Collaborative GAA Clusters in Emerging Three-Tiered Spectrum Markets

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***Abstract*—Evident by the Federal Communications Commission's (FCC) incorporation of a light leasing approach, high utilization of the Citizens Broadband Radio Service (CBRS) spectrum can be achieved by the commercial Priority Access License (PAL) operators sharing resources with unlicensed General Authorized Access (GAA) users. However, proper integration of PAL operators and GAA users into this new three-tiered CBRS spectrum sharing market is an open issue. This work introduces a collaborative GAA-clustered framework to facilitate such integration. We propose GAA users form multiple distinct geographical clusters and utilize the CBRS spectrum collaboratively rather than through individual access requests. Each cluster will nominate a central entity called the GAA leader, who will directly communicate with the PAL operators regarding CBRS spectrum access and set up the necessary PAL-GAA connections. Such direct communication will reduce the messaging overhead between the central CBRS Spectrum Access System (SAS) and the users across PAL and GAA levels, providing a reliable and convenient spectrum-sharing platform. Here, we propose a novel leader selection algorithm (LSA) that uses a GAA user's network density and perceived signal strength to assign a Leader Evaluation Score (LES) to evaluate and nominate the GAA user with the highest score as the cluster leader.**

***Index Terms*—Spectrum Sharing, Network Economics, CBRS Sharing, Collaborative Network, Spectrum Management.**

I. INTRODUCTION

Owing to the widespread increase in the usage of mobile devices and the exponential growth of wireless data traffic, the limited sub-6 GHz spectrum that these devices operate in has become congested and scarce. To cope with this scenario, the US Federal Communications Commission (FCC) has taken the initiative to open up 5 GHz of the federal spectrum in the ultra-wideband, and the mid-band frequency ranges for commercial purposes [1]. In addition, the already auctioned-off and operational three-tiered Citizens Broadband Radio Service (CBRS) offers a unique prospect because it allows commercial operators and unlicensed users to share spectrum with federal incumbent users in the 3.5 GHz band [2]. The three tiers of CBRS are 1) Incumbent users, e. g., naval radars, fixed satellite services, operating in the 3,550-3,700 MHz range; 2) Priority Access License (PAL) operators, operating in the 3,550-3,650 MHz range and consisting of the licensed users, and 3) General Authorized Access (GAA), consisting of opportunistic unlicensed users, who can operate across the entire CBRS band [3]. The spectrum sharing and interference protection of upper-tier users from lower tiers are controlled by a central entity called Spectrum Access System (SAS).

A distinctive characteristic of CBRS is the FCC's adoption of a light leasing approach for the band [4]. As a GAA user, anyone with a CBRS device can access the spectrum. As a result, the unlicensed use of the CBRS spectrum is expected to be the most congested tier. In addition, PAL operators can also use unlicensed access to offload some of their data traffic, exacerbating the congestion at the GAA tier. Thus, leasing of PAL-licensed spectrum to the unlicensed GAA tier will play an essential factor in the optimum utilization of the CBRS band. Under the current CBRS sharing approach, GAA users must submit requests for spectrum access over a limited duration to the SAS individually, which then stores and relays that information using a centralized database to the PAL operators [5]. This process brings a new challenge: submitting individual GAA access requests through a centralized SAS can be prone to a single-point failure affecting a high volume of users, either due to the malfunction of SAS servers or malicious users' infiltration of such servers. This can result in GAA requests being transmitted indiscriminately to PAL operators, making it difficult for them to estimate the probable number of requests they may receive over a certain period [6].

To address this issue, we propose a collaborative GAA clustering approach for CBRS sharing. The users at the GAA tier form distinct local clusters and act as a single entity when requesting to access the CBRS spectrum. These clusters will directly communicate with the PAL operators and, upon having their requests approved, will correspond to the SAS for final approval. In addition, each cluster will elect a central entity, called the GAA leader, to communicate to submit access requests on behalf of cluster members. The leader can also negotiate and set up necessary links with PAL access points, which cluster members can use to communicate outside the cluster network. The key contributions of this work are as follows:

1) Trusted GAA-clustered access to the CBRS spectrum. The GAAs are grouped into multiple geographically distinct regions and operate through a trusted central controlling unit called the GAA leader. The leader communicates with PAL and SAS for spectrum sharing operations to maximize the overall utility of a cluster and keeps cluster data secure.

