Fostering Collaboration in Emerging Three-Tiered Spectrum Markets

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***Abstract*—The Federal Communications Commission (FCC) recently deployed the Citizens Broadband Radio Service (CBRS), a three-tiered spectrum-sharing approach that allows incumbent federal users to share the 3,550-3,700 MHz band with commercial users. In addition, the FCC also aims to encourage licensed providers, called the Priority Access License (PAL), to lease/share their licensed spectrum with unlicensed users, named the General Authorized Access (GAA), for a limited duration, by adopting a light leasing approach. In this paper, we aim to facilitate PAL-GAA collaborative spectrum access by proposing a novel clustered framework where the GAA users are grouped into multiple distinct geographical clusters and request access to the CBRS spectrum resources through the clusters collaboratively rather than individually. This process reduces the control messaging overhead between the CBRS controller and licensed and unlicensed entities, providing a convenient platform for licensed spectrum sharing. Also, submitting aggregated requests from multiple users rather than individuals will allow PAL operators to estimate the data traffic that their network may experience due to sharing. Later, PALs can make arrangements to allocate appropriate spectrum resources for sharing to the GAA layer. Finally, to encourage PALs to share, we also propose a government incentive model where PALs are allotted additional bandwidth for a limited span to be used as an extension to their licensed spectrum based on their level of sharing.**

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

I. Introduction

With the deployment of 5G, in a bid to cope with the ever-increasing wireless data traffic demand and shortage of frequencies available for wireless networks, the Federal Communications Commission (FCC) has approved the sharing of the Citizens Broadband Radio Service (CBRS) spectrum. This three-tiered environment offers users access to the 3.5 GHz band previously occupied by the U.S. Department of Defense (DoD). The tiers are 1) Incumbent Users (IU), e.g., naval radars, fixed satellite services, etc., 2) Priority Access License (PAL) users, and 3) General Authorized Access (GAA) users [1], Fig. 1. PAL users are provided licensed access to the spectrum, which is obtained via competitive auctions. They are provided on a county basis, with a maximum of 40 MHz per PAL per county, where 70 MHz are licensed to all PALs from 100 MHz that can be allocated for PAL use [2]. GAAs are opportunistic users and can use any spectrum not occupied by the other two layers. Finally, a central entity called Spectrum Access System (SAS) ensures interference protection to upper-tier users from lower levels.

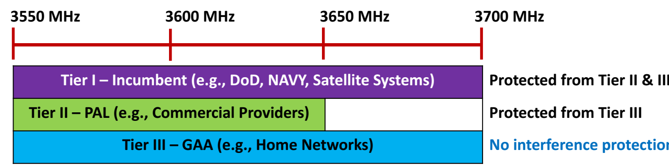


Fig. 1: 3-Tiered CBRS Sharing [6].

A convenient way to offer up licensed spectrum to secondary users for a limited period is essential for the optimum utilization of the CBRS spectrum, evident by the light leasing approach incorporated by the FCC. However, the current practice of CBRS sharing for that purpose is not adequate as 1) GAAs have to submit their requests for licensed access through the SAS, who then transmit those requests to the PAL operators, thus gaining access to the spectrum becomes time-consuming for GAAs [3], 2) the SAS stores and forwards the requests to PALs through centralized servers, which can suffer from single-point failures due to server malfunction or infiltration from malicious users affecting a high volume of users, making it difficult for a PAL to predict the total GAA traffic that they may receive over a fixed period, rendering them unprepared to support that increased data traffic [4], and 3) there are no incentives for PAL operators to share their spectrum, which would result in increasing the congestion in the unlicensed band, negatively affecting the performance of the GAA users [5].

We propose a GAA-clustered CBRS model to address these issues, where the GAA users are grouped into multiple geographically distinct clusters. These clusters will act as a singular body while requesting licensed spectrum access through PAL infrastructure. Each cluster accumulates all user requests within and directly submits to PAL operators using an entity called the GAA leader elected from the related cluster's user pool. This will allow PAL operators to understand the number of GAA users interested in using their spectrum. It also enables them to decide on accepting access requests accordingly so that it does not negatively impact their customers in terms of congestion while allowing them to offer up spectrum in convenient and secure settings. To encourage PALs to share CBRS bandwidth, we propose an incentive model where PAL operators are provided with the additional spectrum for limited access. It will be a free extension to their licensed spectrum. This paper primarily focuses on the economic viability of the clustered approach by evaluating PAL operators' participation and revenues. The contributions of this work are as follows:

- A novel CBRS sharing approach, where GAA users are grouped into distinct clusters, each acting as a single entity while requesting spectrum access from PAL for a certain period.
- Formulation of a government incentive model in the form of PAL operators' free access to additional bandwidth from the CBRS or other mid-band spectra for a limited period according to their level of sharing.
- Modeling PAL's revenue depending on selecting the optimum subscription fees and allocating CBRS bandwidth to clusters, for maximizing revenues.

The rest of the paper is as follows: Section II illustrates current undertakings in CBRS spectrum sharing. Section III exhibits our proposed model, PAL operators' objectives, and the government reward model. Section IV depicts our formulation of a simplified two-PAL CBRS sharing structure and related procedures to solve the objective functions. Section V illustrates the results of the framework simulation. Finally, Section VI concludes the paper.

