hence, this is the first attempt to quantitatively analyze the communication reliabilities of GAA CBSDs near an incumbent-dominated region in the United States from a GAA CBSD's viewpoint.

The rest of the paper is outlined as follows: Section II demonstrates an outdoor GAA CBSD installation process. Section III briefly mentions the SAS-curated outdoor CBSD authorization procedure on the CBRS shared spectrum. This is followed by Section IV, which elaborates on the experimental observations for the two GAA CBSDs installed near an incumbent-dominated region. Finally, we conclude our observations with future research directions in Section V.

TABLE I
Essential GAA CBSD installation parameters

Critical parameters	**Values used for our experiments**
Product type	Type B (i.e., outdoor)
Product brand	Baicells Nova 436Q with HaloB
Product firmware version	BaiBS_QRTB_2.9.14
Used radio technology	Evolved Universal Terrestrial Radio Access (E-UTRA)
Maximum allowable EIRP	47 dBm/10 MHz
Maximum antenna gain	18 dBi
Antenna beamwidth	64°
Height of antenna	Approximately 20 meters above ground level
Antenna azimuth	90°
Antenna downtilt	0°
GPS features	High rejection anti-jamming and full lightning protection-enabled low noise device
GPS horizontal accuracy	Approximately 50 meters
GPS vertical accuracy	Approximately 3 meters

II. GAA CBSD Installation

We deployed Baicells Nova 436Q advanced two-carrier outdoor eNodeB [14] as outdoor GAA CBSDs at the following experiment locations: (i) UC San Diego Park & Market Building's rooftop [15] and (ii) UC San Diego Main Campus' Atkinson Hall rooftop antenna garden [16]. Note that Nova 436Q consists of Baicells HaloB feature [17], which allows the GAA CBSD to retain connectivity during link failure and reestablish connection faster after the link restoration. In addition, each of the CBSDs is accompanied by one high rejection anti-jamming and full lightning protection-enabled low noise GPS antenna [18]. Moreover, one 2-port 64° sector antenna [19] is connected to each CBSD via low-loss coaxial N-male to N-male connectors. Finally, an antenna mounting pole is used to assemble the entire setup (see Figure 1(a)). Also, refer to Figures 1(b)-(d) that depict satellite views of the two GAA CBSDs and the relative locations of the CBSDs and MCAS Miramar.

Once the CBSD setup is complete, it is updated with the following firmware version: BaiBS_QRTB_2.9.14. After that, the CBSD GUI is accessed to configure a few important fields, such as carrier details, network interfaces, and management server. We also access the SAS GUI portal[2] to update device-specific details and authenticate the details using our Certified Professional Installer (CPI) credentials. Note that we also furnish the latitude and longitude details of the GAA CBSD setup because the device installation location information is critical to identifying the CBRS shared spectrum availability by the SAS administrator. We mention some important installation details in Table I.[3] A detailed description of an outdoor CBSD installation is outside this paper's scope.

III. SAS-curated GAA CBSD Authorization Steps

Once an outdoor GAA CBSD is ready with all required installation steps (see Section II), the SAS administrator must approve its request to communicate on the CBRS shared spectrum. Initially, when a GAA CBSD gets authenticated at the SAS GUI portal by the CPI credentials, the CBSD remains at the *unregistered state* (State 1) until the SAS administrator approves the submitted details (see Figure 2). After the SAS administrator approves, the device enters the *registered state* (State 2) and waits for the transmission rights on the CBRS.

Note that the SAS administrator, with the help of the ESC networks, senses the incumbent presence in the nearby region of the requesting GAA CBSD. If any CBRS channel exists for non-incumbent access near the GAA CBSD requesting region, the SAS administrator takes the registered CBSD to the *grant suspended state* (State 3) for necessary interference estimation from the nearest DPA's incumbent protection point. If the contributing interference remains within the tolerable limit and no incumbent movements exist, the SAS administrator allows the device to transit to the *granted state* (State 4). Conversely, whenever the ESC networks detect any incumbent movement near a GAA CBSD, the SAS administrator revokes all transmission rights from the nearby CBSDs and temporarily shifts the devices to State 3 until the shared spectrum becomes available for non-incumbent transmissions. Once the shared channels become available, after estimating the interference contributions, the suspended GAA CBSDs get back their transmission rights if feasible. However, being in State 4 does not allow a CBSD to transmit on the CBRS shared spectrum. Therefore, the SAS administrator must approve the device to enter the *authorized state* (State 5) to achieve the transmission rights. Once a GAA CBSD enters State 5, the device can communicate on the allowed CBRS channel(s).