2) Development of a leader selection algorithm (LSA). It uses the GAA users' network density and the PAL's services available to the GAA users. We determine the Leader Evaluation Score (LES) to select a GAA with the highest score as the cluster leader for a specified period.

The rest of the paper is as follows: Section II includes current undertakings from the literature on CBRS and leader selection in distributed systems. Section III provides a brief outline of the PAL-GAA collaborative CBRS access model. Section IV illustrates the formulation and working procedure of the LSA. Section V shows the performance results. Finally, Section VI concludes the paper.

II. Related Work

Hyper-graph-based CBRS spectrum allocation models for secondary sharing can offer improved revenue to the PAL operators compared to the interference avoidance method [7]. Such sharing method was further enhanced in [8]. It utilized an online deterministic algorithm based on a modified version of the ski-rental problem. It assisted operators in making optimum decisions regarding the number of opportunistic channels to be leased and the number of customers to be served through those channels.

Effective and scalable use of SAS has been a central challenge for the three-tiered CBRS spectrum access. Approaches for opportunistic access to the PAL spectrum by GAA were proposed in [9] using Q-learning, based on a listen-before-talk scheme. These frameworks significantly improved the secondary node's utility at the cost of minor degradation of the primary nodes. A distributed blockchain model for CBRS was explored in [10], which relocates the SAS responsibilities to PAL for a more cost-effective approach. The authors also used a reinforcement learning-based consensus strategy to optimize the number of GAA service requests the PAL responds to. However, these models didn't consider collaborative GAA access, thus leaving room for improvement.

Multiple leader selection algorithms for distributed networks were proposed in [11] for synchronous and asynchronous systems. These include 1) the secure extrema finding algorithm, which uses a single evaluation function for all nodes to select the leader, 2) the secure preference-based leader election algorithm, which uses different utility functions for various nodes to determine individual node's leader preference and aggregate them to elect a single system-wide leader, and 3) the asynchronous extrema finding algorithm which employs diffusing computation and is capable of handling topological changes during the election process. In addition, for distributed cognitive radio networks, [12] proposes a novel evaluation function for leader selection consisting of each node's remaining energy capacity, cluster density, and the number of neighboring nodes within the communication range of a particular candidate node.

To the best of our knowledge, proposed work is the first collaborative GAA-clustered access in the CBRS spectrum where PAL gets incentives for sharing. However, details of the PAL operator's incentives are outside of this paper's scope and are being carried out separately. Instead, we focus on the GAA-clustered access and leader selection for such CBRS-sharing.

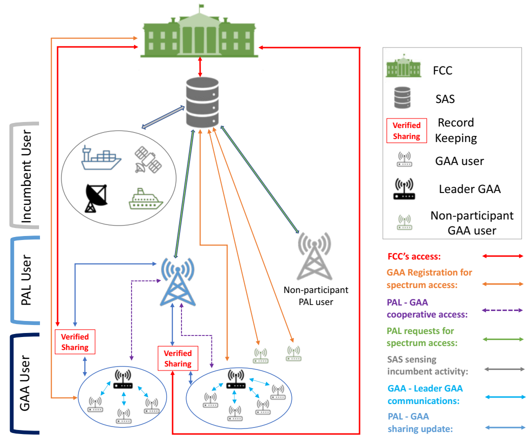


Fig. 1: PAL-GAA Collaborative CBRS Framework.

III. System Model

We propose a clustering approach in the GAA tier of the CBRS band that facilitates spectrum sharing with PAL operators. These clusters are located in geographically distinct sites spread over a service region, with cluster requests managed by an entity, the GAA leader. Any GAA user within the cluster is eligible to become a leader, and this selection is made periodically.

The leader will accumulate all spectrum use requests from the cluster members and transmit them directly to the PAL operators over fixed intervals. PAL operators are free to choose any portion of those requests, which will be communicated to the leader, who will relay the information to the rest of the cluster. Upon gaining acknowledgment from PAL for spectrum access, the GAA leader will notify the SAS. The SAS will be able to ensure the legitimacy of the cluster/leader through its centralized database and offer final approval providing no interference is caused to the incumbent users by adding the GAA users. Upon authorization from the SAS, GAA users start using the PAL-licensed spectrum. To encourage PAL operators to allow GAA access to their spectrum without charge, we consider incentive models [13] that reward PAL operator based on the level of sharing. The proposed model is illustrated in Fig. 1.

