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Fostering Collaboration in Emerging Three-Tiered Spectrum Markets

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FOSTERING COLLABORATION IN EMERGING THREE-TIERED SPECTRUM MARKETS

A Thesis

by

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ABSTRACT

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Ensuring optimum spectral efficiency is a critical requirement for current wireless networks to cope with the ever-growing flow of wireless data traffic, using limited spectral resources. As such, spectrum sharing, which allows different grades of users, as well as multiple networking standards to co-exist and utilize in the same frequency band, has become a topic of great intrigue. Due to the inherent advantages of these schemes, the US government has opened up vast amounts of federal spectrum that supports spectrum sharing. The Citizens Broadband Radio Service (CBRS) proposed by the Federal Communications Commission (FCC) is one of them. A tiered spectrum sharing approach, CBRS allows end commercial users to share the radio spectrum with federal incumbent users in the 3,550-3,700 MHz range. Employing a light leasing approach, the FCC aims to encourage the licensed providers of CBRS called the Priority Access License (PAL), to lease/share their licensed spectrum with unlicensed users named the General Authorized Access (GAA) for limited duration, which is essential for the maximum utilization of the CBRS bandwidth, but the current approach proves ineffective for that purpose. In this thesis, we propose a novel clustered framework to facilitate this sharing, where GAA users are grouped into multiple distinct geographical clusters and request access to licensed spectrum through the clusters in a collaborative manner rather than individually. Each cluster will nominate a central entity denoted as the GAA leader to communicate their requests to the PAL operators, as well as establish temporary connections with PAL access points once granted permission for licensed CBRS access, to be used by GAAs outside the operators coverage range. The leaders will also receive information from the PAL operators regarding the number of requests they are willing to accept and transmit that to the GAAs within the cluster. This process reduces the amount of information flow between the licensed and unli-

censed entities, thereby providing a convenient platform for CBRS spectrum sharing. In order to determine the leader, the role of which can be assumed by any of the GAA users within the cluster, we formulate a distributed leader selection algorithm algorithm called the LSA, which takes into account the signal strength of the PAL access points available the GAA users, as well as the network density of each GAA node, to assign a score called the leader evaluation score (LES) to each GAA user and nominate the user with the highest score as the leader. To encourage PAL operators to frequently share their licensed spectrum, we incorporate a government reward model, where operators are incentivized by gaining access to additional spectrum for limited periods based on their level of sharing.

DEDICATION

To my parents and beloved wife for their unequivocal love and support, without whom nothing of this would be possible.

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CHAPTER I

INTRODUCTION

The current wireless space is characterized by an ever-increasing demand of data traffic owning to the wide spread deployment and utilization of wireless devices. According to Statista (2022), Vailshery (2022), the total number of mobile devices in use at the end of 2021 worldwide, was 14.91 billion, with an additional 11.3 billion connected IoT devices, which resulted in a data traffic of 67 EB (Exabytes) per month. These numbers are projected to rise significantly and reach 18.22 and 19.1 billion for mobile and IoT devices respectively by the end of 2025. They are estimated to produce an extraordinary 368 EB of data each month by the end of 2027, which is almost a six fold increase, over a period of the same as depicted in Fig. 1.1, Ericsson (n.d.). The catalyst behind this rapid growth is the expected extensive deployment of 5G networks, which currently constitutes 10 % of all data traffic but is expected to be responsible for as much as 60 % in 2027. This increase in data, has put a lot of strain on the available wireless spectrum which is a limited resource. According to Eddy (2021), overwhelming data demand resulted in the US facing a spec-

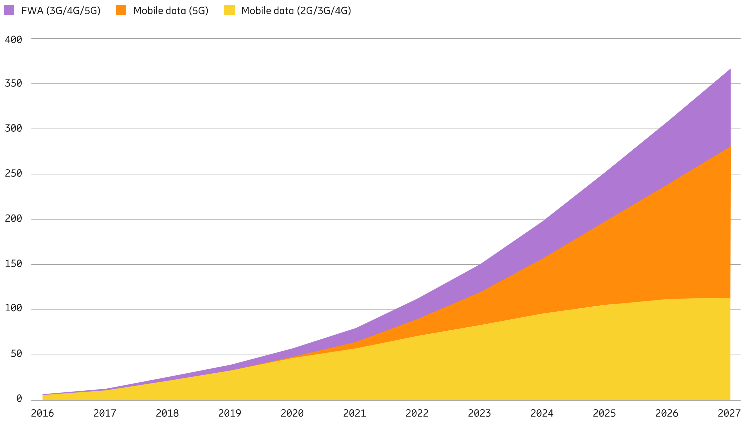


Figure 1.1: Projection of mobile data traffic between 2020-2027

trum deficit of 123 MHz in 2021, which is estimated to rise to 963 MHz by 2025. Thus ensuring efficient utilization of spectral resources will play a key figure in the proper deployment of 5G and beyond wireless networks in future.

Currently there are multiple avenues to improve spectral efficiency such as, carrier aggregation in 4G LTE, were spectrum from different band or component carriers are combined together to increase data transfer rate and available bandwidth, Kamath et al. (2020); dynamic time division duplex (D-TDD), were synchronized base stations are allotted different and fixed time slots for both up and down links, over the same frequency, Kim et al. (2020); dynamic spectrum sharing (DSS), which allows the utilization of the same frequency band and dynamically assign spectrum to both 4G LTE and 5G devices, enabling a quicker and more cost efficient way for the deployment of 5G networks, Ahmad et al. (2020).

In addition to these technical frameworks, another important factor is opening up seldom used frequency bands. Currently in the US, the Department of Defence (DoD) is the largest holder of frequency bands, and they are sporadically used. In order to meet the data traffic demands, it is becoming adamant that a portion of these frequency bands needs to be shared for public usage, as long as they can ensure interference protection. Based on that understanding, the Federal Communications Commission (FCC) has taken the initiative to open up large amounts of federal spectrum for public and private usage. According to 3rd Generation Partnership Project (3GPP) standards, 5G networks operate in two sets of frequency bands, 1) 450 MHz-6 GHz or the sub 6 GHz range, also known as the mid band and 2) 24-52 GHz or the millimeter wave range, also knows as the ultra-wide band, Craven (2020). Based on that, the FCC has already opened up about 5 GHz of federal spectrum through auctions of the 24 GHz, 28 GHz, 37GHz and 39 GHz bands, while looking to open up a further 2.75 GHz of bandwidth for 5G networks in the 26 GHz and 42 GHz bands in the millimeter-wave range, FCC (2021). For the mid-band spectrum, the FCC plans to open up 600 MHz for the purpose of 5G deployment, with two major auctions have already taken place, for the 150 MHz of bandwidth from 3.55-3.7 GHz, known as the Citizens Broadband Radio Service (CBRS) and the 280 MHz from 3.7-4.2 GHz, known as the C-Band, O'Donnell (2020). Between

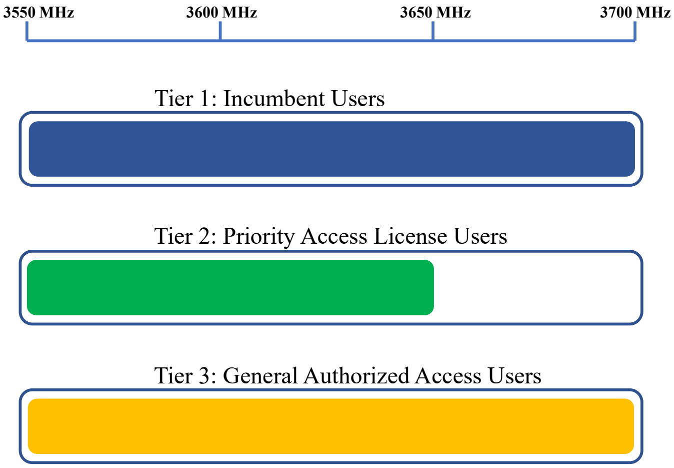


Figure 1.2: General bandwidth allocation of tiers in CBRS

them, the CBRS offers up a unique networking framework. It is a tiered spectrum sharing approach, where commercial users operate in the same frequency band as federal incumbent users, with the assurance of interference protection for a higher tier from all subsequent lower ones, i.e. if a higher tier user wants to use a particular frequency bandwidth, users from lowers tiers in that band must vacate and move to a new one.

There are 3 tiers in CBRS: 1) Incumbent users; consisting of naval radars and fixed satellite services and have access to the entire 150 MHz spectrum if required, 2) Priority Access License (PAL) users, having access between 3550-3650 MHz and 3) General Authorized Access (GAA) users, capable of using the entire spectrum where the top two tiers are not present, Hardesty (2020). PAL users are provided licensed access to the spectrum which were obtained via FCC's auction 107. There are a total of 7 licensed channels available, each with a 10 MHz range, which are provided on a county basis, with a single entity limit of 40 MHz or 4 licensed channels per county, OpenDataSoft (2019). GAA's are opportunistic users and can use any spectrum not occupied by the other two tiers. The spectrum sharing and interference protection of upper tier users from lower ones are controlled and monitored by a central entity, Spectrum Access Systems (SAS), which employs Environmental Sensing Capability operator (ESC), a network of sensors that can detect the activity of federal incumbent users. SAS has the responsibility of assigning spectrum to the GAA and PAL tiers when requested, ensuring that no interference is caused.

An important characteristic of CBRS is that it is a spectrum sharing framework, i.e. GAA users can use the licensed CBRS spectrum of PALs provided that PAL users are not present on the licensed band at that time. GAA users can also sublease licensed CBRS spectrum from PAL operators for a limited amount of time, if agreed upon by that particular PAL, and use the leased license similar to a native PAL user, meaning they are provided with interference protection from other GAA users. As such, a convenient way to offer up licensed spectrum in the secondary market on a temporary basis will be crucial for the optimum utilization of the CBRS spectrum. This is because,

1. The GAA layer is likely to be the most congested portion of the entire spectrum, owing to the fact that, anyone with a CBRS access point called the CBSD (CBRS Device), can access the unlicensed spectrum, CommScope (2021). In addition, PAL users can also chose to use the GAA band to offload some of their data traffic, as they are allowed by the rules of CBRS. So the total GAA bandwidth which is expected to be 80 MHz for vast majority of the time, as incumbents will rarely be present in the band, will always have a large user presence which can degrade the service received by the end users due to the increase of interference between wireless devices.

2. Being a mid band spectrum, the 3.6 GHZ CBRS band is geared towards providing high data speed, but over short coverage, making it suitable for deployment in large cities and urban areas, and then use the dynamic spectrum sharing to expand the coverage area. Thus, most of CBRS licenses were allotted in urban landscapes, despite the requests from rural service providers to rethink the PAL licensing scheme and develop smaller licensed areas which can be used for rural usage, Alleven (2018). So rural areas, which already have poor coverage due to lack of proper infrastructure, will extensively need to rely on the secondary spectrum market.

This importance of sharing licensed spectrum is also recognized by FCC, evident by the incorporation of a light leasing approach, Fletcher (2020). In the current CBRS architecture, to gain access to PAL spectrum through this sharing, GAAs are required to submit requests to PALs through the SAS individually. This proves to be an inadequate process because,

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, as well as having a high messaging overhead, CommScope (2021).
2. The SAS stores and forwards the requests to PALs through centralized servers, which can suffer from single point failure due to server malfunction or infiltration from malicious 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, Xiao et al. (2022).
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, Woodley (2022).

In this work, we try to address these challenges by developing a cluster-based CBRS model, where the GAA users form multiple geographically distributed GAA clusters. These clusters act as a single entity and directly communicate with PALs regarding licensed CBRS spectrum access, by submitting an aggregated number of requests from all the GAA users within the cluster, thus reducing the communication overhead between GAA users and SAS, although the SAS will still be required to provide final authorization for licensed access. All GAAs within a cluster will elect and report to a central entity, termed as a GAA leader, when requesting access to the licensed spectrum. The leader will be responsible for communicating the requests to the PAL users and receiving information from them regarding their level of sharing, i.e. the requests they are willing to accept. To elect the leader, we develop a novel leader selection which uses the network density and signal strength of GAA users to elect a leader during each period of licensed CBRS access.

This framework will allow PAL operators to gain an overall idea of the total number of GAA users willing to use the licensed CBRS spectrum, and make a decision regarding accepting

Table 1.1: Pros and Challenges with the Proposed Framework

Criteria	Remarks
Pros	1. Convenient way for PALs to extend services to GAAs. 2. Common spectrum pool and less fragmented spectrum allocation 3. Reduced GAA-SAS messaging overhead 4. Low wait time for GAA to access CBRS spectrum 5. New revenue source for PALs
Challenges	1. Location-wise reward spectrum distribution 2. GAA cluster sizes and trust among cluster members. 3. On-demand GAA spectrum access

access requests accordingly so that it does not negatively impact its native users in terms of interference. This will help minimize the interference between GAA-PAL and GAA-GAA users, as well as allowing PALs to offer up their spectrum in a convenient and secure setting, while allowing GAAs to utilize the PAL spectrum and reduce the congestion in the GAA layer. In order to encourage PALs to sublease their spectrum, we also propose an incentive model where PAL operators are incentivized according to their level of spectrum sharing to the GAA users, by gaining access to additional spectrum for fixed periods.

We model the PALs problem as selecting the optimum fee to be charged to its customers and the optimum allocation of bandwidth to the GAA clusters in a competitive environment, that would allow them to maximize their revenues. Our simulations indicate that, the fee increases with the amount of licensed bandwidth owned by a PAL, while for bandwidth allocation, in a equally competitive environment, i.e. when they have identical amounts of licensed CBRS bandwidth, PALs tend to migrate and allocate more bandwidth to the clusters where they face a lower amount of challenge in terms of attracting GAA requests, whereas in an environment with unequal licensed CBRS channels, the migration process appears to be slower, although it does occur. For GAAs, their problem was set up in terms of maximizing the total cluster utility, which exhibited a strong dependency on the appropriate leader selection. For both types of users, our model managed to outperform the traditional CBRS approach. The pros and some of the challenges related to our proposed model is summarized in Table 1.1.

1.1 Motivations

Currently there are no effective frameworks to facilitate licensed spectrum leasing for CBRS that will allow the optimal spectral efficiency/ spectrum utilization. The traditional approach is inadequate in the sense that GAAs have to go though the SAS to even place an access request, which is time consuming, as well as a security risk, because they are required to share networking information such as their location, transmission parameters etc. After all that, it does not even ensure that PALs will accept their requests because, 1) there are no incentives for PAL operators to do that, and they will just degrade the utility of their native users by sharing, which would introduce congestion in their licensed band, and 2) if the requests are submitted individually, there is no way for PALs to estimate the data traffic that they may expect to experience form the GAA access, as the requests will just be forwarded by SAS when received, resulting in PALs selecting GAA users indiscriminately for licensed access. The lack of proper sharing framework will particularly affect the rural areas, which will extensively depend on the shared bandwidth of PALs to gain access, due to the poor networking infrastructure as well as not many PAL licenses have been allotted there. Thus, our goal in this work is to eradicate these issues with sharing, by grouping the GAA users into clusters and then through the clusters, directly communicate with PALs regarding the licensed access by submitting cumulative requests for CBRS access from each cluster. This will allow PAL operators to have a broad idea about the service requirement of the GAA layer and accept appropriate proportions of the requests that would makes sense for their own service requirement.