Hence, a CPI-verified GAA CBSD transits among five process states on the CBRS shared spectrum. However, only the authorized state allows the device to get transmission rights on the CBRS. Therefore, to enhance operational reliability, a GAA CBSD should operate in State 5 most of the time.

[2] In our experiment, we use the SAS GUI portal provided by Google, Inc.
[3] EIRP is the Effective Isotropic Radiated Power

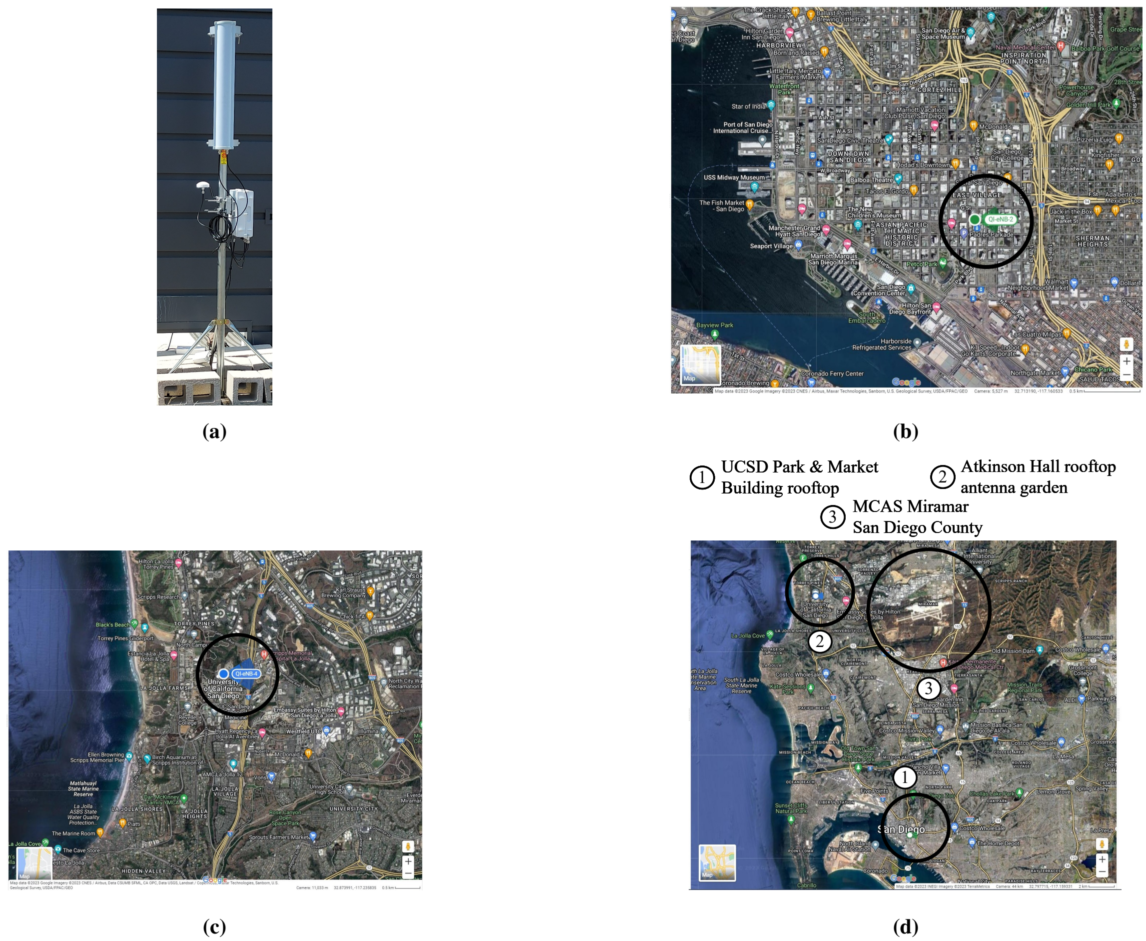

Fig. 1: (a) An outdoor GAA CBSD installation, (b) GAA CBSD at the UC San Diego Park & Market Building's rooftop (thick black circle), (c) GAA CBSD at the Atkinson Hall's (UC San Diego main campus) rooftop antenna garden (thick black circle), and (d) relative locations of two GAA CBSDs and MCAS Miramar area (thick black circled indexed locations).