Suppose a set of G GAA clusters denoted by $\mathcal{G} = \{1, 2, 3, ..., g\}$ and a set of P PAL operators denoted by $\mathcal{P} = \{1, 2, 3, ..., p\}$ are participating in our proposed PAL-GAA collaborative CBRS spectrum sharing. The GAA clusters aim to optimally distribute GAA users to various access points of the PAL operators, ensuring the overall best suitable utility. We consider $u(x_{dp}, b_{dp})$, an increasing concave function to determine the received utility of user d of cluster p and define it as follows

$$u(x_{dp}, b_{dp}) = \theta x_{dp} \sqrt{\Psi_{dp}}. \quad (1)$$

Here, x_{dp} is the number of access points and b_{dp} is the bandwidth of PAL p made available to the user. Ψ_{dp} is a function of available bandwidth and expressed as an average signal strength at user d by utilizing approach depicted in [14].

$$\Psi_{dp} = \frac{1}{x_{dp}} \sum_{k=1}^{x_{dp}} \frac{1}{d_{kp}^2} \tag{2}$$

where d_{kp} is the distance from user d to PAL p's k'th access point. θ is a smoothing factor > 0, used to control the sensitivity of $u(\cdot)$ to x_{dp} and Ψ_{dp}.

The perceived utility can be affected negatively due to the increase in congestion for supporting additional GAA users in the same band. To quantify this effect, we propose *cost of sharing*, $c_{gp}(x_{gp}, b_{gp})$, which is essentially the PAL p's service degradation due to the congestion caused by the presence of cluster g's users. Where x_{gp} is the number of access points and b_{gp} is the bandwidth of PAL p made available for sharing with cluster g. We formulate $c_{gp}(\cdot)$ as follows:

$$c_{gp}(x_{gp}, b_{gp}) = \begin{cases} x_{gp} e^{-\frac{b_p}{b_{gp}}}; & x_{gp} > 0, 0 < b_{gp} \leq b_p \\ 0 \quad ; & x_{gp} = 0, b_{gp} = 0. \end{cases} \tag{3}$$

Here, b_p is the total licensed bandwidth of PAL operator p. High values of x_{gp} and b_{gp} allow the operator to support more GAA users. But it will reduce the effective utility received by the users due to an increase in congestion, meaning a higher sharing cost, while decreasing or lower values mean the operator can support a smaller number of GAA users, thereby reducing the negative impact of the GAA users on the effective utility in PAL's network, i.e., a low sharing cost. The cost is 0 when a PAL operator does not share any bandwidth and access points with GAA users, while the highest value, x_p/e, obtains when the PAL shares all access points with the entire available spectrum.

If PAL operator p shares its spectrum with all G clusters, the average utility received by the GAA user d of cluster g after incorporating sharing costs becomes:

$$U_{dp} = u(x_{dp}, b_{dp}) - \sum_{g=1}^{G} c_{gp}(x_{gp}, b_{gp}) \tag{4}$$

The objective of the GAA clusters will be to appropriately distribute their users across different PAL operators, which maximizes the overall cluster utility. In doing so, each user's perceived utility contributes to making a GAA user the cluster leader, which we formulate next.

IV. GAA Leader Selection

The GAA leader serves as a central communicating medium between the PAL operators and GAA clusters which is essential for the optimum performance of the shared CBRS spectrum. To elect the leader, we propose a distributed leader selection algorithm (LSA), based on the approach of termination detection in diffusing computation depicted in [15], [16]. These algorithms form a Spanning Tree (ST) stemming from a primary source user within the network toward the terminal users. In our case, the primary source user can be the GAA leader of a cluster from the immediately previous time frame of spectrum access or randomly selected any GAA