To encourage PAL operators to share their spectrum and accept a higher population of GAA users, we incorporate a government reward scheme in our model, where PALs will be compensated by given access to federal spectrum for a limited duration based on their sharing performance. These federal bands are rarely occupied by the incumbent users, meaning the risk of causing interference to their operation is low, thus the government would be willing to offer these reward spectrum as it will expand the total coverage area of wireless operation, increasing social welfare, Lopez (2022). We formulate two iterative algorithms to help PAL operators in making optimum decisions to maximize their revenue. PAL licenses are obtained through a competitive spectrum auction, thus it requires capital investment, which would also reflect on the fees they charge for their service. An operator who has bid for multiple licenses, will be able to offer better service using their higher bandwidth compared to an operators with a single license. So, our fee selection algorithm is used to aid operators by providing advice on how the fees should be set based on the amount of licensed CBRS spectrum owned, that would help maximize their earnings from native PAL customers. On the other hand, their revenue from the reward band will be dependent on how much of their license spectrum they share. A higher shared bandwidth mean they would be receiving a higher portion of the reward bandwidth, but this would also result in an increase in congestion in their licensed spectrum, which would degrade the service received by their native customers, who may choose to change operators, if the degradation is significant enough. So our bandwidth sharing algorithm will look to enable PALs in selecting the optimum shared bandwidth that would be beneficial to both the operators and their customers.

The utility of the GAA clusters will be significantly dependent on the GAA leaders, as the leader is responsible for setting up the temporary PAL-GAA connections which would be used by GAA users outside the operational/coverage region of PAL operators. Selecting a sub-optimum leader would mean those users would have access to a reduced number of PAL access points, as well as receive poor signal strength for their services which will fail to optimize their payoffs. The goal of our proposed distributed leader selection algorithm is to make sure the appropriate leader is selected that would maximize the service utility of the entire cluster.

1.2 Contributions

The main contributions of this work to facilitate the optimum usage of the CBRS spectrum that maximizes the return of all users involved are as follows:

1. We develop a cluster model for CBRS, where the GAAs are grouped into multiple geographically distinct regions and operate through a central controlling unit called the GAA leader. The leader is responsible for all spectrum sharing operations, while ensuring privacy for all constituent cluster members.

2. We propose an incentive model for the PAL operators, where they are provide with additional spectrum for limited duration to be used as an extension to their current licensed network, based on their level of sharing to clusters, that includes the number of requests from GAAs for licensed access that they accept and for what duration of time they allow licensed access.

3. We formulate the objective functions of PAL operators based on determining appropriate subscription fees and level of sharing to clusters that maximize their revenue. The GAA objective function was set in terms of selecting a GAA leader that maximizes the total cluster utility.

4. We construct a simplified network environment in CBRS with two PAL operators and two clusters for our simulations, where the PALs compete with one another for users, and solve their objective functions using two iterative algorithms, which managed to reach convergence swiftly and with the same number of iterations with varying network parameters.

5. In order to select the GAA leader, we develop a novel leader selection algorithm (LSA), which uses the network density and perceived signal strength at each GAA user to assign them a score, called the leader evaluation score (LES), and the GAA with the highest score is elected.

6. Our model indicates the behaviour of PALs in terms of their leasing allocation to clusters with regards to the strategies of other PALs. Simulations show that, when a particular PAL increases its allocated bandwidth on one cluster, other PALs tend to migrate from that cluster and, move and increase their allocation on other clusters where they will face less competition for attracting more GAA requests.

7. We demonstrate the effectiveness of our leader selection algorithm in ensuring peak cluster utility. Under favorable networking conditions, network density of nodes play the key factor in determining the leader, whereas in poor networking conditions, the distance and number of accessible access points to the GAA nodes play the defining part.

8. For PAL operators, the simulations indicate that our framework manages to produce a higher revenue for PALs compared to the traditional approach, while for GAA users, their overall utility outpaces the utility from the current non-clustered approach.

1.3 Organization of the Thesis

The organization of the rest of the thesis is as follows: in Chapter II, we look at some of the current developing trends in CBRS from the literature in terms facilitating secondary access to GAAs, managing interference between GAA-GAA and GAA-PAL, and obtaining optimum clusters sizes. We also explore some topics on leader election is distributed computer and wireless networks. In Chapter III, we formulate our clusters framework over a single county with multiple PAL operators and GAA clusters. We develop their objective functions in terms of maximizing revenue for PAL operators and optimizing total utility for GAA clusters. We also formulate the government's objective that aims to maximize the social welfare of the entire CBRS band incorporating all GAA and PAL users. Next in Chapter IV, we establish a simplified configuration of our proposed framework with two PALs and two clusters, owing the high computational cost of simulating an n-provider, n-cluster model. We also illustrate our fee selection and bandwidth allocation algorithms in this section. After that, in Chapter V, we formulate our leader selection algorithm, in terms of defining the LES, the messages involved in the election process, and the total election procedure in a distributed manner. In Chapter VI, we illustrate our simulation results. We define the values of the system parameters involved in the simulation process, as well as the initialization of our design variables, and display the performance of our model. Finally, Chapter VII depicts some of the future works associated with the thesis and concludes our work.

CHAPTER II

LITERATURE REVIEW

Spectrum sharing has become a prominent concept in the wireless world in order to cope up with massive rise in data traffic brought by the ubiquitous use of mobile and IoT devices, and ensure efficient and widespread deployment of 5G and beyond wireless networks. In this chapter, we look at some of the recent developments in spectrum sharing found in the literature, that allows primary users (PU) to share their spectrum with secondary users (SU) in a secure and effective manner. We also observe some of the research on reward models used to incentivize PUs to share their spectrum. These frameworks are quite essential in the sense that PUs generally have to gain licenses to use their spectrum without outside interference through competitive auctions, which involves capital investments, while allowing SUs to use those licensed bands will introduce congestion resulting in a degradation of their services offered, thus it does not make sense for PUs to share without receiving any sort of compensation. Finally, we look at some of the work on developing leader selection algorithms for distributed wireless networks, that help coordinate certain networking tasks within in the system through a singular node.

2.1 Dynamic Spectrum Sharing in Regular and Tiered Networks

Sub-licensing scheme incorporating spatial grid mapping techniques to reduce the interference between PUs and SUs was proposed in Wang et al. (2017). The model formulates a spatial interference-free grid to control interference between subleased users, offering them a higher quality of service (QoS), by adjusting their interference contours using grids. To solve the issue when multiple secondaries have overlapping boundaries (service regions), a term called boundary sensitivity was introduced which refers to the maximum number of shared users allowed in the same spatial region. The model managed to obtain the highest profit for PUs at the optimum resolution of the grid (grid length).

A similar interference mapping enabled spectrum sharing approach was proposed in Duan et al. (2017), with the help of software defined networking (SDN) controllers. Here, the authors formulate a convoluted network incorporating end users, operator base stations, incumbent base stations and SDN controllers, where the incumbents share their spectrum occupancy information, which is used to form a real time 3D interference map, and SUs can access the spectrum when the interference is below a preferred threshold level, with the help of SDN which offers global control and coordination capabilities to heterogeneous networks. The framework greatly reduces the number of access requests denied for SUs.

Hyper-graph based models for optimum spectrum allocation in the secondary market was illustrated in Stojadinovic & Buddhikot (2019), which provides improved area coverage and profit from sub-licensing over the interference avoidance methods mentioned above. The proposed model uses hyper-graphs to help SAS adjust regions of licensed access offered to the secondary users, allowing more users to be given access. The model also aids in reducing the interference and allowing appropriate coexistence of multiple secondary users in the same geographical region by limiting the number of secondaries in a fixed area, and manages to significantly boost the financial gains for the licensed users.

Deterministic online algorithms to obtain spectrum allocation strategies in the second market was depicted in Saha et al. (2016), designed on the basis of the popular ski rental problem. Using a time-slotted model, the proposed algorithm assists the operators in making decisions on the optimum value of the intended number of channels to be leased, the amount of customers to be served through opportunistic channels and the customer demand to be rejected in a specified time-frame. An advantage of the algorithm is it does not depend on current market statistics and variables, thus making it highly effective in the early part of CBRS deployment. A drawback however for this work is that the developed online algorithms exhibit sub-optimal competitive ratio, which is essentially the ratio between the worst case and best case computational costs.

Profit or revenue optimization problems for commercial operators in a shared spectrum environment similar to CBRS was explored in Ghosh & Berry (2020), using a game-theoretic framework, which depicts how operators would compete in the spectrum market, in terms of accessing licensed and unlicensed bands, as well as how they would invest on infrastructure. The authors formed a multi-stage game using two operators and a single PAL license with the goal of first determining their level of investment, which is considered to reduce the congestion cost of customers and then decide on their bid for the PAL license. Analysis of the model showed that when both the operators are in the GAA level, the one with the higher investment enters the market, i.e. bid for the license, whereas if one of them is in the PAL layer, based on its investment and traffic route, the unlicensed operator's revenue reduces to zero, meaning the amount of data that a PAL can transmit through the GAA layer has to be limited by a regulator, i.e. SAS, to ensure a competitive secondary/GAA market.

Opportunistic channel access approaches allowing GAA users to use PAL spectrum in CBRS was proposed in Tarver et al. (2019), based on reinforcement learning enabled listen-before-talk (LBT) schemes. The authors explored two LBT methodologies, called the beginning-of-subframe LBT and end-of-subframe LBT, which allows GAA users to access licensed spectrum after sensing it has been left unoccupied for a certain amount of time and greatly increased the user utility of the secondary nodes (GAA users). To mitigate the negative impact such sharing has on PAL users, a Q-learning algorithm was proposed to modify the level of opportunistic access using an improved carrier sensing topology, which managed to nullify the performance penalty of licensed users caused due to the presence of additional GAA users in the same spectrum, although some reduction in utility still occur.

A distributed block-chain based framework for CBRS was illustrated in Zhang et al. (2020), where the responsibility of a traditional SAS was relocated to the PAL users in order to reduce the administrative cost of GAA users, who now only had to query the database in FCC/PAL to find out the available spectrum location, as well as provide an effective mode to detect and prevent malicious users from accessing PAL spectrum. The model allocated more spectrum resource to PALs than they need and incentivized them depending on their service to the GAA. A novel consensus strategy was also formulated that aims at optimizing both the number of GAA service request the PAL responds to i.e. maximizing the service number of GAA users and also individual PAL's own service number, using reinforcement learning. The model greatly improved the security aspect of network, but did not offer any improvement in terms of total users utility, compared to the current approach. Another thing of concern with this model is that no procedures have been mentioned to ensure that PALs must share or else they will be penalized. This will have an adverse effect in the GAA level performance, as PALs are not obliged to share their spectrum, meaning the spectrum available to GAA users in the licensed spectrum may be extremely limited.

2.2 Incentive Models for Spectrum Sharing

A spectrum sharing market incorporating a government subsidized reward scheme was explored in Merwaday et al. (2018). Here, the government incentivize spectrum by offering subsidy support to wireless operators, based a performance parameter called the number of foreign customers served, which is essentially the number of customers served from other providers in the shared spectrum environment. Game theory was used to formulate the proposed market using two operators through a non-cooperative game where the goal of the operators were to distribute their subsidies in different regions in a manner that help maximize their total revenue. The model was simulated using real life base station locations and illustrated that by offering subsidies, which where subsequently invested by operators on different regions to improve infrastructure, in a bid to serve more foreign users for higher rewards, the coverage area of the operators as well as the total service utility of the customers improved significantly.

Game theoretic model for a similar subsidy based scheme was illustrated in Rahman & Yuksel (2019), with an aim to reducing free riding among primary users in a shared spectrum market, which is the phenomenon of operators unethically exploiting spectrum sharing frameworks by advertising lower than fair market fees to attract customers from others. This work uses the same performance metric as the previous one, and operators are required to support a lower threshold number of foreign users to gain access to the subsidy, which is formulated incorporating a penalty function. The model also considers user probability to switch operators and provide insight into how to regulate subscription fee of the operators. Simulation indicates that the model manages to reduce free riding considerably and ensure an increase of operator revenue, particularly for larger operators, whose worst case revenue does not fall below from existing non-sharing models.

Two novel government reward schemes were proposed in Rahman & Yuksel (2019), which incentives PUs to share their spectrum to the unlicensed layer. These include, 1) Government Spectrum as Reward (GRS) model, where an operator is given access to federal spectrum for limited periods and 2) Government Cell as Reward (GRC) model, where the operators are rewarded by assuming control of government implemented cell towers for limited duration.The GRS model offers higher utility gain to the customers at moderate operating cost, but fails to increase the existing coverage/service region. The GRC model on the other hand, offers the ability to increase the wireless serviceable region at low operating costs, but offers little increase in total service utility, as well as not being highly scalable.

Spectrum trading approach based on demand and supply economics is explored in Bajaj et al. (2015), where the SUs bid for licensed access for limited duration to the PUs. The model allows three types of collaboration between the two types of users in terms of spectrum sharing, spectrum access and relaying, each having specific cost, and the goal is to use utility measures in the unlicensed layer to determine the optimal cost of service for the PUs. Simulations indicate that, the model greatly improved the spectral efficiency of the licensed band, as well as increasing the revenue for PUs, while for SUs, it offers increased transmission opportunities and higher rate gains compared to others in the literature.

Incentive model for cognitive IoT networks was illustrated in Lu et al. (2020), that rewards unlicensed IoT devices(UID) to forward the signal of PUs to increase their coverage, by allowing them access to dedicated spectrum. The authors use contract theory to develop the reward model in an environment with incomplete information, meaning the private information of UIDs is not known to PUs. The contracts between the users are formulated in the form of a labor market and includes information regarding expected signal-to-ratios and and payments over each sub-carrier, with a goal to maximizing PUs utility. The authors also propose a heuristic algorithm to select appropriate PUs given a limited budget for contracts. Analysis of framework depicted improved signal to noise ratios (SNR) over complete information models in the literature, while managing to improve the data transfer rates of the UIDs through the licensed spectrum.

Contract theory enabled incentive model for cooperative sensing in cognitive radio networks (CRN) was explored in Gupta et al. (2020), which encourages spatially distributed SUs to cooperate with each other for sensing the occupancy of licensed spectrum and adjusting operating parameters to reduce interference on the PUs spectrum. The authors use contract theory deal with the incomplete information phenomenon mentioned in the previous work, with the contracts limiting the number of participating SUs in the sensing process to ensure energy efficient operation. Simulations show that the framework significantly improved the cooperation among SU and provided increased probability of detection of the presence of PUs compared to other benchmark approaches.

2.3 Leader Selection in Distributed Networks

Leader selection algorithms for distributed synchronous and asynchronous networks were proposed in Vasudevan et al. (2003). These include the secure extrema finding algorithm (SEFA), which uses a single evaluation function for all nodes to select the leader, the secure preference-based leader election algorithm (SPLEA), 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 the asynchronous extrema finding algorithm (AEFA), which is based on the method of termination detection for diffusing computation and is capable of handling topological changes during the election process. SEFA and SPLEA are formulated with a bottom-up hierarchy construction, resulting them acting similar to clustering approaches, but does require the node to remain static during the election process, which is relaxed in the AEFA. However, both the SEFA and SPLEA prove to be more secure compared to AEFA.

A novel evaluation function for leader selection in distributed cognitive radio networks was illustrated in Olabiyi et al. (2012). The function takes into account the normalized values of remaining energy capacity of each node of the network, along with cluster density and number of neighboring nodes within the communication range of a particular candidate node for election purposes. To determine spectrum/channel availability, the authors use a binary hypothesis testing problem while taking into consideration the transmission behaviour of PUs. Analysis demonstrate the proposed algorithm to be more time and energy efficient compared to others in the literature.