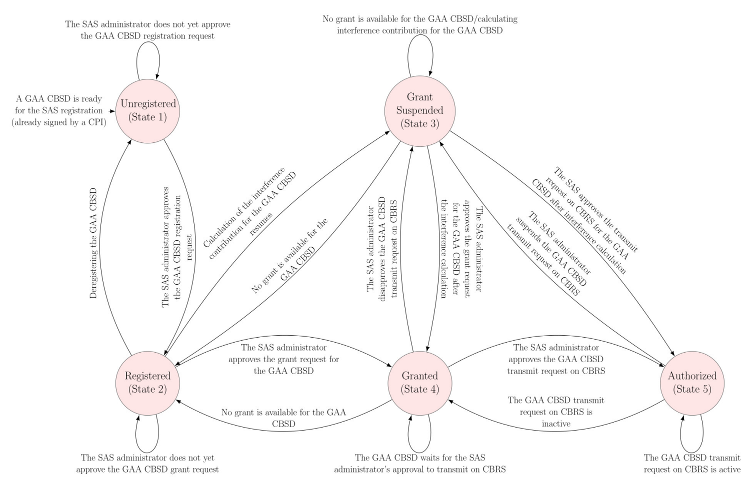

Fig. 2: GAA CBSD process state transition diagram to operate on the CBRS shared spectrum.

IV. Experimental Results and Discussion

We gathered the information communication logs of the two GAA CBSDs for approximately two months (February 22, 2023 to April 14, 2023) to analyze the devices' communication reliabilities at the two installation locations mentioned in Section II. A brief discussion of the mathematical preliminaries to design the hidden state machine of the SAS administrator as a one-step time-homogeneous Markov chain is discussed in the following. Next, we introspect the communication reliabilities of the two CBSDs through stationary distribution, hitting time, and return time analyses using the measured dataset.

A. Modeling Preliminaries

We assume a process state of an outdoor CBSD at time instant $m \in \{0,\ 1,\ 2,\ 3, \ldots\}$ as a random variable $\mathbb{Y}_m$ belongs to a state space S. To model the process state transitions of the device, we assume that the state transitions follow a one-step time-homogeneous Discrete Time Markov Chain (DTMC) [20]–[22] approach while transiting from a current process state y, at the m^{th} time instant, to the next process state z (i.e., p_{yz}), at the $(m+1)^{th}$ time instant. The transition probability $P_r\{\cdot\}$ represents the transition probability of a process state that only relies on the present state and does not take past states into account:

$$\begin{aligned} p_{yz} &= P_r\{\mathbb{Y}_{m+1} = z | \mathbb{Y}_m = y, \mathbb{Y}_{m-1} = y_{m-1}, \\ &\quad \mathbb{Y}_{m-2} = y_{m-2}, \ldots, \mathbb{Y}_1 = y_1, \mathbb{Y}_0 = y_0\}, \\ &= P_r\{\mathbb{Y}_{m+1} = z | \mathbb{Y}_m = y\}. \end{aligned} \tag{1}$$

Therefore, an N process states' state transition matrix $\mathbb{P}$ can be represented as

$$\mathbb{P} = \begin{bmatrix} p_{11} & p_{12} & p_{13} & \cdots & p_{1N} \\ p_{21} & p_{22} & p_{23} & \cdots & p_{2N} \\ \vdots & \vdots & \vdots & \ddots & \vdots \\ p_{N1} & p_{N2} & p_{N3} & \cdots & p_{NN} \end{bmatrix}. \tag{2}$$

It can be noted that $0 \leqslant p_{yz} \leqslant 1, \forall y,\ z \in \{1,\ 2,\ 3, \ldots,\ N\}$, and $\sum_{z=1}^{N} p_{yz} = 1$, where $y \in \{1,\ 2,\ 3, \ldots,\ N\}$.