II. Related Work

Majority of research on CBRS sharing has focused on operators' revenue or profit maximization using graph or game theory models. An optimum spectrum allocation method was proposed in [7] for the secondary spectrum market using hypergraph-based models, which provides improved area coverage and profit from sub-licensing over the traditional interference avoidance method. [8] and [9] depicts an improved approach to such graphical methods, where the authors propose an online deterministic algorithm, which is based on a modified version of the ski-rental problem (SRP) [10] and aims at maximizing profits of operators in CBRS. The developed algorithm assists the operators in making decisions on the optimum value of the intended number of channels to be leased, the number of customers to be served through opportunistic channels, and the customer demand to be rejected in a specified time frame. Similar profit or revenue optimization problems for commercial operators were also explored in [11] and [12] with the help of game theory.

Machine learning methods have been explored for designing access strategies in the three-tiered spectrum markets. Opportunistic channel access approaches were proposed in [13], [14], allowing GAA users to use the PAL spectrum based on listen-before-talk (LBT) schemes. Furthermore, to mitigate the negative impact of such sharing has on PAL users, a Q-learning algorithm is also proposed to modify the level of channel access. These frameworks significantly increased the user utility of the secondary nodes (GAA users). Reinforcement learning was used, [15], to develop a consensus strategy that optimizes the number of GAA service requests the PAL responds to and individual PAL operators' own customer service with security for the GAA users.

The effects of government rewards in shared spectrum networks were observed and showed utility improvement for

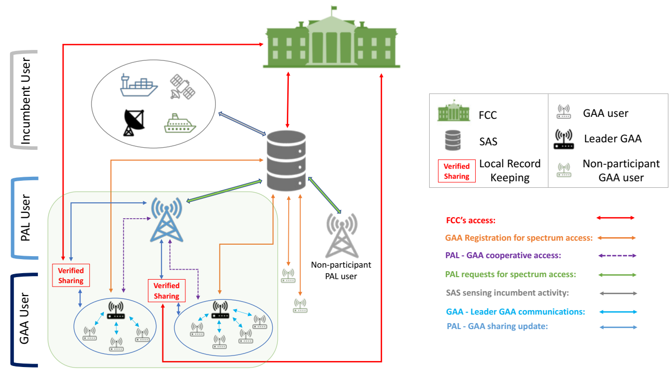


Fig. 2: PAL-GAA Collaborative CBRS Framework.

operators and customers in [16]–[18]. Using these incentive-design concepts from our earlier work, we explore the viability of more collaboration among GAA users in the emerging CBRS markets. To the best of our knowledge, this is the first study to consider explicit incentives for collaboration in three-tiered spectrum markets.

III. System Model

Our proposed model is depicted in Fig. 2. The GAA users form clusters across the region and communicate with the PAL operators through the GAA leader for submitting licensed CBRS spectrum access requests. PAL operators can choose their preferred portion of these requests and exchange that decision with the GAA leader, who then communicates it to the SAS for final authorization to ensure interference protection for IU. Once authorized, GAA users can use the PAL-licensed spectrum using their own network facilities and communicate outside the GAA cluster through the PAL access points by setting up essential PAL-GAA links. If any GAA user is outside the coverage region of available PAL access points, it will use the link set up by the leader for licensed access. We primarily consider the PAL-eligible CBRS spectrum (100 MHz) portion in our model for simplicity. However, the GAA leader must communicate with the SAS to access the spectrum available only to IU and GAA users. Any PAL or GAA not wanting to participate in this framework will follow the current CBRS approach for spectrum access.

Let us consider a county where C number of GAA clusters are denoted by $\mathcal{C} = \{1, 2, 3, ..., c\}$, and J number of PAL operators are denoted by $\mathcal{J} = \{1, 2, 3, ..., j\}$, with the total number of PAL subscribers being $\mathcal{N}_p$. A list of all symbols used in the paper is given in Table I.

A. PAL Subscribers' and GAA Users' Problem

Subscribers of PAL operators are required to pay a fee to avail of their services. Hence their goal is to select the operator that matches their service requirements. This service can be formulated as the utility received from using the operators' infrastructure, such as access points and bandwidth minus the fee paid to procure the service [16], [17], and this can be expressed as follows:

$$\mathcal{U}_j = u(x_j, b_j) - f_j \tag{1}$$

TABLE I: Symbols and Notations

Symbol	Description
$\mathcal{C}$	Set of clusters
$\mathcal{J}$	Set of PAL operators
$\mathcal{N}_p$	Number of total PAL subscribers
$\mathcal{U}_j$	PAL j's subscribers' utility in a non-sharing market
$\mathcal{U}_{ej}$	PAL j's subscribers' effective utility in a shared market
$\mathcal{U}_{cj}$	Cluster c's users' effective utility from PAL j's service
$u(.)$	Utility function
δ	Scaling factor
x_j	PAL j's number of access points
x_{cj}	PAL j's available access points for cluster c
b_j	PAL j's available bandwidth
f_j	PAL j's subscription fee
z_{cj}	PAL j's sharing cost for to cluster c
b_{cj}	PAL j's shared bandwidth with cluster c
$\mathcal{P}_j$	Probability of subscribing PAL j
$\mathcal{P}_{cj}$	Cluster c's users' probability of selecting PAL j
i_{cj}	Number of requests submitted to PAL j from cluster c
n_c	Number of GAA users in cluster c
n_j	PAL j's number of subscribers
α_{cj}	% of requests accepted by PAL j from cluster c
n_{cj}	Number of requests accepted by PAL j from cluster c
R_j	Revenue of PAL j from subscription fees
R_{rj}	PAL j's total reward revenue
r_j	PAL j revenue from serving a single GAA user
μ_j	PAL j's subscription revenue from each unit of bandwidth
$\otimes_{\mathcal{T}}$	Available total reward bandwidth
Ω_j	Reward bandwidth obtained by PAL j
t_{cj}	Total duration of cluster c's spectrum access from PAL j
w_{cj}	Cluster c's willingness to switch to PAL j
m_{cj}	Number of migrating users to PAL j from cluster c