Leader election process in mobile ad hoc networks was discussed in Alslaity & Alwidian (2012), which aims at enabling an energy efficient process by reducing the number of messages exchanged between nodes during the election process. The proposed algorithm called the k neighbor-based, energy aware leader election algorithm (KELEA), takes both network density and energy into consideration and maintains these parameters in a descending order list, which is then utilized to complete an election process using reduced number of nodes, that matches the required performance levels in terms of the parameters mentioned above. Analysis shows the proposed algorithm outperforms traditional flooding approaches, although the extent of the simulations run were quite limited.

Spanning tree approach for leader selection in wireless sensor networks is illustrated in Bounceur et al. (2017), where a novel algorithm called Branch Optima to Global Optimum (BROGO) is proposed. Based on the minimum finding algorithm, BROGO operates by obtaining the spanning tree network and then transmit election messages from the leaf node to the root of the tree to find the global leader. The algorithm proved to be highly energy efficient due to the broadcasting of messages from reduced number of nodes, but does however face the risk of single point failure within the spanning tree.

Multi-leader election approach for singular dynamic sensor networks is explored in Yu et al. (2017), with the aim of energy efficient operation and prolonging network life. A combination of three algorithms are proposed here called the voronoi based Multi-leader election Algorithm (VLE), which a centralized leader selection method, node moving based distributed multi-leader election algorithm (NMDLE), which operates as a distributed leader selection approach and periodic sleeping mechanism based multi-leader election algorithm (PSMLE) which is a multi-leader election framework, that ensures efficiency by selecting the minimum number of leaders required for proper networking operation. Voronoi diagrams are used to partition the network which help determine the optimum number of leaders required. Simulation results indicate the algorithm manages to effectively reduce the energy consumption of the communication modules.

Network topology aware approach for leader selection in dynamic networks was depicted in Favier et al. (2020). Here, a novel algorithm was proposed that works using the localized knowledge of all connected nodes to form a communication graph and select the node with the highest closeness centrality as the leader, as it allows faster transfer of information to all nodes. The algorithm was analyzed in the PeerSim simulator, Montresor & Jelasity (2009), and proved to be more stable compared to traditional flooding approaches, while requiring only half as much messages to be transmitted for the election, as well as nodes being able to reach the leader using shorter paths.

CHAPTER III

CLUSTERED CBRS FRAMEWORK

With a view to facilitating the formation of a secondary market for CBRS, that maximizes the utilization of the entire spectrum, improves the service received by users as a whole, increases the revenue stream of the operators involved, all the while ensuring privacy of information to the users, we propose a clustering approach in the GAA layer of CBRS. These clusters are geographically distinct locations spread over a service region (county), with the operations of each being handled by a controlling entity, the GAA leader. Any GAA user within the cluster is eligible to become a leader and this selection is done periodically.

When a GAA user intends to use the CBRS spectrum under PAL-GAA collaborative access, it will submit a request to the leader. GAA users also have to register to the FCC for using the CBRS spectrum and will be provided with an unique id, which will also be stored an FCC database, and has to be included with the spectrum access request. The database is accessible to only the SAS and will allow them to determine the authenticity of the user. The leader will accumulate all requests from members of the cluster over a fixed period, and forward all the requests to the PAL operators. PALs will then decide on what proton of those requests they will accept based on their performance requirements in the licensed band, as well as the bandwidth they are making available to facilitate those additional GAA users, information of which will be communicated to the leader via a verified sharing approach, Rahman, Ahmed & Yuksel (2018). The leader will then transmit the unaccepted requests to other PAL operators, and communicate the final number of accepted requests to all other members of the cluster.

To encourage PAL operators to lease their spectrum frequently in order to ensure the optimal utilization of the spectrum, a reward model is proposed, in which the FCC will reward PAL users according to their level of sharing, which is dependent on the number of accepted share requests from the GAAs and for what duration of time. The offered rewards will be in terms of providing access to additional bandwidth from the GAA spectrum. The rewards will be provided over a fixed period of time like bi-annually or annually and they will allow the PAL operators to further improve their revenues by using the additional spectrum or infrastructure to offer their services to additional customers. However, an increase in the level of sharing will have a negative impact on its native customers utility in terms of increased interference, so finding the optimum level of sharing for PALs are important for preserving their customers quality of service.

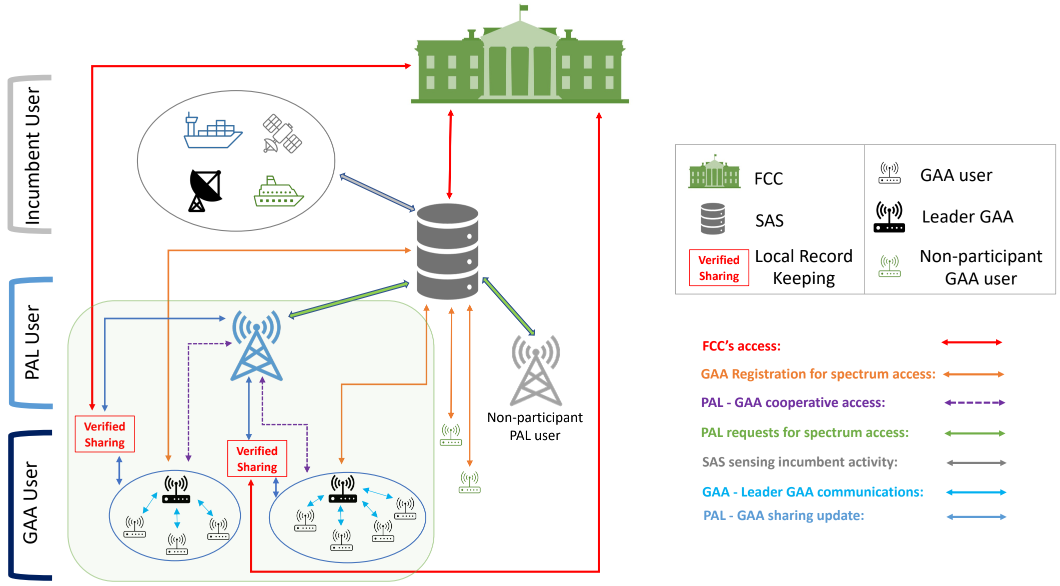


Figure 3.1: Proposed clustered CBRS framework.

Upon receiving approval from PAL for CBRS access, the GAA leader will then communicate with the SAS and send the unique IDs of GAAs accepted for access to PAL spectrum, as well as the bandwidth range the PAL operators are going to use to accommodate those users. The SAS will use the FCC database to prove the legitimacy of the GAA users through their unique IDs. They will also check for incumbent activity in the bandwidth made available by PALs for the clusters and if every thing checks out, they will authorize the clusters for licensed CBRS access via the leader. All the cluster nodes then will then set up temporary PAL-GAA links that will be used to access the licensed spectrum. Under the circumstance that a GAA node is outside the coverage region of all available PAL access points, those particular users will then use the links set up by the leader through the other cluster nodes. The entire model is illustrated in Fig. 3.1.

Table 3.1: List of Symbols and Notations

Symbol	Description
I	Set of clusters
C	Total number of Clusters
J	Set of PAL operators
P	Total number of PAL operators
n_p	Number of total PAL users
U_p	Utility Received by a user from PAL j
$u(.)$	Utility function
δ	Scaling factor
x_j	Number of access points of PAL j
b_j	Licensed bandwidth of PAL j
f_j	Subscription fee of PAL j
P_j	Probability of selecting PAL j as a provider in a non sharing framework
$c_j(b_{cj})$	Sharing cost of PAL j due to cluster c
b_{cj}	Bandwidth of licensed channel shared with cluster c by PAL j
U_{ej}	Effective user utility in a shared environment
P_{ej}	Probability of selecting operator j by both PAL and GAA users
n_{pcj}	Number of requests submitted to PAL j from cluster c
n_c	Number of users in cluster c
α_{cj}	% of requests accepted by PAL j from cluster c
n_{cj}	Number of requests accepted by PAL j from cluster c
R_{N_j}	Revenue of PAL j from native users
n_{nj}	Number of native users of PAL j
Ω_T	Total reward bandwidth available
Ω_j	Reward bandwidth obtained by PAL j
t_{cj}	Total time of licensed access for cluster c in PAL j
R_{uj}	Per unit bandwidth revenue for PAL j
β_j	Tuning parameter of PAL j
R_j	Per user reward revenue for PAL j
R_{rj}	Reward revenue from clusters for PAL j
n_{mj}	Number of migrating users to PAL j
R_{Tj}	Total reward revenue for PAL j

3.1 PAL Customers Problem

Let, a certain county be considered in the CBRS spectrum, where a set of clusters are formed, denoted by $I = \{1,2,3,....,C\}$. The PAL operators in that county are denoted by $J = \{1,2,3,....,P\}$, with the total number of PAL users/customers being n_p. A list of all symbols used in this chapter is given in Table 3.1.

PAL customers are required to pay a fee to avail the services of PAL operators, hence from a customer standpoint, 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, bandwidth minus the fee paid to procure the service similar to, Rahman & Yuksel (2019), Merwaday et al. (2018), Rahman et al. (2019), and can be expressed as follows:

$$U_j = u(x_j, b_j) - f_j \tag{3.1}$$

where, U_j is the total service received by a PAL customer from operator j, $u(x_j, b_j)$ is the utility function which is a measure of the utility received from using PALs services. It has concave characteristics and is dependent on the bandwidth, b_j and the number of access points made available to the customer, x_j by j, and f_j is the monthly subscription fee paid by the customers to avails the service. To obtain the utility function, we follow a similar method depicted in Merwaday et al. (2018) which also defines a concave utility function and formulate it as:

$$u(x_j, b_j) = \delta x_j \sqrt{b_j} \tag{3.2}$$

where, $\delta << 1$ is a scaling factor which is basically used to control the curvature of the utility function. In terms of the subscription fee, f_j has to be higher than the fair market fee for that particular operator's service, otherwise it will allow them to unfairly attract customers from other operators by setting a lower fee, Rahman & Yuksel (2019).

Now in hindsight, it would make sense that the customers choose the operator with the highest value of U_j as it provides the highest utility, but that is not the case. This is because the expression in (3.1) leaves out other network parameters, such as the level of congestion, which is basically the degradation of service/network performance due to the interference caused by different network resources in the spectrum. The congestion is not known by the customers and thus, rather their selections can be made on a probabilistic manner based on the contest theory, Corchon (2007). The probability of choosing any operator, j by a customer can be obtained as follows:

$$P_j = \frac{U_j}{\sum_{i=1}^{P} U_i} \tag{3.3}$$

This ensures that, the operator with the highest utility does not get all the customers, which would create a monopoly situation, although they are more likely to be preferred by users.

3.2 GAA Users Problem

The GAA users are not provided with any interference protection against the other two layers of CBRS, as well as other GAA users, rather the SAS tries to assign them to channels in a such a way that reduces the level of interference. However, this becomes difficult when the number of GAA users are high leading to a higher level congestion in the spectrum, thereby degrading the user utility in the GAA layer, World (2022). One way to overcome this by taking advantage of the light leasing approach implemented in the CBRS and opportunistically use the licensed spectrum of PALs over fixed period of times. Thus, the goal of the GAA clusters in our framework, is to determine the optimum distribution of their users in the PAL layer, that ensures the best total possible utility. To achieve that, we propose using a parameter called the sharing cost, $c(.)$ which is essentially the performance degradation of the licensed spectrum due to the interference caused by the presence of additional users from the GAA layer. We formulate this parameter as follows:

$$c_j(b_{cj}) = \begin{cases} e^{-\log_{10}\frac{b_j}{b_{cj}}} ; when \;\; 0 < b_{cj} \leq b_j \\ 0 \qquad\quad ; when \;\; b_{cj} = 0 \end{cases} \tag{3.4}$$

Here, b_{cj} is the bandwidth made available for sharing by PAL operator j. A higher value or increase of b_{cj} allows the operator to support more GAA users, but will also reduce the effective utility received by the users in the licensed band due to an increase in the sharing cost. On the other hand, decreasing or a lower value of b_{cj} means the operator can support a smaller number of GAA users, there by reducing the negative impact of the additional users on the effective utility in the licensed spectrum, i.e. a lower sharing cost. The cost is 0 when a PAL operator does not share any bandwidth (i.e., $b_{cj} = 0$) with the GAA, while the highest value of $c(.)$ is 1, and obtained when the PAL shares their entire licensed spectrum. The reason for choosing this particular form to define the sharing cost is to maintain the concavity of the utility function and formulate the PAL operators' objective as a concave optimization problem.

By incorporating the sharing cost from different clusters, the effective utility received by the users (both PAL and GAA) in PAL j's licensed spectrum is formulated as follows:

$$U_{ej} = u(x_j, b_j) - \sum_{c=1}^{C} c_j(b_{cj}) - f_j \tag{3.5}$$

Thus, using the same selection approach mentioned in section (3.1), the probability of selecting a particular PAL for licensed access, which is applicable for both PAL and GAA users can be given as follows:

$$P_{ej} = \frac{U_{ej}}{\sum_{i=1}^{P} U_{ei}} \tag{3.6}$$

If the number of GAA users that a cluster wants to incorporate in the licensed spectrum of different PAL operators is denoted by n_c, and the bandwidth made available to the cluster by operator j is b_{cj}, the number of preliminary access requests submitted to operator j will be:

$$n_{pcj} = P_{cj}(b_{cj}) * n_c \tag{3.7}$$

After receiving the requests, the PAL operators will make a decision on what proportion of the requests to accept in their spectrum, based on the government reward and performance degradation incurred by their native users due to the presence of the additional GAA users. This decision metric can be expressed in a probabilistic manner through α_{cj} where,

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

Using α_{cj}, thus the actual number of users granted access to the PAL spectrum is as follows:

$$n_{cj} = \alpha_{cj} n_{pcj} \tag{3.8}$$

So, the objective of a GAA cluster will be to maximize the overall utility of these n_{cj} users by assigning them to appropriate PAL operators. Based on that, the objective function of the GAA cluster will be as follows:

$$\max_{\{n_{cj}\}} \quad \sum_{j=1}^{P} U_{ej} n_{cj} \tag{3.9a}$$

$$\text{such that} \sum_{j=1}^{P} n_{cj} \leq n_c, \tag{3.9b}$$

$$n_{cj} \geq 0; \forall c \forall j. \tag{3.9c}$$

3.3 PAL Operators Problem

For PAL operators, their goal will be to maximize the total revenue generated from their licensed spectrum. This revenue is generated in two fronts: 1) from their native users via subscription fee, and 2) from the government rewards due to sharing their spectrum with the GAAs. The revenue from the native users for any PAL operator j will be basically the total monetary gain from charging the subscription fee, f_j to all its native customers denoted by n_j, which can be calculated using equation (3.6). This native revenue can be obtained using the following:

$$R_{Nj} = n_{nj} f_j = P_{ej} n_p f_j \tag{3.10}$$

To obtain the revenue from the government rewards, we consider a reward model, where the government provides PAL with access to additional reward spectrum for a limited amount of time, based on their level of sharing. This reward spectrum can be allotted from the CBRS GAA spectrum or any other mid-band spectrum if the GAA layer in that particular region is highly congested, to the operators and will provide interference protection from GAA operators, working as an extension of the PALs licensed spectrum. The bandwidth of the reward spectrum is denoted by Ω_T and PAL operators will receive portions of Ω_T based on the number of GAA users they serve/ requests they accept, n_{cj} and how long they access the spectrum, t_{cj}. The amount of bandwidth received as reward by operator j can be found using the following probability:

$$\Omega_j = \frac{\sum_{c \in C} n_{cj} t_{cj}}{\sum_{i=1}^{P} \sum_{c \in C} n_{ci} t_{ci}} \Omega_T \tag{3.11}$$