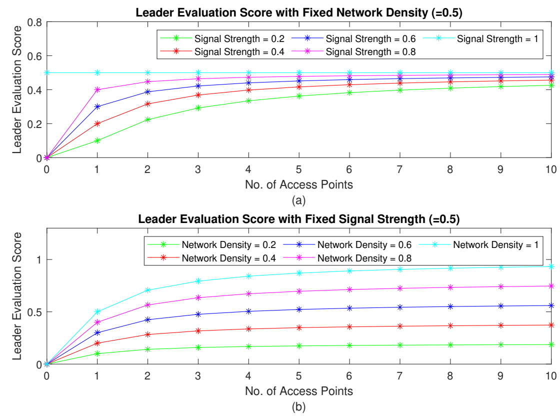


Fig. 2: Leader Evaluation Score

user of that cluster at the beginning of this process when no leader is available. The source user (GAA leader) initiates the election procedure by sending an election initiation message to its direct neighbors (GAA users), who do the same to their immediate neighbors until all network users have been covered. Upon receipt of the message, each GAA user calculates his eligibility to become the leader using the leader evaluation score (LES). Finally, the scores backtrack through the spanning tree to the primary source user, which evaluates all LES and selects a new cluster leader with the highest score.

A. Leader Evaluation Score (LES)

The LES is used to determine and compare the worthiness of a user d within a GAA cluster g to become the leader. Every user will calculate its LES once the election initiation message is received. The LES of user d, L_{dg}, is formulated as the following:

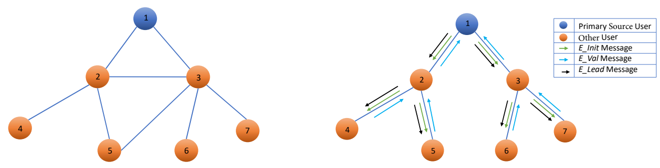
$$L_{dg} = \eta_{dg}(\Psi_{dp})^{\frac{1}{x_{dp}}} \tag{5}$$

Here, η_{dg} is the network density of user d, which is the ratio of the number of users it can directly communicate with to the total number of users in the cluster g. The inverse of x_{dp} is used in determining Ψ_{dp} to signify the importance of the number of access points accessible to user d on LES. A large number of access points will allow data traffic to be distributed more sparsely, offering a better utility because of reduced congestion. It also ensures that more users can use the PAL spectrum resources. The value of L_{dg} ranges in $[0, 1]$. We visualize the effect of η_{dg}, x_{dp}, and Ψ_{dp} on L_{dg} in Fig. 2. L_{dg} rises with the increase of any of the three parameters. The results become concave with the rise of the access points in all cases, similar to our utility function, proving the LES's adequacy for the leader election process.

B. Assumptions

We considered following assumptions for the GAA leader selection process:

- Each cluster consists of multiple GAA users, which can serve as access points for others users if needed, with every user having the ability to become a leader.
- The users communicate using bidirectional links with the same link capacity.



(a) Cluster Connection (b) Cluster Spanning Tree

Fig. 3: GAA cluster configuration.

- All the users have unique IDs which can be used to distinguish them during the election process.
- Each user maintains a routing table containing information regarding its ID and LES, the ID of its primary source user, the ID and LES of its neighbors, and the ID field for the newly elected leader.
- All users are active during the election process, and the leader from the previous iteration initiates the election.

C. Used Messages

Our proposed algorithm creates and uses three types of messages to communicate between GAA users through the spanning tree during the election.

1) **E_Init**: The election initiation message indicates the start of a new election process. After a cycle of spectrum access, the primary source user, aka leader GAA will send an E_Init message to its immediate neighbors to start the election process, who will forward it to their neighbors except for the sender of this message and repeat until reaching the terminal GAA users of the network. Each E_Init will contain the unique ID of the primary source user and the ID of the user from which it receives the E_Init.

2) **E_Val**: The evaluation message is used to transmit LES to a user's immediate E_Init message sender. After receiving an E_Init, each user will calculate its LES using (5). LES backtracks from the terminal users to the primary source users through intermediate users. Each intermediate user will wait to receive the E_Val messages from all its neighbors, after which it will compare their scores with its own and send an E_Val message to its E_Init message sender containing the maximum value of LES with the corresponding user ID. This process continues until the primary source user is reached, where E_Val message propagation stops.

3) **E_Lead**: This message is used to inform cluster members about the leader. Once the primary source user receives all the E_Val messages, it will select the user with the maximum LES as the leader, whose ID will then be transmitted using the E_Lead to all users.

D. LSA Illustration

Using assumptions and messages mentioned above, we summarized our developed LSA in Algo. 1. To illustrate LSA, we consider a network shown in Fig. 3, consisting of 7 users, with IDs ranging from 1 to 7. Assume user 1 was the leader of the immediately previous time frame (or got selected randomly at the beginning) of spectrum access and will initiate a new election by sending an E_Init containing its ID to neighboring users 2 and 3, who will use that E_Init to update the source entries of their tables and send new E_Init to their immediate neighbors {4, 5} and {6, 7} respectively, compute their LES and wait for the response of the later users.