where, $\mathcal{U}_j$ is the net utility received by a subscriber from operator j, and $u(x_j, b_j)$ is the utility function which is a measure of the quality of the experience received from using j's services. It has concave characteristics and is dependent on the bandwidth, b_j, and the number of access points, x_j, made available to the subscriber by operator j, and f_j is the monthly subscription fee paid by the subscriber. To obtain the utility function, we follow a similar method depicted in [16], which also defines a concave utility function and formulate it as:

$$u(x_j, b_j) = \delta x_j \sqrt{b_j} \tag{2}$$

where, $\delta << 1$ is a scaling factor used to control the curvature of the utility function.

In hindsight, it would make sense that the users choose the operator with the highest value of $\mathcal{U}_j$ as it provides the highest utility, though that is not the case. Because the expression in eq. (1) leaves out other network parameters that affect customer experience. Instead, their selections can be made in a probabilistic manner based on the Contest Theory [19]. However, to determine the probability, we need to incorporate the effects of sharing on the perceived utility of the PAL subscribers. We propose a measure called the cost of sharing, $z_{cj}(x_{cj}, b_{cj})$, which is essentially the performance degradation at the PAL's network due to the congestion caused by the presence of additional users from the GAA cluster c. x_{cj} is the number of PAL j's access points shared with cluster c. For simplicity, we assume PAL j shared the same bandwidth b_{cj} with c across all shared access points. We formulate $z_{cj}(\cdot)$ as follows:

$$z_{cj}(x_{cj}, b_{cj}) = \begin{cases} x_{cj} e^{-\frac{b_j}{b_{cj}}}; \text{when } x_{cj} > 0, 0 < b_{cj} \leq b_j \\ 0 \qquad ; \text{when } x_{cj} = 0, b_{cj} = 0. \end{cases} \tag{3}$$

We adopted this form of $z_{cj}(\cdot)$ to maintain the concavity of the utility function and define the GAA users' objective as an optimization of diminishing returns as the PAL operator shares more bandwidth, i.e., increases b_{cj}. Here, b_{cj} is the bandwidth made available for sharing by PAL operator j. An increase of x_{cj} and b_{cj} allows the operator to support more GAA users which, in turn, will also increase the congestion, resulting in a higher degradation of the effective utility received by the users, i.e. increase of z_{cj}. On the other hand, decreasing the value of x_{cj} and b_{cj} means the operator can support a smaller number of GAA users, reducing the congestion caused by the GAA users, and offering a reduced degradation in effective utility, i.e. decrease of z_{cj}. The cost is 0 when a PAL operator does not share any bandwidth and access points. It reaches its highest value, x_j/e, when the PAL shares all available access points and the entire spectrum.

By incorporating the cost of sharing from different clusters, the average effective perceived utilities received by PAL operator j's subscriber, $\mathcal{U}_{ej}$, and GAA cluster c's user, $\mathcal{U}_{cj}$, from PAL j's available service is formulated as follows:

$$\mathcal{U}_{ej} = u(x_j, b_j) - \sum_{c=1}^{C} z_{cj}(x_{cj}, b_{cj}) - f_j \tag{4}$$

$$\mathcal{U}_{cj} = u(x_{cj}, b_{cj}) - \sum_{c=1}^{C} z_{cj}(x_{cj}, b_{cj}) \tag{5}$$

$$\begin{gathered} \text{where } \; 0 \leq b_{cj} \leq b_j, 0 \leq x_{cj} \leq x_j, \\ f_j > 0, x_j > 0, b_j > 0, \sum_{c=1}^{C} b_{cj} \leq b_j. \end{gathered} \tag{6}$$

Based on the Contest Theory [19], the probabilities of selecting PAL operator j for service by PAL subscriber, $\mathcal{P}_j$, and GAA user, $\mathcal{P}_{cj}$, can be given as follows:

$$\mathcal{P}_j = \frac{\mathcal{U}_{ej}}{\sum_{j=1}^{J} \mathcal{U}_{ej}} \quad and \quad \mathcal{P}_{cj} = \frac{\mathcal{U}_{cj}}{\sum_{j=1}^{J} \mathcal{U}_{cj}}. \tag{7}$$

This ensures that the operator with the highest utility does not get all the users (or subscribers), creating a monopoly. However, they are more likely to be preferred by users.

B. GAA Requests to PAL

The total CBRS access requests a cluster will make to a particular PAL can be determined using (7). If the total number of GAA users in a cluster, c, wanting to use the CBRS spectrum is denoted by n_c, the number of intial access requests submitted to operator j from c will be:

$$i_{cj} = \mathcal{P}_{cj} n_c. \tag{8}$$

After receiving the requests, the PAL operator j will decide on what proportion of the submissions to accept based on the potential government reward and estimated performance degradation incurred by the PAL users due to the presence of additional GAA users. This decision metric can be expressed in a probabilistic manner:

$$\alpha_{cj} = \frac{\text{number of requests accepted by } j}{\text{number of requests received by } j}.$$