The value of Ω_T will be determined by the government based on the usage of the unlicensed spectrum by the GAA, and is discussed further on the governments problem section. This reward spectrum will be offered over a fixed amount of time, which can be annually or bi-annually, and allow PAL operators to utilize this spectrum in addition to their own to serve their native customers, or partake other business ventures which are beyond the scope of this work. Our goal now is to formulate the reward as a monetary gain based on the number of GAA users served by the PAL. To achieve that, we consider a simple linear model where the revenue generated by a PAL is directly proportional to its available bandwidth in a non sharing environment as it is not certain that the PAL will use the additional reward spectrum for serving GAA users. Thus the revenue generated from each unit of bandwidth by operator j will be:

$$ru_j = \frac{P_j n_p f_j}{b_j} \tag{3.12}$$

Here, the numerator represents the total revenue from PAL customers in a non-sharing environment, which is why P_j is used instead of P_{ej}, as in a non-sharing environment, the utility is not effected by the sharing cost of the clusters. So using Ω_j, the total revenue earned will be:

$$r_j = \beta_j \frac{P_j n_p f_j}{b_j} \Omega_j; 0 \leq \beta_j \leq 1. \tag{3.13}$$

Here, β_j is a tuning parameter used indicate the preference of PAL j for earning revenue. A higher value β means, j prefers to earn more revenue from the reward spectrum at the cost of losing revenue from native customers as the increase in reward revenue is achieved by allowing more GAA users to use the licensed spectrum, which reduces the total utility of its native user, and may cause them to migrate to the service of other PAL operators, vice-versa. So the revenue earned from serving a single GAA user will be as follows:

$$R_j = \frac{r_j}{\sum_c n_{cj}} \tag{3.14}$$

Thus the revenue generated from serving all the users of different clusters can be given as follows:

$$R_{rj} = \sum_{c=1}^{C} n_{cj} R_j \tag{3.15}$$

Now, in addition to this, PAL operators can also attract GAA users from each other by changing their level of sharing/ bandwidth allocation across the clusters during the sharing period. This is because increasing or decreasing their shared bandwidth will also have an effect on the sharing cost, thereby influencing the clusters to move a portion of their users to a new PAL operator. To determine this, we introduce the parameter, w_{cj} which is essentially the complement of the sharing cost $c_j(b_{cj})$. Clusters will prefer a PAL with a higher value of w_{cj} (lower value of $c_j(b_{cj})$) as it indicates a higher effective utility received. So the number of users that will migrate to PAL j from other PAL operators can be given as follows:

$$n_{mj} = \sum_{c=1}^{C} \frac{w_{cj}}{\sum_{k \in J} w_{ck}} \sum_i n_i; i = J - j \tag{3.16}$$

This migration phenomenon is similar to the case of free riding as mentioned in Merwaday et al. (2018), Rahman, Yuksel & Quint (2018), but will not require any regulatory intervention as in those cases. This is because, free riding occurs when a provider charges less than fare market fees for their services in a shared spectrum environment, which allows them to unfairly attract users from other providers while using their infrastructure and having no impact on the user utility. In our case, the migration is caused by changing the licensed bandwidth allocation, which is proprietary to each individual PAL operator, thus the effect is limited to them only. They can change bandwidth allocation to attract more GAA users, but that will also negatively impact the utility perceived by their native users, who may prefer to move to other providers if the utility degradation caused by the sharing is too high. The total revenue obtained from the reward including the additional n_{mj} users thus will be:

$$R_{Tj} = \sum_{c=1}^{C} (n_{cj} + n_{mj}) R_j \tag{3.17}$$

Now, based on equations (3.10) and (3.17), the revenue of the PAL operators are controlled by two parameters: 1) subscription fee, f_j, an increase in fee will increase the revenue obtained per customer, but also reduce the number of users choosing that particular operator based on equation (3.3) and vice-versa; 2) bandwidth of shared channel, b_{cj} used to support n_{cj}, an increase in bandwidth will allow PALs to accept more requests, increasing the reward obtained from the government, but will also increase the congestion in that channel due the presence of the GAA users and degrade user utility, vice-versa.

So the objective for the PAL operators is to select the optimum values of b_{cj} that will be made available to different clusters and the value of f_j that will be charged to their native users in a such a way that maximizes their revenue i.e. sum of equations (3.10) and (3.17). This can be expressed using the following maximization problem:

$$\max_{f_j,\{b_{cj}\}} P_{ej} n_p f_j + \sum_{c=1}^{C} (n_{cj} + n_{mj}) R_j \tag{3.18a}$$

$$\text{such that} \quad \sum_{c=1}^{C} b_{cj} \leq b_j, \tag{3.18b}$$

$$f_j, b_{cj} \geq 0; \forall c, \forall j. \tag{3.18c}$$

3.4 Government's Problem

The goal of the government is to maximize the payoff of all users and operators in the clustered framework. This includes all the PAL customers and GAA users within the clusters, as well as all PAL operators. While the utilities of the PAL customers are dependent on their respective operators, the case for the GAA users and PAL operators is partially dependent on the total available reward spectrum, Ω_T. If Ω_T is set high, PAL operators will increase their level of sharing to get a higher portion of the reward bandwidth and improve their reward revenue. This will also allow more GAA users to use the licensed spectrum but will negatively impact the utility PAL users due to the increase in congestion in the licensed band caused by the presence of additional GAA users.

A similar effect will also be faced by other GAA users who are not part of the sharing framework and will have less of the GAA band to use, increasing the congestion in the GAA layer and reducing utility. On the contrary, a lower value of Ω_T, means PAL's will generate a lower reward revenue from the reduced reward spectrum, thus reduce their level of sharing by lowering the tuning parameter β_j to accept fewer requests from the clusters. This would mean lower number of GAA users will be eligible for using the licensed spectrum, which in turn will increase the congestion in the GAA layer due to the presence of increased number of GAA users, and reduce the unlicensed spectrum utility. Another issue here will be that, as PAL will not be extensively sharing their spectrum, the spectral efficiency of the licensed layers will be reduced, because in instances when the PAL data traffic demand is not so high, that spectrum will remain vacant or underutilized. Thus the optimum selection of the reward spectrum Ω_T is essential to maintain adequate service levels in all layers of CBRS and ensure maximum spectral efficiency of the band.

Thus, the objective for the government will be to maximize the service utility of all PAL customers and GAA users within the clusters based on equation (3.5), and the total revenue earned by the PAL operators from both their customers and the reward band according to equations 3.10 and 3.13 respectively, by selecting an optimum amount of reward bandwidth to be made available that encourages PAL operators to share a decent amount of licensed CBRS spectrum with the GAA users to reduce the congestion in the GAA tier, as well as increase their revenue from the reward band, although not so much that it reduces the utility received by its own customers. This can be mathematically expressed as follows:

$$\max_{\Omega_T} \sum_{c=1}^{C} \sum_{j=1}^{P} U_{ej} n_{cj} + \sum_{j=1}^{P} [U_{ej} P_{ej} n_p + P_{ej} n_p f_j + \sum_{c=1}^{C} (n_{cj} + n_{mj}) R_j] \tag{3.19a}$$

such that

$$\Omega_T \leq \sum_{j=1}^{P} \Omega_j, \tag{3.19b}$$

$$\Omega_T \geq 0. \tag{3.19c}$$

CHAPTER IV

SIMPLIFIED TWO-PAL CLUSTERED CBRS MODEL

In order to observe the effects of the clustered framework on the behaviour of the PAL operators, we consider a simplified version of the CBRS market with two PAL operators: PAL 1 and PAL 2 who are competing exclusively with each other for providing service to both PAL and GAA users (from the clusters). The licensed bandwidth of both operators are $10 \leq b_1, b_2 \leq 10m$; where $m = \{1, 2, 3, 4\}$ is the number of licenses owned by each. PAL 1 is assumed to be the larger provider, with its number of access points x_1 being greater than that of PAL 2's x_2. Thus for an equal amount of licensed bandwidth, PAL 1's utility offered to the users will be higher than that of PAL 2 and consequently their subscription fee should also be more ($f_1 > f_2$). We further assume that, two clusters: cluster 1 and cluster 2 request licensed access from the PAL operators with cluster 1 having a larger users base compared to cluster 2. The amount of bandwidth shared with clusters 1 and 2 by PAL 1 and 2 are b_{11}, b_{21} and b_{12}, b_{22} respectively. One thing to note that, although we are considering two PAL operators, they may not be the only ones, i.e. $b_1 + b_2 \leq 70MHz$, rather their actions taken regarding fee selection and sharing allocation to the clusters, only effect each others total revenue gain, not the others, vice-versa.

The optimization problems for the two operators based on (3.18a) using the expanded expressions of the parameters can be given as follows:

PAL 1's problem:

$$\max_{f_1, b_{11}, b_{21}} \frac{U_{e1}}{U_{e1} + U_{e2}} n_p f_1 + \frac{U_{e1}}{U_{e1} + U_{e2}} (n_1 + n_2) R_1 + \frac{w_{11}}{w_{11} + w_{12}} \frac{U_{e2}}{U_{e1} + U_{e2}} n_1 R_1 + \frac{w_{21}}{w_{21} + w_{22}} \frac{U_{e2}}{U_{e1} + U_{e2}} n_2 R_1 \quad (4.1a)$$

$$\text{such that} \qquad b_{11} + b_{21} \leq b_1, \tag{4.1b}$$

$$f_1, b_{11}, b_{21} \geq 0. \tag{4.1c}$$

PAL 2's problem:

$$\begin{aligned} \max_{f_2, b_{12}, b_{22}} \; & \frac{U_{e2}}{U_{e1} + U_{e2}} n_p f_2 + \frac{U_{e2}}{U_{e1} + U_{e2}} (n_1 + n_2) R_2 + \\ & \frac{w_{12}}{w_{11} + w_{12}} \frac{U_{e1}}{U_{e1} + U_{e2}} n_1 R_2 + \frac{w_{22}}{w_{21} + w_{22}} \frac{U_{e1}}{U_{e1} + U_{e2}} n_2 R_2 \end{aligned} \tag{4.2a}$$

$$\text{such that} \qquad b_{12} + b_{22} \leq b_2, \tag{4.2b}$$

$$f_2, b_{12}, b_{22} \geq 0. \tag{4.2c}$$

4.1 Determining Subscription Fee

The subscription fee for licensed access to PAL network employed on native PAL users will be based on the total number of access points and the number of licensed channels/ total licensed bandwidth of a particular PAL operator. An operator with a higher number of access points will be able to provide a larger utility due to its better infrastructure, thus allowing it to command a larger subscription fee compared to others, under the assumption that they have equal number of licenses. Similarly, if the infrastructure of the providers are identical, the one with the higher number of licenses, i.e. total licensed bandwidth, will charge higher as they will be able to provide better utility due to the capability of spreading out its users base over a larger frequency band, reducing the congestion experienced, as well as the willingness to recoup the additional costs of the bids to attain higher number of licenses.

The level of bandwidth sharing to the GAA layer does not have any implication on the fees set by the operators as they are set before hand and without the operators knowledge of how much spectrum they will eventually make available to the GAA users. Rather, the main goal while determining this fee, is to obtain the maximum revenue from the PAL layer, i.e. PAL customers.

Thus the fees set by the two providers will be basically based on maximizing the monetary gain from the native PAL users in a non-sharing environment and can be obtained as the following:

$$f_1^* = \arg\max_{f_1} \frac{U_1}{U_1+U_2} n_p f_1 \tag{4.3a}$$

$$f_2^* = \arg\max_{f_2} \frac{U_2}{U_1+U_2} n_p f_2 \tag{4.3b}$$

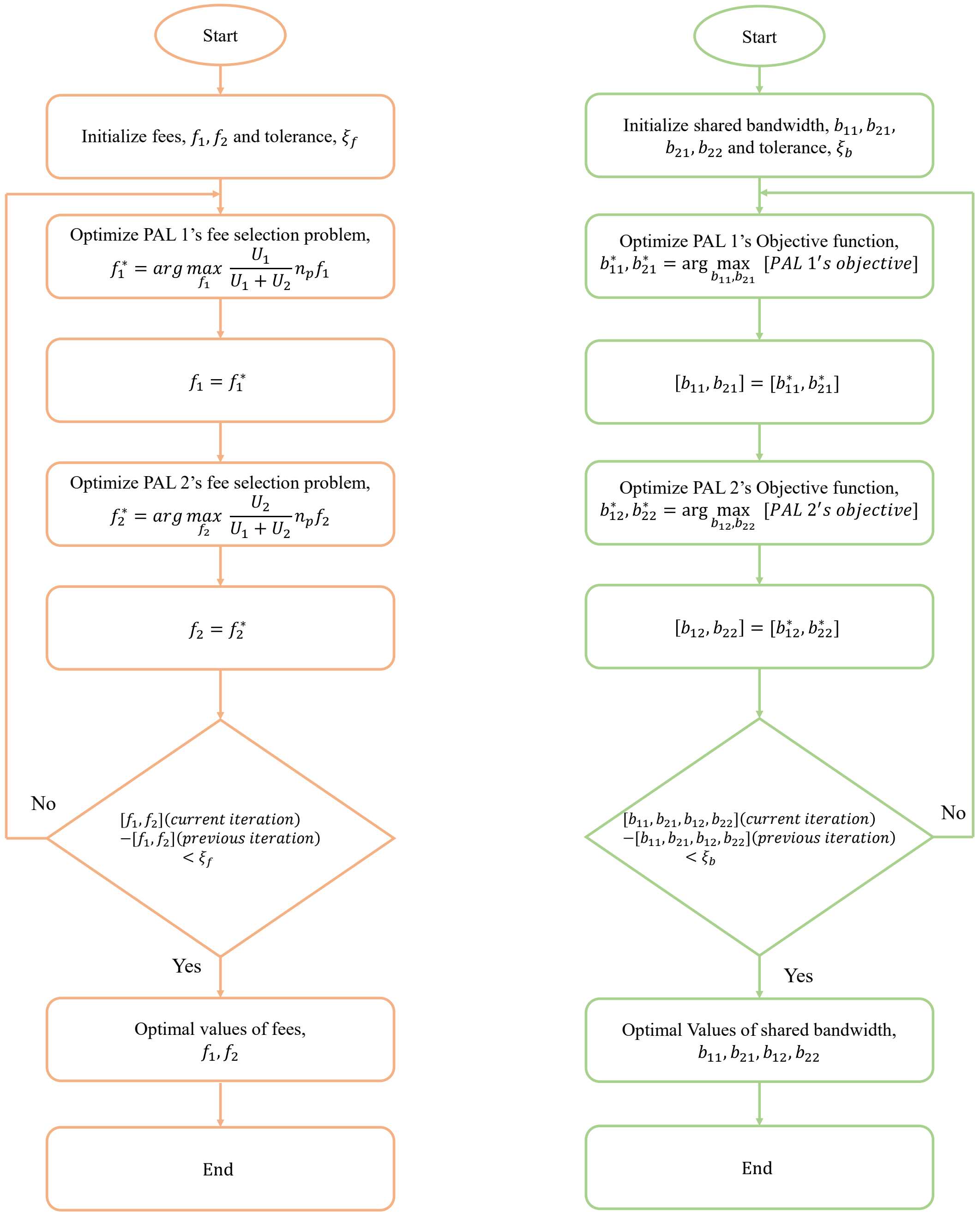
In order to obtain the optimum values of the fees f_1^* and f_2^*, we propose using a simple iterative algorithm that simultaneously solves the equations (4.3a) and (4.3b). The algorithm will start by taking random initial values of fees and use them to solve (4.3a) to obtain f_1, and then use that value, instead of the initial ones to determine f_2. This 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 workings of the fee selection algorithm is depicted in Algorithm 1.