B. Stationary Distribution

In the following, we report our observations on the stationary distributions of the measured information communication logs of the two GAA CBSDs.

a) UC San Diego Park & Market Building Rooftop: While realizing the state transition matrix from the measured dataset, we note that the real-time communication log consists of a few unwanted process state transitions (e.g., unregistered to grant suspended and registered to authorized, to name a few), and the irregularities are removed by applying weighted corrections. The corrected state transition matrix ($\mathbb{P}_{\text{cor1}}$) is

$$\mathbb{P}_{\text{cor1}} = \begin{bmatrix} 0.5000 & 0.5000 & 0 & 0 & 0 \\ 0.0435 & 0.4782 & 0.1738 & 0.3040 & 0 \\ 0 & 0.0199 & 0.7417 & 0.1391 & 0.0993 \\ 0 & 0.0130 & 0.2208 & 0.5844 & 0.1818 \\ 0 & 0 & 0.1216 & 0.0270 & 0.8510 \end{bmatrix}.$$

Note that $\mathbb{P}_{\text{cor1}}$ is an ergodic matrix because it is irreducible and aperiodic [22]. Hence, $\mathbb{P}_{\text{cor1}}$ has a unique distribution as mentioned below:

$$\overrightarrow{\mathbb{S}}_{\text{cor1}} \mathbb{P}_{\text{cor1}} = \overrightarrow{\mathbb{S}}_{\text{cor1}}. \tag{3}$$

Here, $\overrightarrow{\mathbb{S}}_{\text{cor1}}$ is steady state vector. The steady state values of $\mathbb{P}_{\text{cor1}}$ are given below:

$$\overrightarrow{\mathbb{S}_{\text{cor1}}} = \begin{bmatrix} 0.0017 \\ 0.0197 \\ 0.3656 \\ 0.1659 \\ 0.4471 \end{bmatrix}.$$

b) Atkinson Hall Rooftop Antenna Garden: Similar to the previously-mentioned discussion, we applied weighted corrections to realize the state transition matrix $\mathbb{P}_{\text{cor2}}$ as

$$\mathbb{P}_{\text{cor2}} = \begin{bmatrix} 0 & 1 & 0 & 0 & 0 \\ 0.0244 & 0.5122 & 0.1707 & 0.2927 & 0 \\ 0 & 0.0339 & 0.7232 & 0.1525 & 0.0904 \\ 0 & 0.0104 & 0.2292 & 0.5521 & 0.2083 \\ 0 & 0 & 0.1429 & 0.0214 & 0.8348 \end{bmatrix}.$$

The steady state values of $\mathbb{P}_{\text{cor2}}$ are

$$\overrightarrow{\mathbb{S}_{\text{cor2}}} = \begin{bmatrix} 0.0008 \\ 0.0314 \\ 0.3771 \\ 0.1691 \\ 0.4216 \end{bmatrix}.$$

c) Discussion: From the stationary distribution analyses of the two installed GAA CBSDs in two different locations of San Diego County, we observed that both the CBSDs remained non-authorized for more than half the time. Also, in both cases, the devices remained grant suspended for more than 35% of the total time. Due to the closeness of the incumbent establishments (i.e., MCAS Miramar), both devices stayed at grant suspended (i.e., at State 3) for a long duration, and the communication reliabilities of the two GAA CBSDs remained questionable for delivering timely services to end users. We also observed during the experiments that the GAA CBSDs were suspended from accessing the CBRS channel(s) whenever the devices did not utilize the allotted channel(s) longer. However, if utilized, the devices' access did not get revoked due to inactivity until any incumbent movements were detected.

C. Hitting Time and Return Time

We previously noted that the two CBSDs remained non-authorized (i.e., being in the unregistered, registered, grant suspended, or granted state) for a long time. In this section, we quantitatively measure the expected hitting time to reach a particular process state and the expected return time to a specific state (e.g., authorized or non-authorized states). To estimate the hitting time, let us consider a random variable $\mathcal{T}_{S_H}$ to capture the expected time to reach a target state (for the first time) from the current process state set $S_H \subset S$:

$$\mathcal{T}_{S_H} = min\{m \in \{0,\ 1,\ 2, \ldots\} : \mathbb{Y}_m \in S_H\}. \quad (4)$$