Using α_{cj}, the actual number of granted GAA users, n_{cj}, to the PAL spectrum can be found as follows:

$$n_{cj} = \alpha_{cj} i_{cj}. \tag{9}$$

C. PAL Operator's Problem

The goal of the PAL operator is to maximize revenue. The revenue is generated on two fronts: 1) from user subscription fees and 2) from the government rewards because of sharing spectrum with the GAA users. For PAL operator j, the revenue from all subscribers, $n_j = \mathcal{P}_j \mathcal{N}_p$, will be the total monetary gain for charging the subscription fee, f_j, which can be obtained using the following:

$$\mathcal{R}_j = n_j f_j. \tag{10}$$

We propose a reward model to obtain PAL incentives from the government rewards where the government provides free access to PALs to an additional spectrum for a limited duration, based on their level of sharing. This reward spectrum can be allotted from the CBRS or other mid-band spectra, which are currently being opened up by the FCC [20], and will provide interference protection from GAA users, working as an extension of the PALs' licensed access. The bandwidth of the reward spectrum is denoted by $\otimes_{\mathcal{T}}$, and PAL operators will receive portions of $\otimes_{\mathcal{T}}$ based on the number of GAA users they serve or requests they accept, n_{cj}, and how long they access the spectrum, t_{cj}. Then, the amount of bandwidth received as a reward by operator j can be found using the following:

$$\Omega_j = \frac{\sum_{c \in C} n_{cj} t_{cj}}{\sum_{j=1}^{J} \sum_{c \in C} n_{cj} t_{cj}} \otimes_{\mathcal{T}}. \tag{11}$$

The government can determine the value of $\otimes_{\mathcal{T}}$ based on the usage of the unlicensed spectrum by the GAA or the availability of other spectra. Our goal is to formulate the reward as a monetary gain based on the number of GAA users served by the PAL. Operator j generates subscription revenue from each unit of bandwidth as follows:

$$\mu_j = \frac{\mathcal{R}_j}{b_j}. \tag{12}$$

Thus, utilizing reward bandwidth, Ω_j, Operator j can generate an additional $\mathcal{R}_{rj}$ $(= \mu_j \Omega_j)$ revenue.

PAL operators can capture GAA users from one another by adjusting bandwidths and access points sharing. It will affect the cost of sharing and, subsequently, the perceived service utility, influencing GAA clusters to move the members to a new PAL operator. We introduce willingness to switch, w_{cj}, which measures a cluster's proclivity to change PAL operators based on the variations of received utility. We compute it by taking the complement of the normalized cost of sharing, $z_{cj}(\cdot)$, with the maximum value, x_j/e, as follows:

$$w_{cj} = 1 - \frac{e z_{cj}}{x_j}. \tag{13}$$

Clusters will prefer a PAL with a higher value of w_{cj} (lower value of $z_{cj}(\cdot)$) as it indicates a higher utility received. So the number of GAA users from cluster c currently being served by other PAL operators, m_{cj}, that will migrate to PAL j can be presented as follows:

$$m_{cj} = \frac{w_{cj}}{\sum_{k=1}^{J} w_{ck}} \sum n_{cl}; \quad l = \mathcal{J} - \{j\}. \tag{14}$$

If PAL operator j earns on average r_j reward revenue for serving single GAA user, the total reward revenue will be:

$$\mathcal{R}_{rj} = \sum_{c=1}^{C} (n_{cj} + m_{cj}) r_j. \tag{15}$$

Subscription fees and shared bandwidths across access points to support GAA users primarily contribute to the revenue of PAL operators. Thus, the objective of PAL operator j is to select the optimum b_{cj} that will be shared with clusters and f_j that will be charged to the subscribers to maximize revenue can be expressed as follows:

$$\max_{f_j, \{b_{cj}\}} \mathcal{R}_j + \mathcal{R}_{rj} \tag{16}$$

$$\text{such that } f_j > 0, x_j > 0, x_{cj} \leq x_j, \\ b_j > 0, 0 \leq b_{cj} \leq b_j; \forall c, \forall j. \tag{17}$$

IV. Two PAL and Two GAA Cluster CBRS Market

We consider a simplified CBRS market consisting of 2 PALs (PAL 1, PAL 2) and 2 GAA clusters (cluster 1, cluster 2) to evaluate our proposed model. The licensed bandwidth of the operators are $10 \leq b_1, b_2 \leq 10m$; where $m = \{1, 2, 3, 4\}$, with $b_1 \geq b_2$ and $b_1 + b_2 = 70$ MHz, meaning the entire PAL spectrum is allocated to the two operators, thus providing an approximate representation of the CBRS PAL tier. PAL operators' revenues depend on the number of GAA users they serve, which plays a defining role in determining the decisions made by PAL operators. Thus the number of GAA clusters will not affect the relative performance of our model, meaning the proposed simplified CBRS market approximately resembles a complex one.