Algorithm 1 Fee Selection Algorithm

```
initialize, $f_1, f_2$
initialize tolerance, $\xi_f$
while $|f_1^*(i) - f_1^*(i-1)| \geq \xi_f$ & $|f_2^*(i) - f_2^*(i-1)| \geq \xi_f$ do
    $f_1^*(i) = \arg\max \frac{U_1}{U_1+U_2} n_p f_1$
    $f_1 = f_1^*(i)$
    $f_2^*(i) = \arg\max \frac{U_2}{U_1+U_2} n_p f_2$
    $f_2 = f_2^*(i)$
    $i \leftarrow i+1$
end while
```

4.2 Licensed Bandwidth Sharing

Using the fees obtained from Algorithm 1, optimum bandwidth sharing strategies of the two operators can be determined by finding the values of $b_{11}, b_{21}, b_{21}, b_{22}$ that maximizes PAL 1's and PAL 2's problems depicted in 4.1a and 4.2a respectively. For this purpose, we again follow a similar iterative approach to the one used in Algorithm 1. Firstly, the algorithm will solve equations (4.1a), (4.1b) and (4.1c), considering f_1 as a design parameter obtained from the fee selection algorithm rather than a design variable, to determine optimum allocations b_{11}^*, b_{21}^*. Using this, a similar strategy will then be employed to solve the equations (4.1a), (4.1b) and (4.1c) to obtain PAL 2's optimum allocations b_{12}^*, b_{22}^*, considering f_2 as a design parameter and continue the process until convergence is reached.



(a) Fee selection algorithm

(b) Bandwidth sharing algorithm

Figure 4.1: Work-flow of the overall solution approach for PAL objectives.

The bandwidth allocation algorithm is illustrated in Algorithm 2, while the overall solution approach to find the optimum values of the decision parameters are illustrated in Figure 4.1.

Algorithm 2 Bandwidth Sharing Algorithm

```
initialize, $b_{11}, b_{21}, b_{12}, b_{22}$
initialize tolerance, $\xi_b$
obtain $f_1, f_2$ from Algorithm 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 Objective)
    $b_{11} = b^*_{11}(i), b_{21} = b^*_{21}(i)$
    $[b^*_{12}(i), b^*_{22}(i)] = \arg\max$ (PAL 2's Objective)
    $b_{12} = b^*_{12}(i), b_{22} = b^*_{22}(i)$
    $i \leftarrow i + 1$
end while
```

CHAPTER V

GAA LEADER SELECTION

In the proposed framework, the GAA leader serves as a central communicating medium between the PAL operators and clusters, submitting the licensed access requests from GAA users within the clusters to the PAL operators, as well as relaying the accepted number of requests from the PAL operator to the GAA users. They are also responsible for setting up the temporary licensed connection with the PALs which can then be used by members of the cluster, outside the service region of PAL operators, through the leader's access point. Thus the proper selection of the leader is essential for the optimum performance of the shared spectrum scheme. To achieve that, we propose a novel leader selection algorithm based on the approach of termination detection in diffusing computation depicted in Dijkstra & Scholten (1980), Vasudevan et al. (2003). The algorithm works by forming a spanning tree steaming from a primary source node within the network until the terminal nodes are reached. The source node can be the GAA leader from the immediate previous time frame of licensed access or any other node if the leader becomes inactive. The source nodes initiates the election procedure by sending an election initiation message to its directly neighbouring nodes, called the subordinate nodes, who then do the same to their direct subordinates until all the nodes of the network have been covered. Upon recipient of the message, each nodes calculates its eligibility to become a leader using a function called the leader evaluation score (LES). These scores are then transmitted back through the spanning tree to the primary source node, who then evaluates all the LES and selects the leader having the highest score.

5.1 Leader Evaluation Score (LES)

The center of our proposed algorithm is the leader evaluation score or LES, which is used determine and compare the worthiness of nodes within to network to become the leader. Every node will calculate its LES once the election initiation message is received. The LES is formulated as the following:

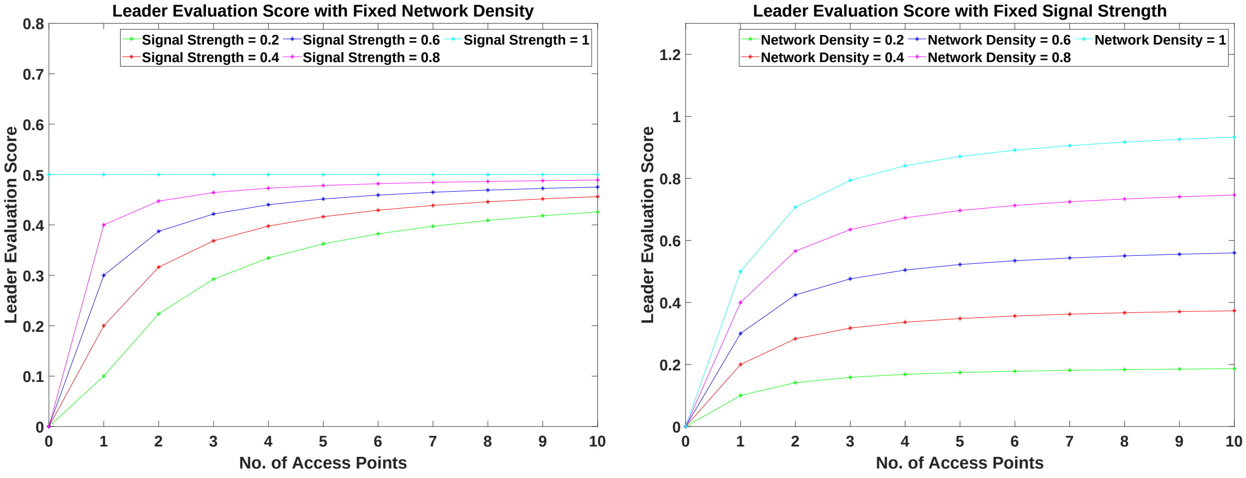
$$L_d = \eta_d \Psi_d = \eta_d (\Psi_{av})_d^{\frac{1}{x_d}} \tag{5.1}$$

Here, η_d is the network density for cluster node d, which is ratio the number of nodes that node d can directly communicate and the total number of nodes in the cluster. Ψ_d is the observed signal strength at node d, which is essentially the average signal strength of the all the access points accessible to node d, powered to the inverse of the number of those access points. To determine the signal strength of each individual access point, we follow the approach depicted in Rahman, Yuksel & Quint (2018), where signal strength = 1/(distance to access point)^2. So Ψ_{av} can be written as:

$$\Psi_{av_d} = \frac{1}{x_d} \sum_{k=1}^{x_d} \frac{1}{d_k^2} \tag{5.2}$$

where, x_d is the number of access points within the range of node d. The inverse of x_d is used in determining Ψ_d to signify the importance of the number of access points accessible to node d on LES. This is because a larger number of access points will allow data traffic to be distributed more sparsely, offering a better utility because of reduced interference. It also ensures that a larger number of users will be able to use the PAL spectrum.

The value of LES, L_d ranges between [0 1], and the effect of the variables η_d, x_d and Ψ_d on the score is depicted in Figure 5.1. L_d rises with the increase of any of the 3 variables. The rise is higher with changes to x_d, compared to Ψ_d, which intuitively makes sense, as x_d has linear characteristics, meaning an increase of each unit of x_d, would result in an identical increase in L_d. On the other hand, Ψ_d is concavely related to L_d, meaning an unit increase of Ψ_d would result in an increase of L_d, following the concept of diminishing return, i.e. a smaller increment for increasing Ψ_d. Also, the curves in all cases become concave with the rise of the number of access points,



(a) For fixed network density, $\eta_d = 0.5$

(b) For fixed average signal strength, $(\Psi_{av})_d = 0.5$

Figure 5.1: The effect of network density, signal strength and number of access points on the Leader Evaluation Score (LES).

which is identical to the case of our utility function, proving the adequacy of the LES function for the leader election process.

5.2 Messages for Election Process

Throughout the election process, the nodes will generate and use 4 types messages to communicate with each other through the spanning tree. They are:

1) **E_Init**: *E_Init* or the election initiation message is used to indicate the start of the new election process. After the end of previous cycle of licensed access, the previous leader will start the election by sending the *E_Init* to its directly adjacent neighbouring nodes. In case the previous leader is inactive or becomes disconnected, another node which is able to sense the absence will initiate the process instead. The *E_Init* will contain the unique of ID of the source node, helping the recipient nodes to coordinate later messages in the election process. Each neighbouring node, after receiving *E_Init*, will send their own version of *E_Init* to its neighbours incorporating its own ID as well as the ID of its source. This process is continued until the terminal nodes of the network the reached.

2) **E_Val**: *E_Val* or the evaluation message is used to communicate each nodes LES to their respective source nodes. When a node receives the *E_Init*, it will calculate its LES using (5.1). The

terminal nodes will then immediately transmit their scores using the *E_Val* message to their source nodes as well as their unique IDs. The source nodes except the primary one will wait to receive the *E_Val* messages from all its subordinate nodes, after which it will compare their scores with its own and send an *E_Val* message to its own source containing the maximum value of LES with the corresponding node ID. This process is continued until the primary source node is reached, which is the only node in the network that does not send an *E_Val* message.

3) **N_Rep**: *N_Rep* or the no repeat message is used by nodes to indicate a source node that the subordinate node will not be responding to it with *E_Val* message. This can occur either when a) two nodes have the same source node which can be identified from the received *E_Init*, or b) when a node receives multiple *E_Init* from different source nodes, and will send the *N_Rep* to all the nodes except the one for which the *E_Init* was received the earliest. This helps reduce the number of messages shared during the election process by eliminating redundant or duplicate *E_Init* and *E_Val* messages.

4) **E_Lead**: *E_Lead* or the elected leader message is used to define the leader to all the nodes of the network. Once the primary source node receives all the *E_Val* messages, it will select the node with the maximum LES as the leader, whose ID will then be transmitted using the *E_Lead* to all the nodes.

5.3 Assumptions During Leader Selection Procedure

The following assumptions are considered for the leader selection process:

- Each cluster consist of multiple nodes, which essentially serve as the access points for the GAA users, with every node having the ability to become a leader.
- All the nodes have unique IDs which can be used to distinguish them during the election process.
- Each node maintains a routing table which holds information regarding its own ID and LES, the ID of its source, the ID and LES of its subordinates and the ID of the newly elected leader. The entries are updated during the election process through the 4 types of messages.

- The nodes communicate with each other using bidirectional links having the same link capacity and supporting an identical number of GAA users.

- All nodes are active during the election process, i.e. no node is disconnected from the network. Thus the leader from the previous time-period initiates the election process.

Using the assumptions and messages mentioned above, the LSA is summarized in Algorithm 3.

5.4 Working Procedure of the Leader Selection Algorithm

To illustrate the operational procedure of our proposed leader selection algorithm (Algorithm 3), we consider the example network in Fig. 5.2. The network consists of 11 nodes each having an unique ID ranging from 1 to 11. Node 1 was the leader of the immediate previous time frame of licensed access and upon finish of that, it will initiate the election process by sending an *E_Init* message containing its ID to adjacent subordinate nodes 2 and 3. They will use that *E_Init* to update the source entries of their tables and send new *E_Init* to their subordinate nodes 3, 4, 5 and 2, 5, 6, 7 respectively. After sending their *E_Init*, nodes 2 and 3 will compute their LES and wait for the response of the subordinates.

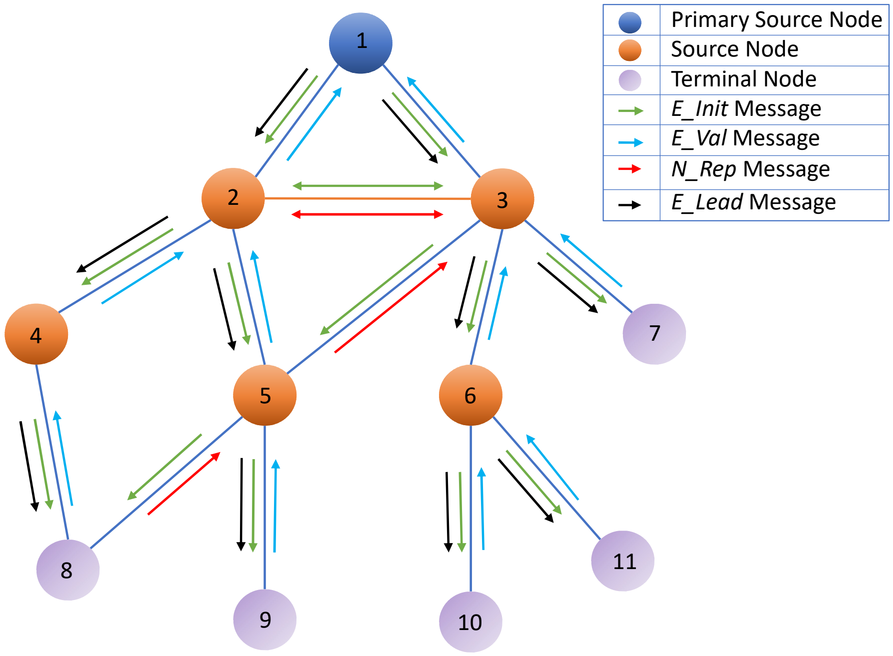


Figure 5.2: Message flow between nodes during the leader selection process.

Algorithm 3 Leader Selection Algorithm, LSA

```
1:  $X_{id}$ ←Store all the IDs    ▷ Assign unique IDs to all nodes
2:  $X_{dc}$ ← List all directly connected nodes for each node    ▷ Define node connections within the cluster
3:  $X_n$ ←Store network densities of all nodes

4:  $\delta$ ← Define maximum service region around each access point    ▷ Identify Signal Strength
5:  $X_{ap}$ ← Store number of access points accessible to each node

6:  $s_{pi} = rand(X_{id})$ ←Store primary source ID    ▷ Select primary source node
7:  $s_{pc} = X_{dc}(s_p)$ ← Store directly connected node 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:         $\eta$ ← calculate and store LES of $s_{pc}(i)$
12:         Send $E\_Val(s_{pc}(i), \eta)$ to source
13:         if Additional $E\_Init(s_{pi}, s_{pj} \neq s_{pi})$ received then
14:             Send $N\_Rep(s_{pc}(i))$ to all $s_{pj}$'s
15:             $n_r$ ← Store number of $N\_Rep$ sent
16:         end if
17:     else
18:         Send $E\_Init(s_{pi}, s_{pc}(i))$ to all $X_{dc}(s_{pc}(i))$
19:         if Additional $E\_Init(s_{pi}, s_{pj} \neq s_{pi})$ received then
20:             Send $N\_Rep(s_{pc}(i))$ to all $s_{pj}$'s
21:             $n_r$ ← Store number of $N\_Rep$ sent
22:         end if
23:         $\eta$ ← calculate and store LES of $s_{pc}(i)$
24:         $n_e$ ← Store number of $E\_Val$s received
25:         if $n_e == length(s_{pc}(i)) - n_r$ then
26:             $L_p$ ← max (LES from all $E\_Val$'s, $\eta$)
27:             $L_{id}$ ← ID of node with the max LES
28:             Send $E\_Val(s_{pc}(i), \eta)$ to $s_{pi}$
29:         else
30:             Repeat steps 10-28 for all $X_{dc}(s_{pc}(i))$ and subsequent subordinate nodes
31:         end if
32:     end if
33:     $i = i + 1$
34: end while

35: $L_{FS}$ ← max(LES from all $E\_Val$s of $s_{pc}$)
36: $L_F$ ← ID of node with maximum LES from all $E\_Val$s of $s_{pc}$    ▷ New leader selection
37: Send $E\_Lead(L_F)$ to all subordinate nodes
```

The *E_Init* messages of 2 and 3 will include the ID of node 1 indicating as their source, as well as their own IDs which are indicative of them being sources to their subordinate nodes. The reason for including the source node ID is it will reduce the number of messages, as when two nodes such as nodes 2 and 3, notice they have the received *E_Init* from the same source, they do not need to respond to each other rather just respond to their source who will eventually make decision about the higher LES, thereby proving the communication between them to be redundant. In those cases, they will send the *N_Rep* message indicating the other node to not wait for their *E_Val* message. A similar process is followed between node 3, 5 and 8, 5.