Let $\mathbb{H}_y^{S_H}$ be the conditional expected value of $\mathcal{T}_{S_H}$. Then,

$$\mathbb{H}_y^{S_H} = \mathbb{E}\left(\mathcal{T}_{S_H} | \mathbb{Y}_0 = y\right). \quad (5)$$

To estimate $\mathbb{H}_y^{S_H}$, we solve the set of linear equations to get the minimum solution as follows [23]:

$$\mathbb{H}_y^{z \in S_H} = \begin{cases} 1 + \sum_{q \neq z \in S_H} p_{yq} \mathbb{H}_q^{z \in S} & \text{if } y \neq z \in S_H \\ 0 & \text{if } y = z \in S_H. \end{cases} \quad (6)$$

Conversely, to estimate the expected return time from all non-authorized process states to the authorized process state and vice versa, we consider a random variable $\mathcal{T}_{S_R}^R$ to capture the return time in $S_R \subset S$:

$$\mathcal{T}_{S_R}^R = min\{m \in \{1, 2, 3 \ldots\} : \mathbb{Y}_m \in S_R\}. \quad (7)$$

The expected value of the return time to reach a state $z \in S_R$, beginning from the state z, can be estimated as follows:

$$\mathbb{R}_z = \begin{cases} 1 + \sum_{q \neq z \in S_R} p_{qz} \mathbb{R}_z^q & \text{if } q \neq z \in S_R \\ 0 & \text{if } q = z \in S_R. \end{cases} \quad (8)$$

In the following, we analyze the hitting time and return time of the two installed GAA CBSDs.

a) UC San Diego Park & Market Building Rooftop: The hitting time of the installed GAA CBSD between all possible states is shown below ($\mathbb{H}_{\text{cor1}}$):

$$\mathbb{H}_{\text{cor1}} = \begin{bmatrix} 0 & 2 & 8.1032 & 7.9444 & 12.0052 \\ 1.1646e+03 & 0 & 6.1032 & 5.9444 & 10.0052 \\ 1.2670e+03 & 102.4161 & 0 & 10.0916 & 8.5517 \\ 1.2694e+03 & 104.7498 & 6.0178 & 0 & 7.2620 \\ 1.2742e+03 & 109.5656 & 7.8191 & 14.9825 & 0 \end{bmatrix}.$$

Conversely, we estimate return times for two scenarios: (i) return time to the authorized state and (ii) return time to the non-authorized states. For example, to find the return time for a specific state z (see Equation (8)), we estimate $\mathbb{R}_z^q = \sum_{q \neq z} \left(\mathbb{H}_{\text{cor1}}(z,\ q) + \mathbb{H}_{\text{cor1}}(q,\ z)\right)$. Table II mentions the return time estimation. Note that the average time step of the measured dataset is used to calculate the actual return time from the expected return time (i.e., $\mathbb{R}_z^q$).

TABLE II
Return time of UC San Diego Park & Market rooftop's GAA CBSD

Parameters	**Estimated values**
Average time step of measured dataset	2.64 hours
Return time to authorized state	14.95 hours
Return time to non-authorized states	6.83 hours

b) Atkinson Hall Rooftop Antenna Garden: For the GAA CBSD at the Atkinson Hall rooftop antenna garden, we estimate the hitting time matrix ($\mathbb{H}_{\text{cor2}}$) as follows:

$$\mathbb{H}_{\text{cor2}} = \begin{bmatrix} 0 & 1 & 6.7026 & 6.4333 & 10.6885 \\ 1.3053e+03 & 0 & 5.7026 & 5.4333 & 9.6885 \\ 1.3694e+03 & 64.1400 & 0 & 8.7476 & 8.5686 \\ 1.3732e+03 & 67.9401 & 5.5292 & 0 & 6.8418 \\ 1.3760e+03 & 70.7173 & 6.8026 & 13.6896 & 0 \end{bmatrix}.$$

In addition, the return time estimation is depicted in Table III.