PAL 1 is set as the larger provider with a higher number of access points, x_1, compared to PAL 2's, x_2. As for the clusters, cluster 1 is presumed to be larger, with a higher user base, n_1, than that of cluster 2, n_2. The fees charged to PALs' subscribers are denoted as f_1, and f_2, while the licensed bandwidth allocated to the clusters 1 and 2 by PAL 1 are b_{11}, b_{21} and PAL 2 are b_{12}, b_{22} respectively. Utilizing eq. (4) - (7) and (16) - (17), we expand both PALs' optimization problems as follows:

PAL-1's problem:

$$\begin{aligned}\max_{f_1,b_{11},b_{21}} \; & \frac{\mathcal{U}_{e1}}{\mathcal{U}_{e1}+\mathcal{U}_{e2}}\mathcal{N}_p f_1 + \frac{\mathcal{U}_{11}}{\mathcal{U}_{11}+\mathcal{U}_{12}} n_1 r_1 + \\ & \frac{\mathcal{U}_{21}}{\mathcal{U}_{21}+\mathcal{U}_{22}} n_2 r_1 + \frac{w_{11}}{w_{11}+w_{12}} \frac{\mathcal{U}_{12}}{\mathcal{U}_{11}+\mathcal{U}_{12}} n_1 r_1 + \\ & \frac{w_{21}}{w_{21}+w_{22}} \frac{\mathcal{U}_{22}}{\mathcal{U}_{21}+\mathcal{U}_{22}} n_2 r_1\end{aligned} \tag{18}$$

$$\begin{aligned}\text{such that } \; & f_1 > 0, x_1 > 0, x_{11} \leq x_1, x_{21} \leq x_1, \\ & b_{11} \geq 0, b_{21} \geq 0, \; and \; b_{11} + b_{21} \leq b_1.\end{aligned} \tag{19}$$

PAL-2's problem:

$$\begin{aligned}\max_{f_2,b_{12},b_{22}} \; & \frac{\mathcal{U}_{e2}}{\mathcal{U}_{e1}+\mathcal{U}_{e2}}\mathcal{N}_p f_2 + \frac{\mathcal{U}_{12}}{\mathcal{U}_{11}+\mathcal{U}_{12}} n_1 r_2 + \\ & \frac{\mathcal{U}_{22}}{\mathcal{U}_{21}+\mathcal{U}_{22}} n_2 r_2 + \frac{w_{12}}{w_{11}+w_{12}} \frac{\mathcal{U}_{11}}{\mathcal{U}_{11}+\mathcal{U}_{12}} n_1 r_2 + \\ & \frac{w_{22}}{w_{21}+w_{22}} \frac{\mathcal{U}_{21}}{\mathcal{U}_{21}+\mathcal{U}_{22}} n_2 r_2\end{aligned} \tag{20}$$

$$\begin{aligned}\text{such that } \; & f_2 > 0, x_2 > 0, x_{12} \leq x_2, x_{22} \leq x_2, \\ & b_{12} \geq 0, b_{22} \geq 0, \; and \; b_{12} + b_{22} \leq b_2.\end{aligned} \tag{21}$$

A. Determining Subscription Fee

PAL operators will take care of their subscribers first because of the business perspective. They won't share resources that will significantly degrade utility for their subscribers, which will, in turn, dictate how much they can charge for their service. An operator offering a higher utility will be able to charge more, i.e., have a higher subscription fee [21]. This fee, according to eq. (4), will be based on the total number of access points, the available bandwidth of a PAL operator, and the bandwidth they are sharing with the GAA clusters. An operator with a higher number of access points can provide a higher utility and charge a higher subscription fee than other PAL operators assuming that all have equal bandwidth. Similarly, suppose all PAL operators have a similar number of access points. In that case, the one with the higher bandwidth will charge higher as it can provide better utility. On the other hand, a higher shared bandwidth with the clusters will increase the sharing cost, thereby reducing the utility of the PAL subscribers and, subsequently, the fee the operator can charge. Ultimately, the fees charged by the two PAL operators will be based on maximizing the monetary gain from the subscribers, which for our simplified CBRS market, can be obtained as the following:

$$f_1^* = \arg\max_{f_1} \frac{\mathcal{U}_{e1}}{\mathcal{U}_{e1}+\mathcal{U}_{e2}}\mathcal{N}_p f_1, \tag{22}$$

$$f_2^* = \arg\max_{f_2} \frac{\mathcal{U}_{e2}}{\mathcal{U}_{e1}+\mathcal{U}_{e2}}\mathcal{N}_p f_2. \tag{23}$$

In order to obtain the optimum values of the fees, we use a simple iterative algorithm that simultaneously solves (22) and (23). The algorithm will start by taking random initial values of fees and use them to solve (22) to obtain f_1, and then use that value, instead of the initial ones to determine f_2. The process is continued until convergence is reached, i.e., when the gap between the outputs obtained from subsequent iterations is below a specified tolerance. The working procedure of the fee selection algorithm is illustrated in Algo. 1.

B. Bandwidth Sharing

Obtaining each PAL's preferred bandwidth sharing strategy, we follow a similar approach to Algo. 1 and develop the iterative bandwidth sharing algorithm. Incorporating the fees obtained in Algo. 1, the new algorithm starts by taking random values of the bandwidth sharing to the clusters, which is used to solve the objective function of PAL 1, i.e. (18), the output of which is subsequently used while solving the objective function of PAL 2 in the next step, i.e. (20). This process continues until convergence is achieved, i.e., when the gap between the outputs obtained from subsequent iterations is below a specified tolerance. The workflow of the bandwidth-sharing algorithm is depicted in Algo. 2.