After receiving the *E_Init* from nodes 2 and 3, nodes 4, 5 and 6 will follow a similar procedure to nodes 2, 3, updating their tables and sending new *E_Init* to their subordinates. Node 7 on the other hand does not have any such subordinate node and thus will compute the LES and send an *E_Val* message to node 3, containing its ID and LES score. Nodes 8, 9, 10 and 11 will follow suit, and send similar *E_Val* messages to their source nodes.

Table 5.1: Completed Routing Table of Nodes 2 and 3

Node ID	Source Node	LES	Subordinate Nodes Info			Max(LES)	Max(LES) ID	New Leader
			ID	N_Rep Received	LES			
2	1	0.49	3	1	X	0.51	5	3
			4	0	0.32			
			5	0	0.51			
3	1	0.72	2	1	X	0.72	3	3
			5	1	X			
			6	0	0.32			
			7	0	0.55			

Once nodes 4, 5 and 6 receive all the *E_Val* messages from their subordinates, they will update their LES into their tables, compare those scores with their own, and send the maximum score with the ID of the node with that score to their sources 2 and 3, who will then follow a similar procedure and send new *E_Val* to the primary source node 1. Node 1 will then compare the scores and select the node with the maximum LES as the leader. The ID of the new leader will then be transmitted using the *E_Lead* message as depicted in the figure. All the nodes will use that *E_Lead* to update the leader entries of their tables, and start sending information regarding licensed access to the new leader. A completed table for nodes 2 and 3 are depicted in Table 5.1.

CHAPTER VI

SIMULATION RESULTS

In this section, we use the simplified two-provider two- cluster model to test the effectiveness of our proposed clustered framework. We begin by showing the convergence characteristics of the PALs problem using the fee selection and bandwidth sharing algorithms, as well as the effects of their level of sharing on one another. We also demonstrate the effectiveness of the model over the traditional non-clustered approach from a revenue standpoint for the PAL operators. After that, we test out our proposed leader selection algorithm on a randomly generated network. We observe the effects of the network density of the nodes, and the proximity and number of PAL access points on this leader selection approach. Finally we observe how the utility of GAA users through the clusters compared to the traditional CBRS approach.

6.1 Convergence of PAL's Objective

To obtain the equilibrium values of PAL 1 and PAL 2's decision variables, f_1, b_{11}, b_{21} and f_2, b_{12}, b_{22} respectively, we first employ the fee selection algorithm to determine f_1 and f_2, followed by the bandwidth sharing algorithm, incorporating the obtained fees, to derive the shared bandwidth amounts, b_{11}, b_{21}, b_{12} and b_{22}. The procedure for the solution is as follows:

1. Initialize decision variables, f_1, f_2, b_{11}, b_{21}, b_{12}, and b_{22} randomly. Set tolerances, $\xi_f = 0.1$, $\xi_b = 1000$, and maximum number of iterations, $max_{iter} = 10$.
2. Simultaneously solve equations (4.3a) and (4.3b) to obtain the optimum values f_1^* and f_2^*, compare them to the values from the previous iteration and continue until the difference between them is less or equal to $\xi_f = 0.1$. Once achieved, set $f_1 = f_1^*$ and $f_2 = f_2^*$.

3. Solve the PALs objective function simultaneously using the obtained fees from the previous step. This is done by first solving PAL 1's problem, i.e. equations (4.1a), (4.1b) and (4.1c) to obtain the optimum values b^*_{11} and b^*_{21}. Set $b_{11} = b^*_{11}$ and $b_{21} = b^*_{21}$ and then solve PAL 2's problem, i.e. equations (4.2a), (4.2b) and (4.2c) to obtain b^*_{12} and b^*_{22}. Set $b_{12} = b^*_{12}$ and $b_{22} = b^*_{22}$ and compare these obtained values with that of the previous iteration. Continue this process until the difference between them is equal or below ξ_b.
4. Repeat steps 2 and 3 for a 1000 different iterations, by randomizing the design variables of the framework, x_1, x_2, n_p, n_1 and n_2 and obtain the average depiction of the decision process.

The simulation was done in MATLAB, using the optimization toolbox. The maximization problem for the fees i.e. equations (4.3a) and (4.3b) were solved using the non-linear solver for unconstrained problems, the $fminunc$ function, where the equations in step 3 were solved using the non-linear constrained optimization problem solver, the $fmincon$ function. For the unconstrained problems of the fees, the quasi-newton method was followed, as it offers faster and more efficient convergence compared to gradient descent methods, by using both the first and second order behaviour of the objective function as opposed to only the first order, Lam (2020).

As for the constrained optimization problems for determining bandwidth allocation, the sequential quadratic programming (SQP) method was followed, which resembles the newton's method but for constrained optimization and offers great efficiency and accuracy in finding the solutions compared to others in the literature, Simulink (n.d.). One thing to note, as both $fminunc$ and $fmincon$ deal with minimization problems, our objectives functions were converted from maximization to minimization simply by multiplying them with -1.

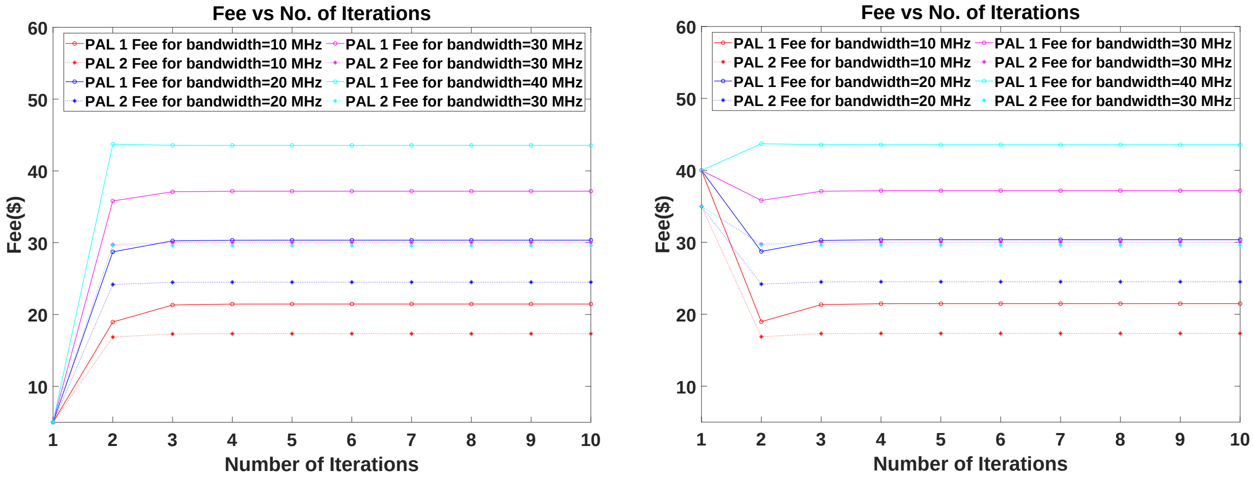
The convergence time of the algorithms as well as the value of the decision variables at the equilibrium is effected by the design parameters. Hence, we run the entire simulation for a 1000 times, taking randomized values of the design variables and obtain an average observation of the convergence performance. The considered values of all parameters involved are depicted in Table 6.1. The reason for using a range of values for the initialization of the decision parameters, is to observe the effects of random initialization on the converge performance, i.e., whether or not the algorithms manage to converge at or close to the same optimum value regardless of the starting point of the simulation. The range for the fee selection algorithm was set to [1, 40], for no specific reason as it is an unconstrained optimization problem, and other ranges can also be considered. For the bandwidth sharing algorithm, that specific range for chosen in order to comply with the constraint in equation (4.1b), when an operator has 10 MHz of licensed spectrum.

The simulation was run in 4 different scenarios with regards to the amount of licensed bandwidth owned by PALs 1 and 2, which were set to (b_1, b_2) = (10, 10) MHz, (20, 20) MHz, (30, 30) MHz and (40, 30) MHz. The average convergence time across all configurations throughout the entire simulation process was 4 iterations with the maximum being 7.

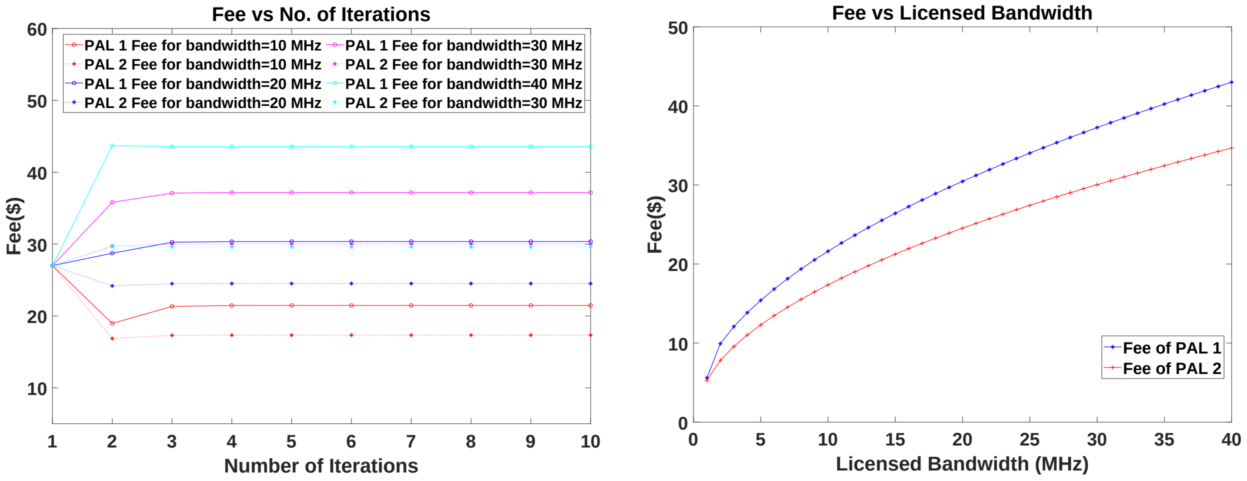
Table 6.1: Parameter Values for Simulation

Parameters	**Values**
x_1	100
x_2	70
b_1	(10, 20, 30, 40) MHz
b_2	(10, 20, 30) MHz
n_p	[1000, 1400]
n_1	[150, 220]
n_2	[90, 140]
$\alpha_{11}, \alpha_{21}, \alpha_{12}, \alpha_{22}$	1, 1, 1, 1
β_1, β_2	0.5, 0.5
initial f_1, f_2	[1, 40]
initial $b_{11}, b_{21}, b_{12}, b_{22}$	[0.1, 2.5]

The results from the fee selection algorithm is depicted in Figure 6.1. In all cases, the algorithm showed similar performance in reaching convergence, regardless of the initial values of the decision parameters, as can be observed from Figure 6.1a, 6.1b. Thus, the random initialization process does not have any effects on the convergence characteristics and the algorithm reaches the same optimum value in all cases. The average values of the algorithm over the entire simulation process in depicted in Figure 6.1c. The effects the licensed bandwidth on the fee is depicted in Figure 6.1d and shows the fees increase with the amount of licensed bandwidth owned. This intuitively makes sense as a higher bandwidth will allow the operators to provide better service/ utility to the users according to equation (3.1), enabling them to charge higher subscription fees.



(a) Initial (f_1, f_2)=(5, 5) (b) Initial (f_1, f_2)=(40, 35)

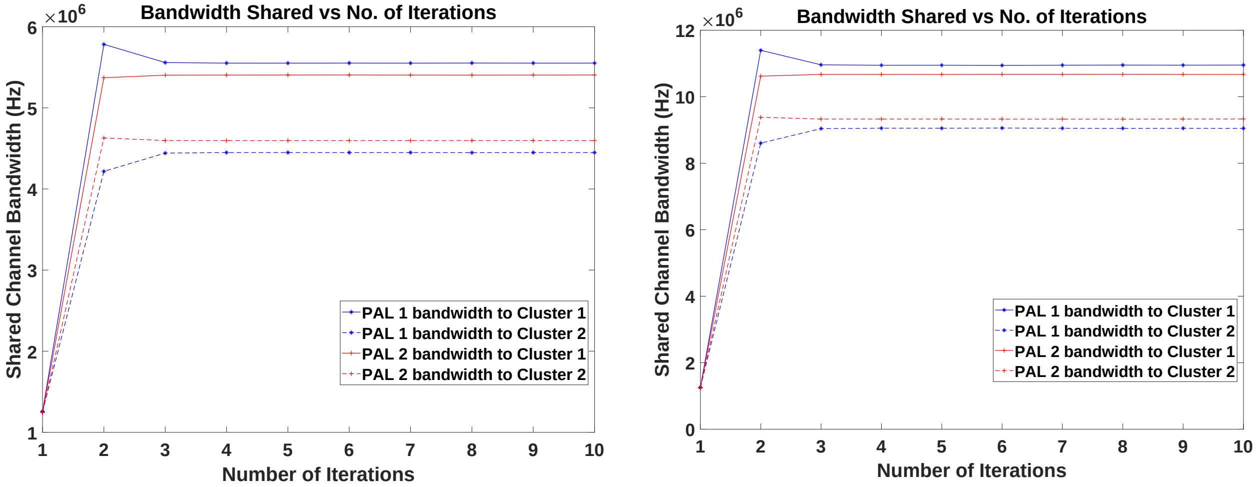


(c) Average convergence over 1000 iterations (d) Effect of licensed bandwidth on fees

Figure 6.1: Convergence of the fee selection

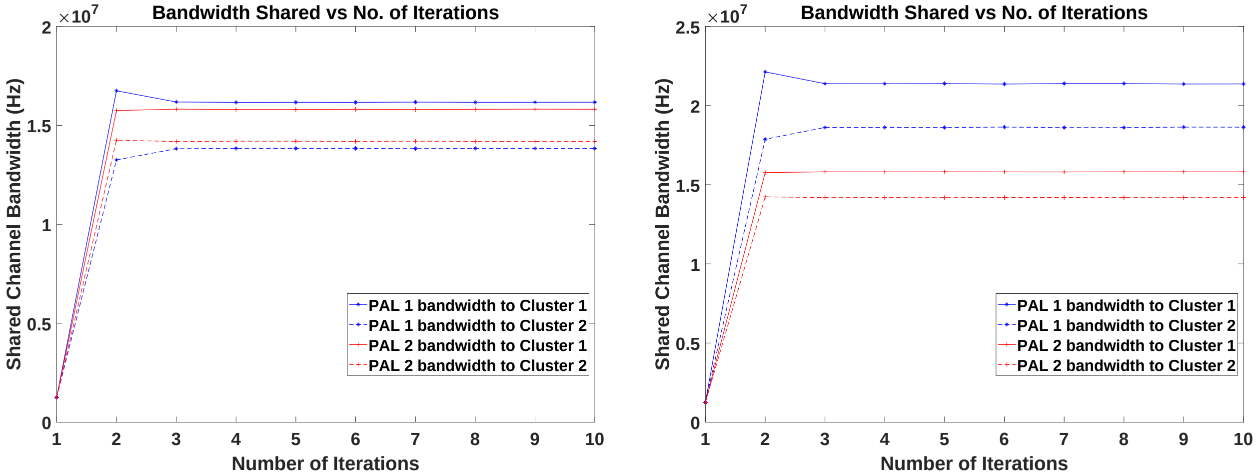
The bandwidth sharing algorithm was also tested on the 4 different scenarios mentioned above and its convergence performance is shown in Figure 6.2. In all cases, the algorithms reached equilibrium at about the same number of iterations. From the graphs it can be observed that, PAL 1 always allocated a higher bandwidth for cluster 1 than PAL 2, while trailing in cluster 2 (except for configuration 4, i.e., Figure 6.2d, where it lead in both cases). This is because PAL 1 is the larger provider with more access points, so it can attract more customers due to offering higher utility. On the other hand, cluster 1 is the larger of the two clusters, meaning it would submit more licensed access requests.