TABLE III
Return time of Atkinson Hall rooftop antenna garden's GAA CBSD

Parameters	**Estimated values**
Average time step of measured dataset	2.41 hours
Return time to authorized state	13.65 hours
Return time to non-authorized states	6.35 hours

c) Discussion: It can be observed from the return time analyses that both the installed GAA CBSDs took longer to return to the authorized state. In particular, the GAA CBSD at the UC San Diego Park & Market Building rooftop took approximately 14.95 hours to return to the authorized state. In contrast, the GAA CBSD of Atkinson Hall rooftop antenna garden returned to the authorized state in a gap of nearly 13.65 hours. On the other hand, both the CBSDs returned to the non-authorized states in approximately 6.83 and 6.35 hours, respectively. Therefore, we found that the communication reliabilities of both CBSDs were not acceptable for time-critical application scenarios (e.g., remote surgery, autonomous driving, and live broadcasting, to name a few). However, time-insensitive (i.e., delay-tolerant) applications may be operated with caution, such as delivering sensor-collected data to remote servers for further processing and applications dependent on time-insensitive bursty data.

D. Observations

We observed at the time of GAA CBSD installation that the SAS portal often obfuscated the available CBRS shared spectrum information to hide the actual incumbent establishments and their present locations. Further, we observed inconsistency in the actual CBRS spectrum availability and the SAS portal-provided information (refer Figure 3 for an example of SAS portal-provided CBRS spectrum information). However, this paper does not detail the SAS-controlled CBRS spectrum obfuscation strategy and its impacts on non-incumbent operations.

We note several uneven gaps exist among measured information logs collected from the GAA CBSD's management cloud. As a result, it is impossible to directly estimate the empirical values of the return times to authorized and non-authorized states with the raw measured datasets. Also, due to such log inconsistencies, the average time step values for both CBSD logs (to estimate the actual return time) are higher. Therefore, developing strategies for empirical estimation of return times from uneven time-stamped SAS-CBSD communication logs and comparing the findings to the estimated return

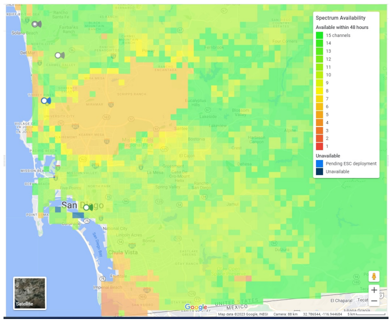

Fig. 3: SAS GUI portal provided a portion of San Diego County's CBRS shared spectrum availability at a particular time. As per the color code, 1 is the worst channel and 15 is the best channel out of all available CBRS channels for non-incumbents.

times utilizing the SAS administrator's hidden state machine modeled as a one-step time-homogeneous Markov chain will be an interesting future research direction.

V. Conclusion

In this paper, we investigated the communication reliability of GAA CBSD near an incumbent-dominated region of San Diego County. We installed two GAA CBSDs near the Miramar Marine Corps Air Station. We analyzed the SAS-CBSD communication link status over an approximately two-month period from log files obtained from the SAS administrator. In particular, we modeled the transitions among the five underlying process states as a one-step time-homogeneous Markov chain and estimated its transition probabilities, steady-state values, and hitting and return times. We found that UC San Diego Park & Market Building's rooftop GAA CBSD has a steady state value of 0.45 to be in the authorized state; it takes 14.95 hours to return to the authorized state and nearly 6.83 hours to return to the non-authorized state. Similarly, the other GAA CBSD at the UC San Diego main campus' Atkinson Hall rooftop antenna garden has its authorized states' steady state value as 0.42, and it returns to the authorized and non-authorized states in 13.65 hours and 6.35 hours, respectively. From a usage perspective, it seems that at locations close to where the incumbents may be active, GAA CBSD's reliability is unacceptable for interactive transfer of text, data, voice, or video traffic but could be satisfactory for delay-tolerant batch transfers. The development of prediction algorithms to accurately estimate the empirical return time from measured information logs can be exercised as an immediate future research direction. In addition, a detailed study of the SAS-controlled CBRS spectrum obfuscation can also be carried out as a future research direction.

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References

[1] Federal Communications Commission, "PART 96 - Citizens broadband radio service," Available at https://www.ecfr.gov/current/title-47/chapter-I/subchapter-D/part-96 (Accessed: 05/31/2023).

[2] Wireless Innovation Forum, "Requirements for commercial operation in the U.S. 3550-3700 MHz citizens broadband radio service band (WINNF-TS-0012)," Available at https://cbrs.wirelessinnovation.org/release-1-standards-specifications (Accessed: 05/31/2023).