Algorithm 1 Fee Selection

Initialize f_1, f_2, x_1, x_2, iterator (i), tolerance (ξ_f), and other parameters
while $|f_1^*(i) - f_1^*(i-1)| \geq \xi_f$ & $|f_2^*(i) - f_2^*(i-1)| \geq \xi_f$ **do**
  $f_1^*(i) = \arg\max \frac{\mathcal{U}_{e1}}{\mathcal{U}_{e1}+\mathcal{U}_{e2}}\mathcal{N}_p f_1$
  $f_1 = f_1^*(i)$
  $f_2^*(i) = \arg\max \frac{\mathcal{U}_{e2}}{\mathcal{U}_{e1}+\mathcal{U}_{e2}}\mathcal{N}_p f_2$
  $f_2 = f_2^*(i)$
  $i \leftarrow i + 1$
end while

Algorithm 2 Bandwidth Sharing

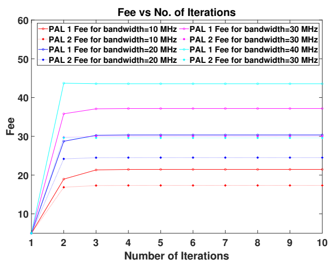
Initialize $b_{11}, b_{21}, b_{12}, b_{22}$, iterator (i), and tolerance (ξ_b)
Obtain f_1,f_2 from Algo. 1
while $|b_{11}^*(i) - b_{11}^*(i-1)| \geq \xi_b$ & $|b_{21}^*(i) - b_{21}^*(i-1)| \geq \xi_b$ & $|b_{12}^*(i) - b_{12}^*(i-1)| \geq \xi_b$ & $|b_{22}^*(i) - b_{22}^*(i-1)| \geq \xi_b$ **do**
  $[b_{11}^*(i), b_{21}^*(i)] = \arg\max$ (PAL 1's Revenue)
  $b_{11} = b_{11}^*(i), b_{21} = b_{21}^*(i)$
  $[b_{12}^*(i), b_{22}^*(i)] = \arg\max$ (PAL 2's Revenue)
  $b_{12} = b_{12}^*(i), b_{22} = b_{22}^*(i)$
  $i \leftarrow i + 1$
end while

V. Simulation Results

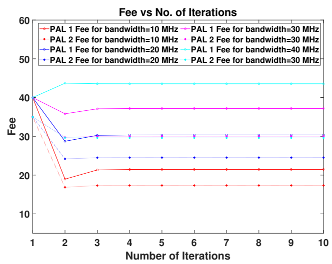
We used the optimization toolbox in MATLAB for the simulation to determine the optimum values of the decision parameters of the PAL operators. We run the fee selection algorithm and integrate the values obtained while executing the bandwidth sharing algorithm later. For the maximization problems in Algo. 1, which are unconstrained, we use the $fminunc$ function or the unconstrained optimization problem solver from the toolbox. As for the maximization problems in Algo. 2, the $fmincon$ function or the constrained optimization problem solver was used from the toolbox. As these functions are meant to work with minimization problems, we transform the maximization problems into minimization by multiplying them with -1.

TABLE II: Parameter Values

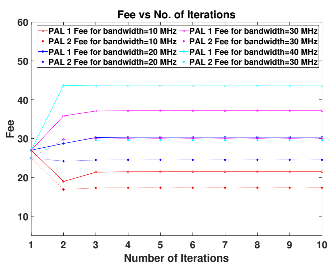
Parameters	Values
x_1	100
x_2	70
δ	0.001
b_1	(10, 20, 30, 40) MHz
b_2	(10, 20, 30) MHz
$\mathcal{N}_p$	[1000, 1400]
n_1	[150, 220]
n_2	[90, 140]
α_{11}, α_{21}, α_{12}, α_{22}	1, 1, 1, 1
initial f_1, f_2	[1, 40]
initial b_{11}, b_{21}, b_{12}, b_{22}	[0.1, 2.5]



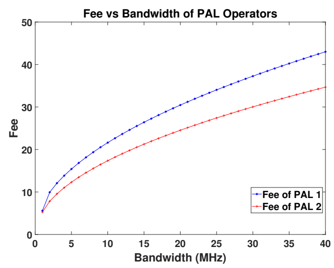
(a) Initial (f_1, f_2) = (5, 5)



(b) Initial (f_1, f_2) = (40, 35)



(c) Average Convergence



(d) Effect of bandwidth on fees

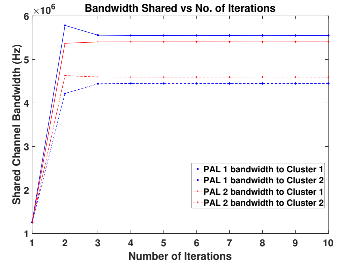
Fig. 3: Convergence of the fee selection

The initial values of f_1 and f_2 in Algorithm 1 were selected randomly in the range of [1, 40], while b_{11}, b_{21}, b_{12}, b_{22} were all randomly initialized within the range of [0.1, 2.5] MHz during each iteration for Algo. 2, to observe the effects of initialization on the optimum value.

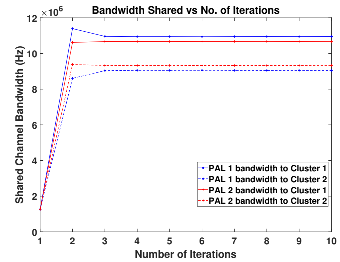
We run the entire simulation 1000 times with randomized system parameters in each iteration to gain an average insight into the convergence performance, i.e., the number of iterations required for convergence and converged values of the decision parameters. Table II illustrates the range of values of the parameters used during the simulation.

The simulations were executed for 4 different configurations of bandwidth for the operators, (b_1, b_2) = (10, 10) MHz, (20, 20) MHz, (30, 30) MHz and (40, 30) MHz. The average convergence took 4 to 7 iterations in all cases.