Algorithm 1 Leader Selection

1: X_{id} ←Store all the IDs ▷ Assign unique IDs to all users
2: X_{dc} ← List of all directly connected users to each cluster member ▷ Define user connections within the cluster
3: X_n ←Network densities of all users
4: δ ← Maximum service region around each PAL access point ▷ Identify Signal Strength
5: X_{ap} ← Number of access points accessible to each user
6: $s_{pi} = rand(X_{id})$ ▷ Select primary source user and store primary source ID
7: $s_{pc} = X_{dc}(s_p)$ ▷ Store directly connected user IDs of primary source
8: **while** $i \leq length(s_{pc})$ **do**. ▷ Initiate new leader selection process
9: Send $E\_Init(s_{pi}, s_{pi})$ to $s_{pc}(i)$
10: **if** $X_{dc}(s_{pc}(i)) == 1$ **then**
11: Calculate and store LES of $s_{pc}(i)$ in η
12: Send $E\_Val(s_{pc}(i), \eta)$ to source
13: **else**
14: Send $E\_Init(s_{pi}, s_{pc}(i))$ to all $X_{dc}(s_{pc}(i))$
15: Calculate and store LES of $s_{pc}(i)$ in η
16: Store number of E_Vals received in n_e
17: **if** $n_e == length(s_{pc}(i)) - n_r$ **then**
18: L_p ← max (LES from all E_Val's, η)
19: L_{id} ← ID of the user with the max LES
20: Send $E\_Val(s_{pc}(i), \eta)$ to s_{pi}
21: **else**
22: Repeat steps 10-20 for all $X_{dc}(s_{pc}(i))$ and subsequent neighbors
23: **end if**
24: **end if**
25: $i = i + 1$
26: **end while**
27: L_{FS} ← max(LES from all E_Vals of s_{pc})
28: L_F ← ID of the user with maximum LES from all E_Vals of s_{pc} ▷ New leader selection
29: Send $E\_Lead(L_F)$ to all users

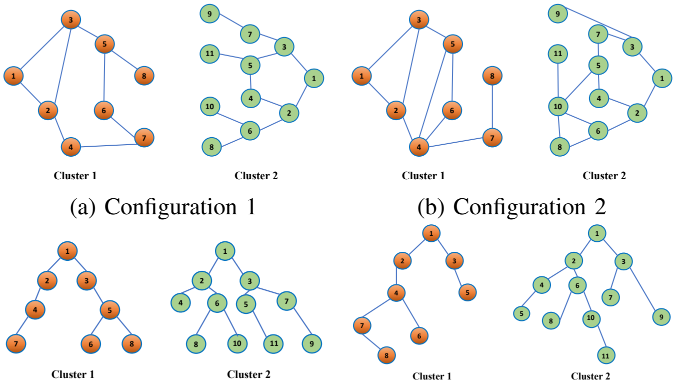
User ID	Source ID	LES	Intermediate User Info		Max(LES)	Max(LES) ID	New Leader
			ID	LES			
2	1	0.49	4	0.25	0.51	5	3
			5	0.51			
User ID	**Source ID**	**LES**	**Intermediate User Info**		**Max(LES)**	**Max(LES) ID**	**New Leader**
			ID	LES			
3	1	0.72	6	0.32	0.72	3	3
			7	0.55			

Fig. 4: Routing tables of users 2 and 3

After receiving the E_Init, users 4, 5, 6, and 7 will compute the LES and send an E_Val message to their respective sources, containing their IDs and LES scores. Once users 2 and 3 receive all the E_Val messages from their neighbors, they will update their LES into their tables, compare the scores with their own, and send the maximum score with the ID of the user with that score using a new E_Val to the primary source user 1. User 1 will then compare the scores and select the user with the maximum LES as the leader. The ID of the new leader will then be transmitted using the E_Lead message. A completed table for users 2 and 3 are depicted in Fig. 4.