[3] E. F. Drocella Jr., J. C. Richards, R. L. Sole, F. Najmy, A. Lundy, and P. M. McKenna, "3.5 GHz exclusion zone analyses and methodology (TR-15-517)," Available at https://www.ntia.doc.gov/report/2015/35-ghz-exclusion-zone-analyses-and-methodology (Accessed: 05/31/2023).

[4] M. R. Souryal, T. T. Nguyen, and N. J. LaSorte, "3.5 GHz federal incumbent protection algorithms," in *Proc. DySPAN*. IEEE, Oct. 2018, pp. 1–5.

[5] D. Boulware, A. Romaniello, R. L. Dorch, and M. G. Cotton, "An analysis of aggregate CBRS SAS data from April 2021 to January 2023 (NTIA Report 23-567)," Available at https://www.ntia.doc.gov/sites/default/files/publications/tr-23-567.pdf (Accessed: 08/15/2023), May 2023.

[6] William Stallings, *5G Wireless: A Comprehensive Introduction*, 1st ed. Addison-Wesley Professional, 2021.

[7] Naval Base San Diego, Available at https://www.miramar.marines.mil/ (Accessed: 05/31/2023).

[8] M. Palola, V. Hartikainen, M. Mäkeläinen, T. Kippola, P. Aho, K. Lähetkangas, L. Tudose, A. Kivinen, S. Joshi, and J. Hallio, "The first end-to-end live trial of CBRS with carrier aggregation using 3.5 GHz LTE equipment," in *Proc. DySPAN*. IEEE, Mar. 2017, pp. 1–2.

[9] N. N. Krishnan, R. Kumbhkar, N. B. Mandayam, I. Seskar, and S. Kompella, "Coexistence of radar and communication systems in CBRS bands through downlink power control," in *Proc. MILCOM*. IEEE, Oct. 2017, pp. 713–718.

[10] M. R. Souryal and T. T. Nguyen, "Effect of federal incumbent activity on CBRS commercial service," in *Proc. DySPAN*. IEEE, Nov. 2019, pp. 1–5.

[11] T. T. Nguyen and M. R. Souryal, "Deterministic move lists for federal incumbent protection in the CBRS band," *EEE Transactions on Cognitive Communications and Networking*, vol. 7, no. 3, pp. 790–801, Sep. 2021.

[12] W. Gao, A. Sahoo, and E. Bradford, "GAA-GAA coexistence in the CBRS band: Performance evaluation of Approach 3," in *Proc. 45th LCN Symposium*. IEEE, Nov. 2020, pp. 39–47.

[13] W. Gao and A. Sahoo, "Performance impact of coexistence groups in a GAA-GAA coexistence scheme in the CBRS band," *IEEE Transactions on Cognitive Communications and Networking*, vol. 7, no. 1, pp. 184–196, Mar. 2021.

[14] Baicells, Inc., Available at https://na.baicells.com/product/details?id=95e4cc20-15f8-42cb-921a-ff0e9298bb35#file (Accessed: 05/31/2023).

[15] UC San Diego Park & Market Building, Available at https://parkandmarket.ucsd.edu/ (Accessed: 05/31/2023).

[16] UC San Diego Atkinson Hall, Available at https://blink.ucsd.edu/sponsor/advancement/advancement-services/stewardship/named-buildings/atkinson-hall.html (Accessed: 05/31/2023).

[17] Baicells HaloB, Available at https://img.baicells.com//Upload/20210617/FILE/193a160b-8288-4947-9fa2-26d81ba611f5.pdf (Accessed: 05/31/2023).

[18] Baicells, Inc., Available at https://na.baicells.com/ (Accessed: 05/31/2023).

[19] KP Performance, Inc., Available at https://www.kpperformance.com/ (Accessed: 05/31/2023).

[20] Mark A. Pinsky and Samuel Karlin, *An Introduction to Stochastic Modeling*, 4th ed. Academic Press, 2011.

[21] Oliver C. Ibe, *Markov Processes for Stochastic Modeling*, 2nd ed. Elsevier, 2013.

[22] Sheldon M. Ross, *Introduction to Probability Models*, 12th ed. Academic Press, 2019.

[23] J. R. Norris, *Markov Chains*, 1st ed. Cambridge University Press, 2012.