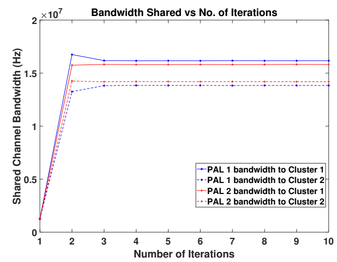
The results of fee selection are illustrated in Fig. 3. The algorithm converges with similar iterations regardless of the randomness in the initialization, Fig. 3a, Fig. 3b, and Fig. 3c. The effects of the bandwidth on the fee are depicted in Fig. 3d and show the fees tend to increase with the amount of bandwidth authorized for both PAL operators. This intuitively makes sense as a higher bandwidth will result in subscribers receiving a higher utility or better service, allowing operators to charge higher fees.



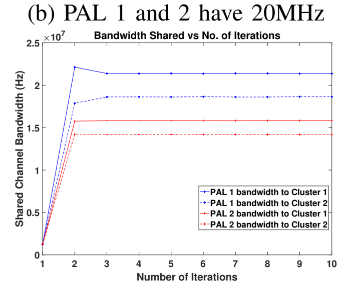
(a) PAL 1 and 2 have 10MHz.



(b) PAL 1 and 2 have 20MHz



(c) PAL 1 and 2 have 30MHz

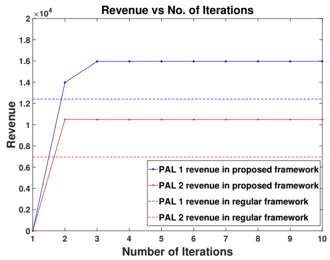


(d) PAL 1 with 40MHz and PAL 2 with 30MHz

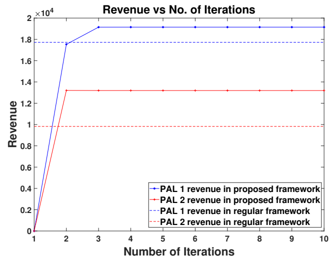
Fig. 4: Convergence of the bandwidth sharing

The observations from bandwidth sharing are depicted in Fig. 4. It also converges with similar iterations regardless of the effects of the random initialization. Across all configurations, PAL 1 always allocated a higher bandwidth for cluster 1 than PAL 2, while trailing in cluster 2 (except for configuration 4, i.e., Fig. 4d). This is because PAL 1 is the larger provider with more access points, so it can attract more GAA users due to offering higher utility. As cluster 1 is the larger of the two, meaning it would submit more licensed access requests. PAL 1 focuses more on cluster 1 and tries to draw a larger portion of its users, enabling PAL 1 to obtain a higher reward.

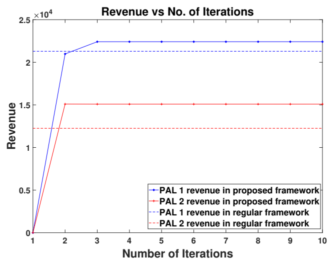
Combining the algorithms' outputs helps us obtain the total revenue of each PAL, illustrated in Fig. 5 and exhibited similar convergence characteristics as prior observations. For all 4 configurations, the revenue of PAL 1 is higher compared to PAL 2, as PAL 1, being the large provider, can offer better utility due to its higher number of access points, resulting in drawing more of the PAL subscribers, as well as the number of GAA requests. Fig. 5 also compares the PAL revenues from the proposed model to the traditional non-rewarding CBRS approach. For all scenarios, our proposed model manages to outperform the existing model. The gap between the two, however, does diminish with the increase in bandwidth, especially for PAL 1. This is because, across all configurations, we kept the number of access points for both the PALs constant, which would not be the case in real life. As bandwidth increases, operators will try to utilize that and extend their coverage to improve their monetary gain by establishing more access points. This would allow them to increase the fees as the service received by subscribers would also improve, resulting in the revenue calculated from our model being higher in real life. Even with that limitation, our framework outperforms the traditional approach in all cases.



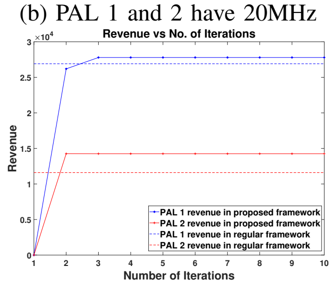
(a) PAL 1 and 2 have 10MHz



(b) PAL 1 and 2 have 20MHz



(c) PAL 1 and 2 have 30MHz



(d) PAL 1 with 40MHz and PAL 2 with 30MHz

Fig. 5: Comparison of traditional and proposed models

An important observation from the figures is that the problems for PAL 2 converge earlier than PAL 1. This is because PAL 1 uses the random initialized values of the decision parameters during the first iteration. In contrast, PAL 2 uses the values obtained from PAL 1 and thus is not as affected by the random initialization process. So if the order of evaluation is reversed, PAL 1 will converge earlier.

VI. Conclusions and Future Work

We proposed a novel framework for CBRS sharing where GAA users form geographically distinct clusters and act as a single entity while requesting and accessing spectrum through PAL. Such collective submission of access requests from the GAA users as a cluster gives PAL operators great insights into the level of GAA traffic they may experience. Thus, PAL reacts accordingly by optimizing bandwidth sharing across GAA clusters so that PAL subscribers are not negatively affected by the increase in congestion due to additional GAA users. Furthermore, the proposed reward model encourages PALs to accept more GAA users to their spectrum to increase revenue. From the simulations, we also observed that our framework outperforms the current CBRS-sharing model regarding PAL's revenue generation. In the future, we want to extend our framework with more PALs, GAA clusters, and other bands, e.g., 37 GHz. We aim to work on optimal GAA cluster formation and leader selection procedures. Further exploration of the cost of sharing and willingness to switch are also worthy of future works. We will also look for more efficient algorithms to solve the optimization problems for extensive networks, owing to the increased computational cost those networks will bring, and include other evaluation parameters such as computation time and reliability index.