V. Simulation Results

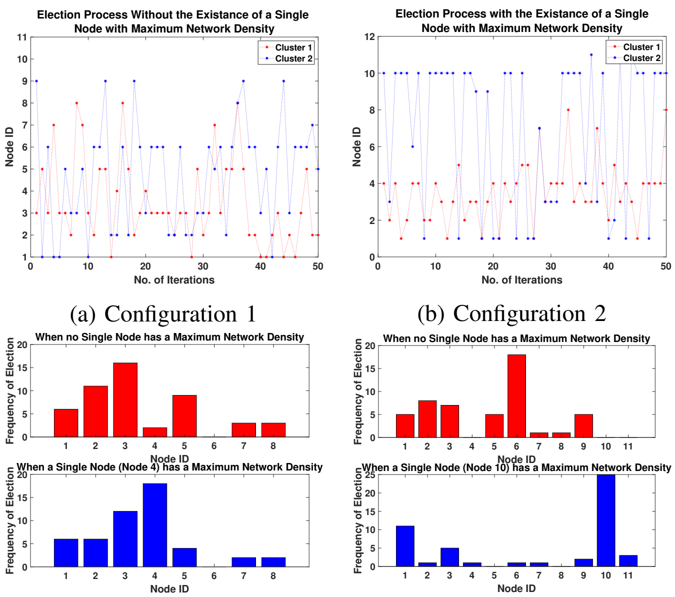
We consider a 30 x 30 square grid in MATLAB as an experimental region to evaluate LSA. It is populated with 20 access points and two clusters. The access points are distributed equally between two PAL operators, PAL 1 and 2, and placed randomly, with a higher density near the center compared to the edges. The positions of the two clusters are



(a) Configuration 1 (b) Configuration 2

(c) STs of Configuration 1 (d) STs of Configuration 2

Fig. 5: GAA cluster configurations.



(a) Configuration 1 (b) Configuration 2

(c) Cluster 1 election frequency (d) Cluster 2 election frequency

Fig. 6: Election process through LSA

fixed, with cluster 1 being placed near the region's center, while cluster 2 is close to the right-hand edge. Each unit of distance within the grid equals 100 meters, and the service region around each access point was set to 450 according to the data obtained from Verizon [17]. We set smoothing factor, $\theta = 10$ for all cases.

A. Evaluation of LSA

We consider two different configurations for two GAA clusters. In configuration 1, no particular cluster user has a maximum network density in both clusters and in configuration 2, a specific user obtains a maximum density. In configuration 1, users 2, 3, and 5 of cluster 1, and 2, 3, 5, and 6 of cluster 2 are provided with the maximum number of direct connectivity to other users, which is three links, i.e., have a maximum network density, Fig. 5a. In contrast, for configuration 2, users 4 and 10 in clusters 1 and 2 have peak network densities of four directly connected links to other users, Fig. 5b.

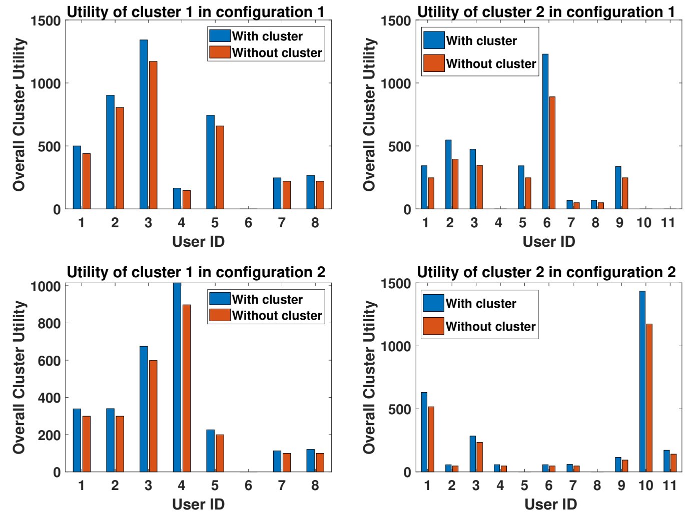


Fig. 7: Utilities in traditional and proposed clustered approach

The simulation ran for 50 iterations for both configurations, with different positioning of access points. The election process results are depicted in Fig. 6. For configuration 1, Fig. 6a, the selection process appears random depending on the PAL access point distribution for any particular iteration. Particularly for cluster 1, where users 2 and 3, both having the peak user densities for that cluster, are selected more often. For cluster 2, node 6 appears as the runaway leader, followed by user 2, elected twice as more. But in configuration 2, Fig. 6b, node 4 in cluster 1 and user 10 in cluster 2, who have the highest values of network density within their respective clusters, are elected the most and by a large margin, in the case of cluster 2 particularly. Thus, when multiple users within the cluster have the same peak network density, the leader is selected based on the total signal strength available to the users, i.e., their proximity to and the number of PAL access points they can access. But if a particular cluster member achieves a peak network density, that user is more frequently elected.