Thus PAL 1 prefers to leverage its superior utility to attract more of the cluster 1 requests, thereby sharing a higher bandwidth with cluster 1, which subsequently leads to a lower allocation for cluster 2 as the total available bandwidth is limited.



(a) Scenario 1: both PAL 1 and PAL 2 with 10 MHz of licensed bandwidth

(b) Scenario 2: both PAL 1 and PAL 2 with 20 MHz of licensed bandwidth



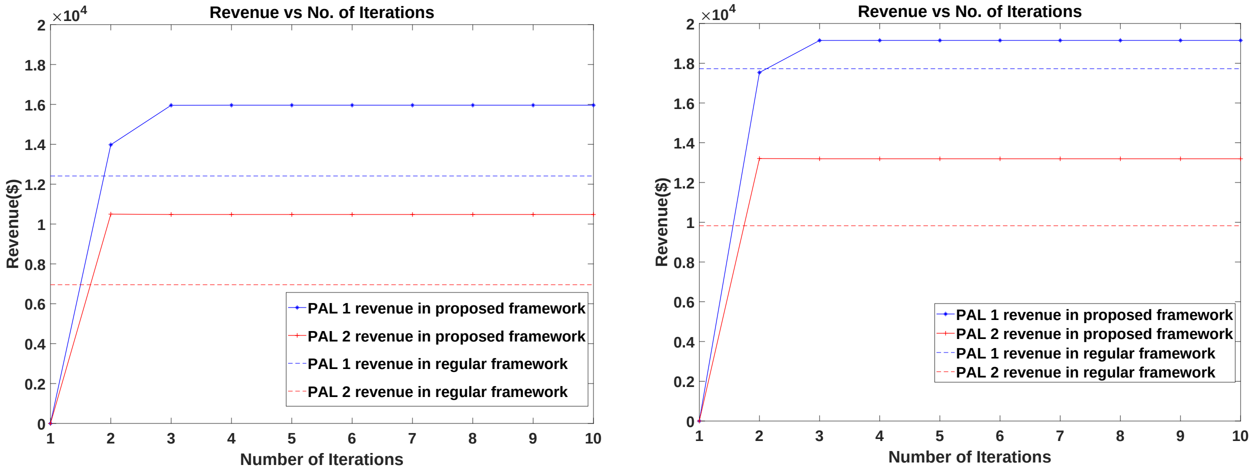
(c) Scenario 3: both PAL 1 and PAL 2 with 30 MHz of licensed bandwidth

(d) Scenario 4: PAL 1 with 40 MHz and PAL 2 with 30 MHz of licensed bandwidth

Figure 6.2: Convergence characteristics of the bandwidth sharing algorithm.

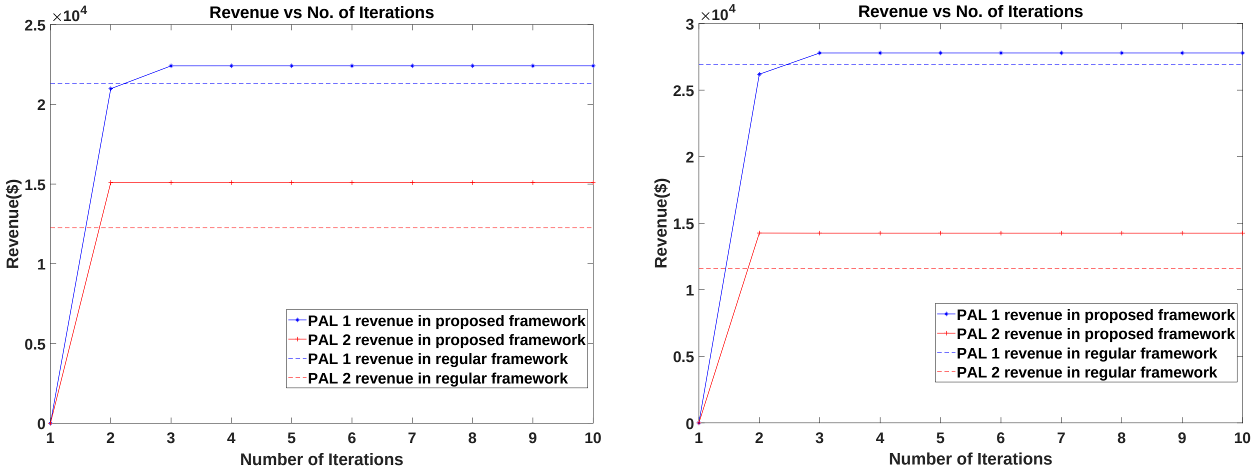
Similarly, PAL 2 also chooses to shared a higher bandwidth with cluster 1, but due to the knowledge of PAL 1's higher service utility and elevated focus of PAL 1, PAL 2 understands that it would find it more difficult to compete with PAL 1 in cluster 1, thus choosing to share a lesser bandwidth compared to PAL 1, which allows it to overtake the shared bandwidth of PAL 1 in cluster

2. As for Figure 6.2d, because PAL 1 has a higher total bandwidth than PAL 2, it is able to beat PAL 2 in terms of sharing in both clusters, although following the similar pattern of allocating a higher bandwidth for cluster 1 than 2.



(a) Scenario 1: both PAL 1 and PAL 2 with 10 MHz of licensed bandwidth

(b) Scenario 2: both PAL 1 and PAL 2 with 20 MHz of licensed bandwidth



(c) Scenario 3: both PAL 1 and PAL 2 with 30 MHz of licensed bandwidth

(d) Scenario 4: PAL 1 with 40 MHz and PAL 2 with 30 MHz of licensed bandwidth

Figure 6.3: Convergence of PAL objective in the form of revenue earned from PAL customers and government reward.

Combining the output of the two algorithms, we obtain the utilities of PAL 1 and PAL 2, which exhibit similar convergence characteristics in all 4 scenarios as illustrated in Figure 6.3. In every case, 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, enabling it to garner a higher revenue from the subscription fees and the reward bandwidth.

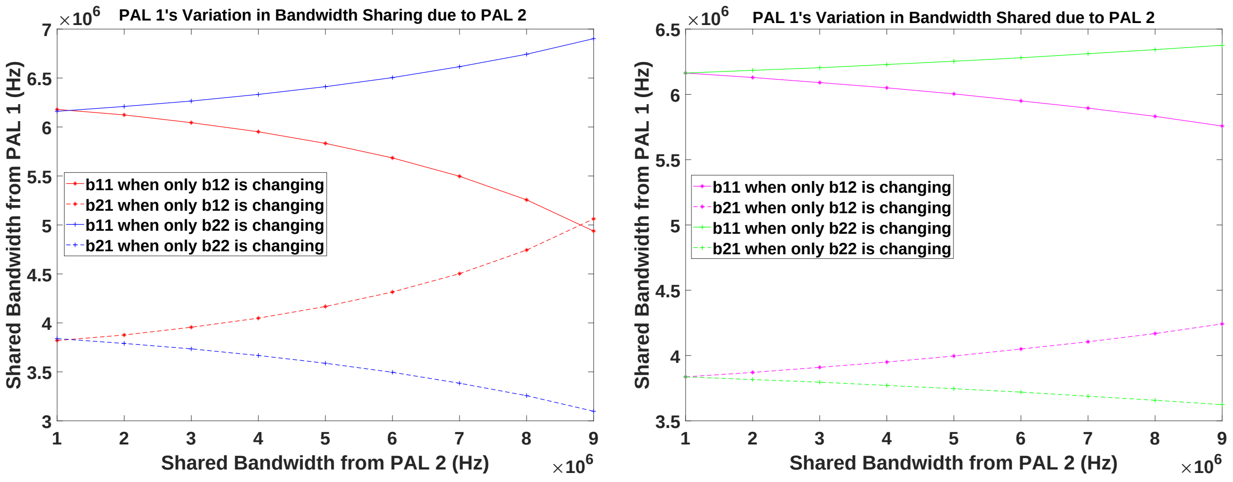
Figure 6.3 also compares the PAL revenues from the proposed model to the traditional non-rewarding CBRS approach and across all scenarios, our model manages to outperform the current model. The gap between the two utilities, however, does diminish with the increase in bandwidth, especially for PAL 1. This can be attributed to the fact that, during the simulation process, we keep the number of access points for PALs same in all 4 scenarios for computational simplicity, but that would not be the case in practical.

Because as bandwidth increases, operators will increase the number of access points to support additional users through their larger bandwidth, which will improve their offered utility and attract more PAL and GAA users, thus increasing their revenue from both native users and government rewards. In the traditional approach in such a case, only the revenue from the native users will increase, thus the gap between the utilities will be higher in favour of our framework, than depicted in the Figure 6.3. But even with that handicap, our framework still manages to out perform the traditional approach in all cases, proving the effectiveness of our clustered model.

One thing that can be noted from Figures 6.1, 6.2 and 6.3 that, the problems for PAL 2 converges earlier compared to PAL 1. This is because during the first iteration, PAL 1 uses the random initial values of the decision variables, whereas PAL 2 uses the values obtained from PAL 1, which offers a better measure for evaluation and is not as affected by the random initialization process. Thus if the order was reversed and PAL 2 was evaluated before PAL 1, the objectives of PAL 1 would converge earlier.

6.2 Bandwidth Sharing Strategy

In order to observe how the operators select or alter their allocation strategies based on each others decision, we consider 2 cases. In case 1, both operators have identical 10 MHz of licensed bandwidth, while in case 2, they have 10 and 20 MHz of licensed bandwidths respectively. To simulate and observe the sharing behavior, the shared bandwidth of PAL 2 is increased steadily from 1 MHz to 9 MHz, and its effect on PAL 1's sharing strategy is observed. The results are depicted in Figure 6.4.



(a) Case 1: Both PAL 1 and PAL 2 have 10 MHz bandwidth

(b) Case 2: PAL 1 and PAL 2 have 10 and 20 MHz bandwidth respectively

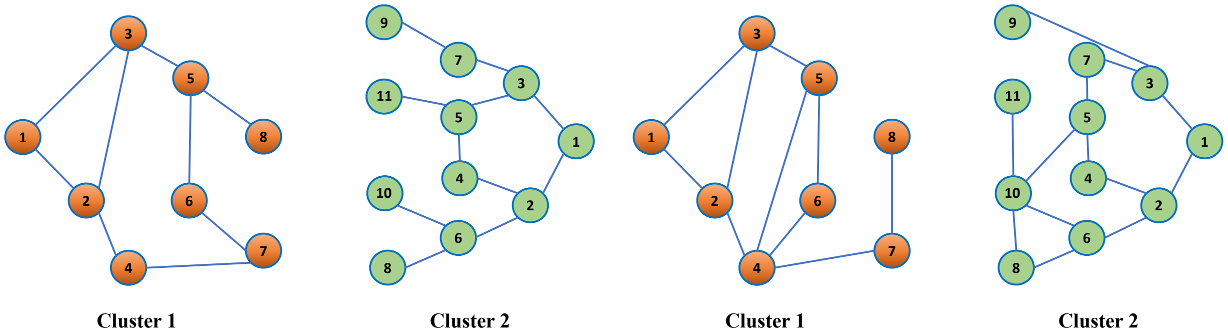
Figure 6.4: Effects of one provider's sharing strategy on others.

In both cases, it can be observed that, as PAL 2 increases it's allocation on any of the clusters, PAL 1 tends to reduce its allocated bandwidth on that particular cluster, while increasing on the other. This is why the curves have opposite trajectories for both clusters. Based on this observation, it can be posited that, when multiples PALs compete over providing licensed access to a multi cluster environment, they tend to prefer allocating higher bandwidths were they face less competition, to attract a higher portion of their GAA requests, which is why when PAL 2 increases its allocation on either one of the clusters while keeping the allocation on the other unchanged, PAL 1 tends to migrate to the latter one, and try to obtain a higher reward bandwidth from there, as it is likely that, due to PAL 1 increasing its bandwidth allocation, it will be able to obtain a larger portion of the GAA users from that particular cluster.

One thing to be noted, the gradient of the curves are much steeper in case 1, compared to case 2. This can be attributed to the difference in licensed bandwidth between them. When they have equal amounts of licensed channels, PAL 1 prefers to quickly migrate its allocation as it knows it will be able to generate a higher reward revenue, owing to the fact that, they both have the same amount of bandwidth to allocate, thus PAL 2 focusing its allocation in one cluster will prevent it from doing the same to the next one. But when PAL 2 has twice the bandwidth, PAL 1 figures out that, even if it relocates its allocation, PAL 2 will still be able to match or even better that due to its increases spectrum resources, thus the allocation migrating process is much slower.

6.3 Evaluation of the Leader Selection Algorithm

We consider a 30 x 30 square grid as our experimental region to test our proposed leader selection algorithm. It is populated using 20 access points, with 10 belonging to each of the PAL operators. The access points were distributed randomly, making sure that no access points share the same coordinates within the grid. Cluster 1 was placed near the center of the region, whereas cluster 2 was placed closed to the right-hand edge. Each unit of distance within the grid equals to 100 meters and region of service around each access point was set to 450 according to the data obtained from Verizon, thus any node of the clusters falling within this serviceable region, will be able use those particular access points for licensed access, Verizon (2020).