Acknowledgments

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References

[1] "What is a private wireless network?" https://www.fiercewireless.com/private-wireless/what-a-private-wireless-network, 2020.

[2] "CBRS: What is it and how does it work? - ConnectivityWireless," https://www.https://connectivitywireless.com/cbrs-what-is-it-and-how-does-it-work/, 2019.

[3] "State of CBRS Priority Access License (PAL) deployments: Q&A with Commscope's Rashid Bhatti," Mar 2021. [Online]. Available: https://ongoalliance.org/state-of-cbrs-priority-access-license-pal-deployments-qa-with-commscopes-rashid-bhatti/

[4] Y. Xiao, S. Shi, W. Lou, C. Wang, X. Li, N. Zhang, Y. T. Hou, and J. H. Reed, "Decentralized spectrum access system: Vision, challenges, and a blockchain solution," *IEEE Wireless Communications*, vol. 29, no. 1, pp. 220–228, feb 2022.

[5] M. Woodley, "CBRS spectrum update after three years ," Sep 2022. [Online]. Available: https://www.ericsson.com/en/blog/6/2022/cbrs-growing-pains-and-progress

[6] "3.5 GHz Band Overview." [Online]. Available: https://www.fcc.gov/wireless/bureau-divisions/mobility-division/35-ghz-band/35-ghz-band-overview

[7] D. Stojadinovic and M. Buddhikot, "Design of a secondary market for fractional spectrum sub-leasing in three-tier spectrum sharing," in *2019 IEEE International Symposium on Dynamic Spectrum Access Networks (DySPAN)*, 2019, pp. 1–8.

[8] G. Saha, A. A. Abouzeid, and M. Matinmikko-Blue, "Online algorithm for leasing wireless channels in a three-tier spectrum sharing framework," *IEEE/ACM Transactions on Networking*, 2018.

[9] G. Saha, A. A. Abouzeid, and M. Matinmikko, "Competitive online algorithm for leasing wireless channels in 3-tier sharing framework," in *2016 54th Annual Allerton Conference on Communication, Control, and Computing (Allerton)*, 2016, pp. 792–799.

[10] A. Khanafer, M. Kodialam, and K. P. N. Puttaswamy, "The constrained ski-rental problem and its application to online cloud cost optimization," in *2013 Proceedings IEEE INFOCOM*, 2013, pp. 1492–1500.

[11] A. Ghosh and R. Berry, "Entry and investment in cbrs shared spectrum," in *2020 18th International Symposium on Modeling and Optimization in Mobile, Ad Hoc, and Wireless Networks (WiOPT)*, 2020, pp. 1–8.

[12] A. Ghosh, V. Aggarwal, and P. Chakraborty, "Tiered spectrum measurement markets for joint licensed and unlicensed secondary access," *IEEE Transactions on Network Science and Engineering*, vol. 7, no. 3, pp. 1295–1309, 2020.

[13] M. Tonnemacher, C. Tarver, V. Chandrasekhar, H. Chen, P. Huang, B. L. Ng, J. Charlie Zhang, J. R. Cavallaro, and J. Camp, "Opportunistic channel access using reinforcement learning in tiered cbrs networks," in *2018 IEEE International Symposium on Dynamic Spectrum Access Networks (DySPAN)*, 2018, pp. 1–10.

[14] C. Tarver, M. Tonnemacher, V. Chandrasekhar, H. Chen, B. L. Ng, J. Zhang, J. R. Cavallaro, and J. Camp, "Enabling a "use-or-share" framework for pal–gaa sharing in cbrs networks via reinforcement learning," *IEEE Transactions on Cognitive Communications and Networking*, vol. 5, no. 3, pp. 716–729, 2019.

[15] H. Zhang, S. Leng, and H. Chai, "A blockchain enhanced dynamic spectrum sharing model based on proof-of-strategy," in *ICC 2020 - 2020 IEEE International Conference on Communications (ICC)*, 2020, pp. 1–6.

[16] A. Merwaday, M. Yuksel, T. Quint, I. Guvenc, W. Saad, and N. Kapucu, "Incentivizing spectrum sharing via subsidy regulations," 11 2014.

[17] M. Rahman and M. Yuksel, "Government reward models for inter-operator spectrum sharing," in *2019 IEEE International Symposium on Dynamic Spectrum Access Networks (DySPAN)*, 2019, pp. 1–5.

[18] M. Rahman, M. Yuksel, and T. Quint, "A game-theoretic framework to regulate freeriding in inter-provider spectrum sharing," *IEEE Transactions on Wireless Communications*, vol. 20, no. 6, pp. 3941–3957, 2021.

[19] L. Corchon, "The theory of contests: A survey," *Review of Economic Design*, vol. 11, pp. 69–100, 02 2007.

[20] B. O'Donnell, "CBRS vs. C-band: Making sense of mid-band 5G," Feb 2020. [Online]. Available: https://www.forbes.com/sites/bobodonnell/2020/02/27/cbrs-vs-c-band-making-sense-of-mid-band-5g/?sh=1873f8037813

[21] C. A. Gizelis and D. D. Vergados, "A survey of pricing schemes in wireless networks," *IEEE Communications Surveys & Tutorials*, vol. 13, no. 1, pp. 126–145, 2011.