We get the overall cluster utility over the entire simulation period by considering the number of users in a cluster and their frequency as elected leaders. The results of the obtained overall utility are depicted in Fig. 7, where it is compared with the utility from the traditional CBRS approach for both configurations. Regardless of which user is the leader, the clustered model outperforms the current model across the entire simulation process. Because, under the traditional approach, when GAA users are not within the coverage region of any PAL access point, they are unable to use the spectrum rendering their utilities to 0, whereas, in our proposed model, they can gain access to the PAL spectrum using the links set up by the GAA leader, obtaining a higher utility, proving the effectiveness of our clustered model. Now for some of the users, the utilities in the graphs are 0 because they are never elected during the entire simulation. Also, the users that are more frequently elected using LSA tend to offer a higher overall utility simply because they are in operation as a leader for a longer duration (more iterations).

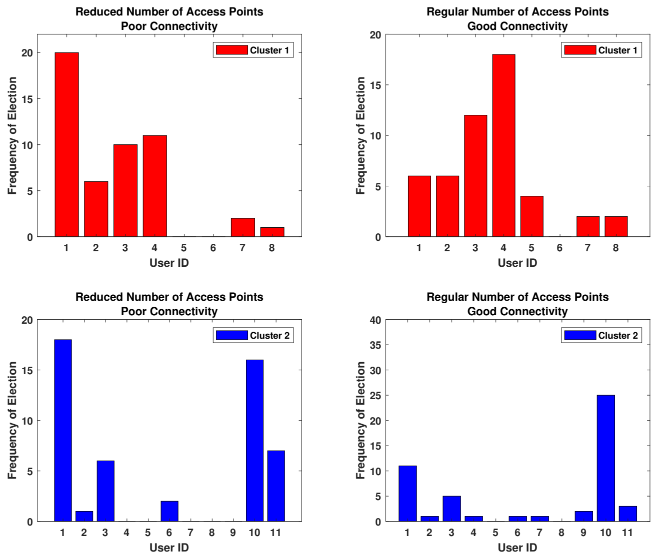


Fig. 8: Election frequencies in various networking conditions

B. Effects of Poor Infrastructure on Election Process

To evaluate our model in poor networking conditions, i.e., a reduced number of access points and poor signal strength, we change the distribution of the access points so that fewer access points are in proximity of the GAA clusters. Using these settings, we simulate configuration 2 for both clusters, and the results are depicted in Fig. 8.

User 1 in cluster 1 becomes the most selected leader despite having half the network density of user 4. Similarly, user 1 in cluster 2 overtakes user 10 as the most frequently elected leader, although node 10 is closely behind. The reason for that can be attributed to the positioning of the clusters. Cluster 1 was placed in the center of the map and thus had a higher number of access points surrounding it in good networking condition. In contrast, cluster 2 was situated close to the edge and had fewer access points accessible to it. Therefore, changing the network configuration to simulate poor networking conditions does not affect cluster 2 as profoundly as cluster 1, although a new user becomes the most probable leader in both cases. Thus, it can be hypothesized that, under good networking conditions, network density plays a more defining role in electing the leader. On the contrary, the signal strength becomes prominent in poor conditions with less accessible networking infrastructure.

VI. Conclusions and Future Work

In this work, we propose a novel approach for CBRS sharing where GAA users form clusters and act as a single entity for spectrum-sharing purposes with PALs. Each cluster nominates a central figure called the GAA leader for effective communication between the GAA users and PAL operators. We propose a distributed leader selection algorithm, LSA, for the leader election, which considers each cluster user's signal strength and network densities. Our model outperforms the current sharing approach in the CBRS GAA tier in both good and poor networking conditions. We aim to extend our procedure to work with clusters having inactive or sudden out-of-reach users in the future. We would also like to explore the effects of the link capacities used by the GAAs to communicate between them within the clusters. Finally, we leave the election process with dynamic link capacity and how the link costs associated with these communications affect the overall utility of the clusters as future works.

Acknowledgments

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