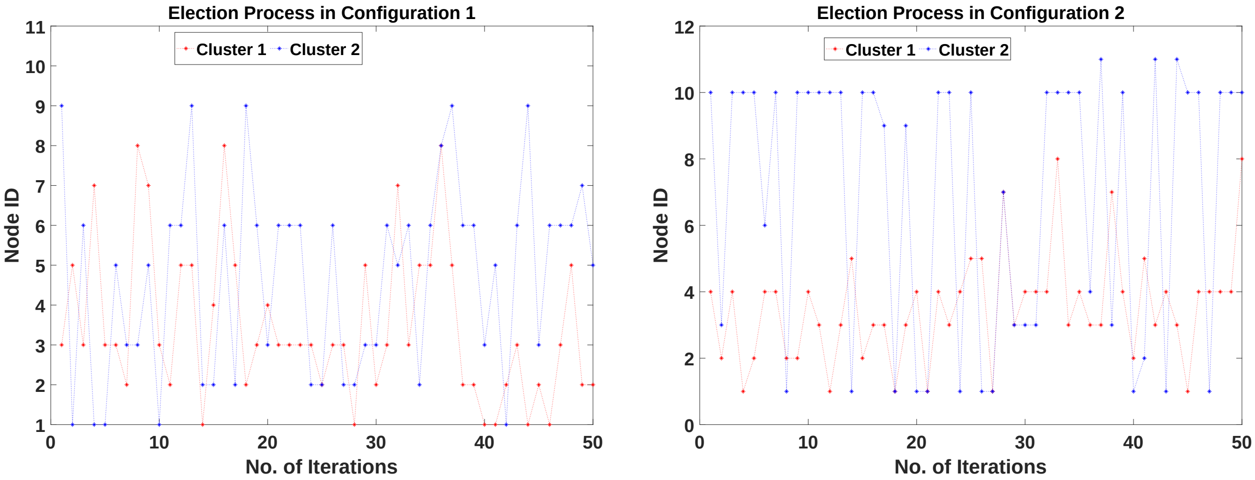


(a) Configuration 1: no singular node with maximum network density

(b) Configuration 2: node 4 in cluster 1 and node 10 in cluster has maximum density in respective clusters

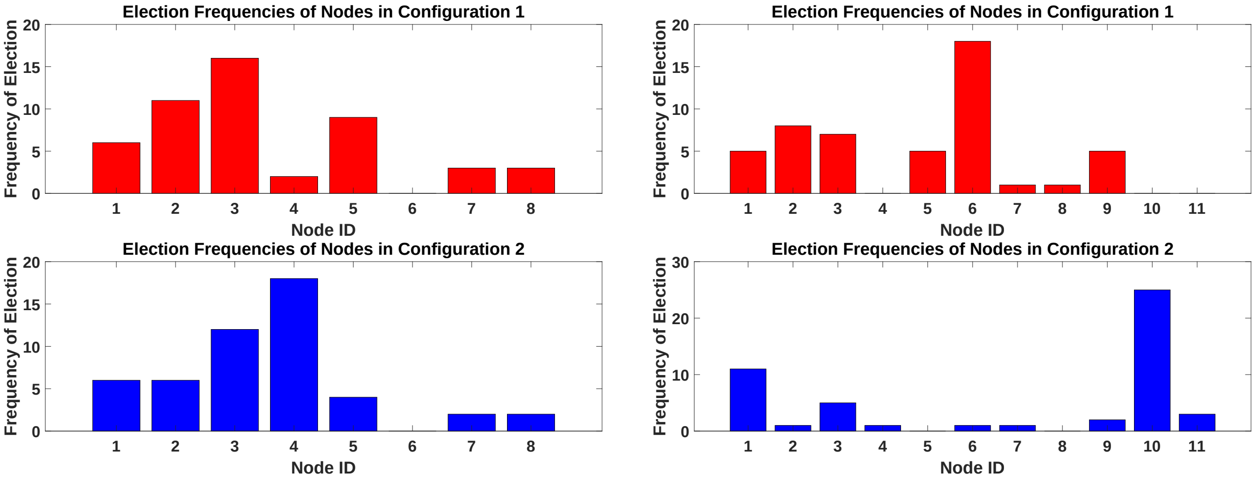
Figure 6.5: Cluster configurations for the simulation of the leader selection algorithm.

We run the algorithm with two separate configurations of each cluster, configuration 1 (Figure 6.5a), where no singular node of the cluster has a maximum network density, i.e. multiple nodes can communicate with the same peak number of neighbouring nodes, and configuration 2 (Figure 6.5a), where a particular node obtains a maximum density and can directly communicate with the highest number of neighbouring nodes. In configuration 1, nodes 2, 3, 5 of cluster 1 and nodes 2, 3, 5, 6 of cluster 2 is provided with the maximum direct connectivity to other nodes at 3, i.e. have the same network density. On the other hand, for configuration 2, node 4 and 10 in clusters 1 and 2 respectively have the peak network densities with direct connectivity to 4 nodes.



(a) Election process in configuration 1

(b) Election process in configuration 2



(c) Election frequency of each node in both configurations of cluster 1

(d) Election frequency of each node in both configurations of cluster 2

Figure 6.6: Simulation of the leader selection algorithm.

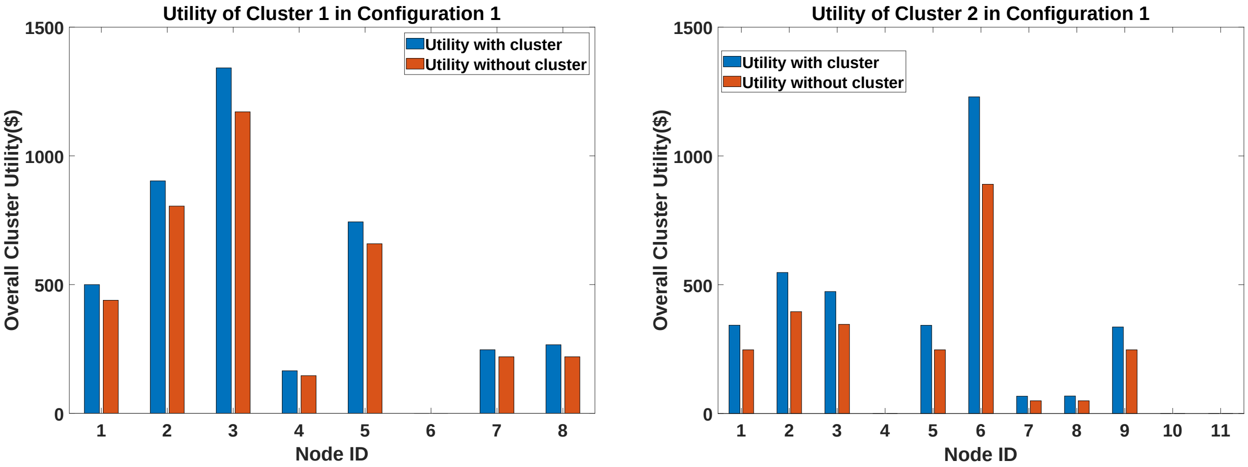
The algorithm was run for 50 iterations for both the configurations in MATLAB, each time with a new distribution of access points, while keeping the positioning of the clusters same. The results of the election process is depicted in Figure 6.6.

For configuration 1 (Figure 6.6a), the selection process appears to be random depending on the access point distribution for any particular iteration, particularly for cluster 1 where nodes 2 and 3, both having the peak node densities for that cluster, are selected more often. For cluster 2, node 6 appears as the run away leader followed by node 2, being elected twice as more. But under the same distributions of access points, in configuration 2 (Figure 6.6b), node 4 in cluster 1 and node 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 it can be posited that, when multiple nodes within the cluster have the same peak network density, the leader is selected based on the total signal strength available to the nodes, i.e. their proximity to and the number of PAL access points they have access to. On the other hand, for similar configuration of access points as before, if a singular node of cluster achieves a peak network density, that node is more frequently elected as the leader.

Now all the cluster nodes will set up the temporary PAL-GAA links with available PAL access points which will be used for licensed access to the CBRS spectrum. Any node outside the service region of all these access points, will be able use the links set up by the leader through the cluster via multi-hop routing. To measure the overall utility offered through this process to the GAA users, we make slight modifications to equation (3.2). As utility is defined as the total service received by a particular entity, in the case of the clusters it would be basically dependent on the signal strength that a node will experience and the number of access points that it would be able to communicate with i.e. the total number of PAL-GAA links set up by the node. Hence, the utility of a singular cluster node can be calculate using the following:

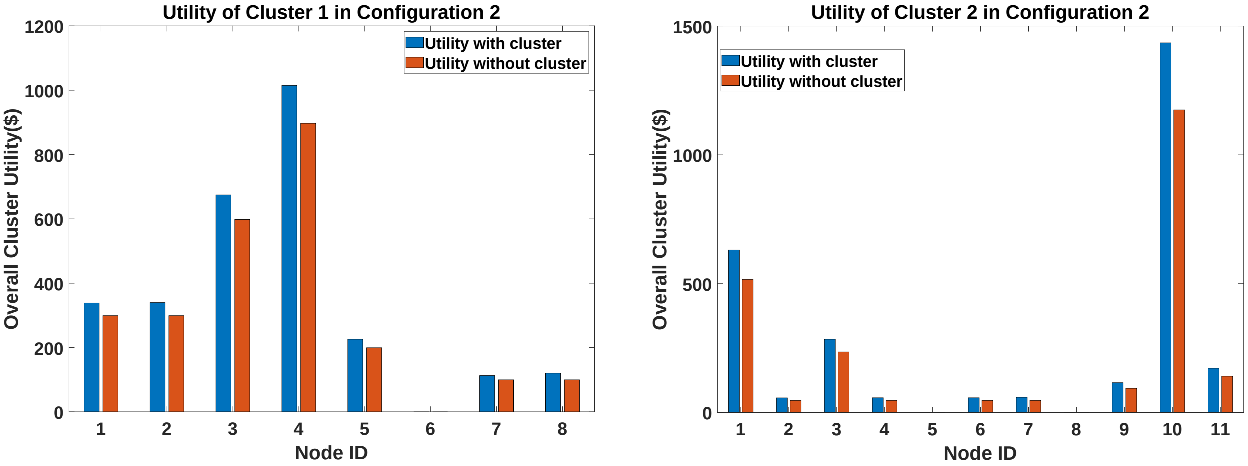
$$u_m = \delta_n X_m \sqrt{(\Psi_{av)_m}} \tag{6.1}$$

where, m refers to the node ID, X_m refers to the number of access points reachable by m, $(\Psi_{av})_m$ is the average signal strength observed by m, and δ_n is a smoothing constant > 0, used to control the sensitivity of u_m to X_m and $(\Psi_{av})_m$.



(a) Cluster 1 in configuration 1

(b) Cluster 2 in configuration 1



(c) Cluster 1 in configuration 2

(d) Cluster 2 in configuration 2

Figure 6.7: Total utility of the GAA clusters during each nodes role as a leader, compared to the traditional CBRS approach.

The total cluster utility obtained during each nodes role as a leader over the entire simulation period can be formulated as follows:

$$u_{tm} = \sum_{i=1}^{e_m} \sum_{m=1}^{N_c} (u_m)_i \tag{6.2}$$

where e_m is the number of times node m is elected as a leader, and N_c is the total number of nodes in the cluster.

The results of the obtained overall utility through the clustered approach are depicted in Fig. 6.7 and compared with the utility from the traditional CBRS approach for both configurations. The smoothing constant, δ_n, was set to 10 throughout the simulation process. In all cases, regardless of which node serves as the leader, the clustered model outperforms the current model across the entire simulation process. This is due to the fact that, under the traditional approach, when GAA nodes are not within the coverage region of any PAL access point, they are unable to use the licensed 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 nodes, the utilities in the graphs are 0, because they are never elected during the entire simulation. Also the nodes that are more frequently elected using LSA, tend to offer a higher overall utility, simply because they are in operation as a leader for longer duration (more iterations).

6.4 Effects of Poor Infrastructure on Election Process

For simulations up to now, the access points were uniformly distributed across our grid environment which ensured that the clusters were surrounded by a good number of access points, i.e. experienced adequate signal strength. Now in order to evaluate the case when the access points available are scarce, i.e. poor network connectivity, which will be the case in rural areas consisting of poor infrastructure, we change the distribution of the access points in a such a way that, fewer number of access points are in proximity of the clusters. Using this environment, the algorithm run for configuration 2 of the clusters and the election results are depicted in Figure 6.8.

It can be seen that, node 1 in cluster 1 becomes the most selected leader in spite of having half the network density of node 4. Similarly, node 1 in cluster 2 overtakes node 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, thus had a higher number of access points surrounding it in good networking condition, whereas cluster 2 was situated close to the edge and had reduced number access points accessible to it. Thus, changing the network configuration to simulate poor networking conditions does not effect cluster 2 as profoundly as cluster 1, although in both cases, a new node becomes the most probable leader.

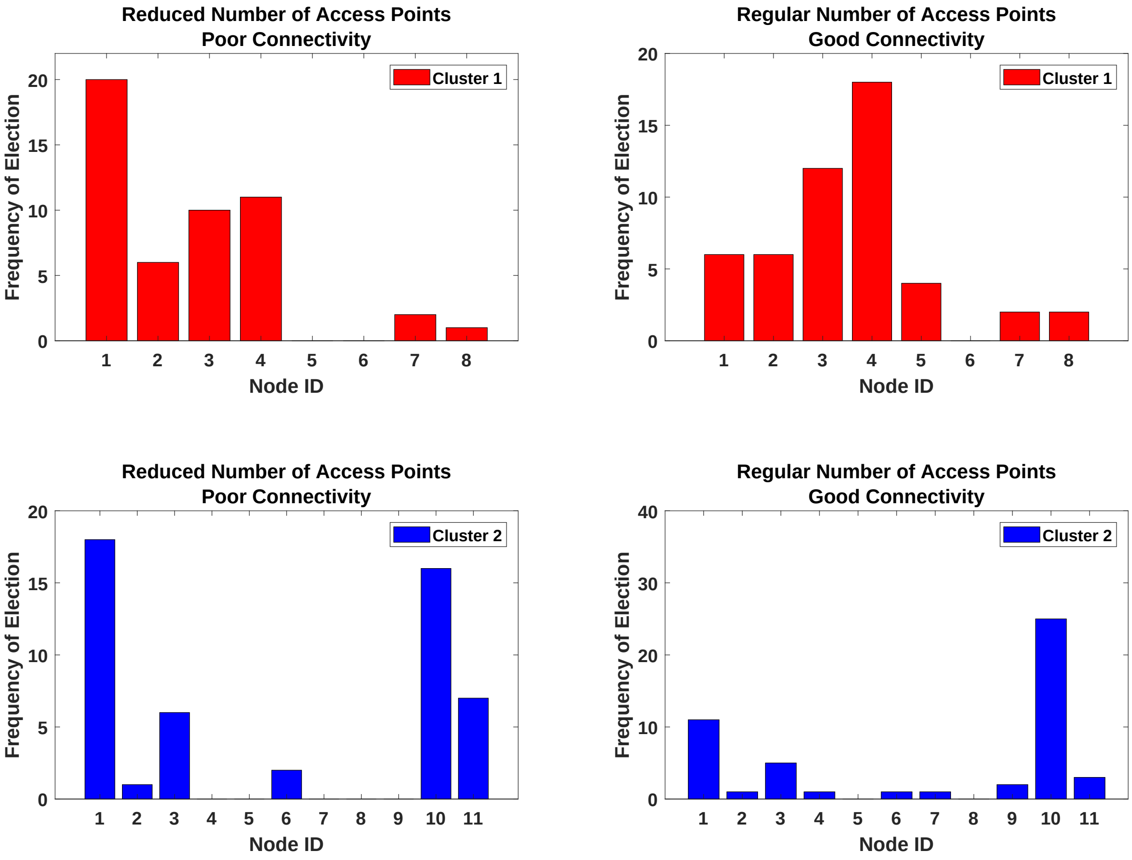


Figure 6.8: Comparison of elected frequencies of all nodes in favorable and poor networking conditions.

So from these arguments, it can be hypothesized that, under good networking conditions, network density plays a more defining role in electing the leader where in poor conditions with less accessible networking infrastructure, signal strength becomes the prominent defining factor.

CHAPTER VII

CONCLUSION AND FUTURE WORKS

Wireless spectrum will play a key figure in meeting the ever growing demand of wireless connectivity and ensuring the effective deployment of 5G and beyond networks. As such, the efficient utilization of this limited resource has been extensively studied by the research community with techniques such as dynamic spectrum sharing, carrier aggregation, dynamic time division duplex, etc, as well as receiving significant attention from the governments, evident by the opening of large amount federal spectrum for commercial usage. One such band is the CBRS, which allows commercial users to operate in the same frequency band as federal incumbent users, through spectrum sharing, with a particular emphasis towards effective sharing between the licensed and unlicensed layers. The current model uses the centralized SAS to facilitate that sharing, but it proves to be quite efficient in the sense that it fails to provide licensed operators an estimation of the total data demand that they may receive from the unlicensed layer, while requiring a higher messaging overhead for unlicensed users to gain that access. Also, currently there are no incentives for licensed operators to share their spectrum, all of which may result in the unlicensed GAA layer to become congested as more users begin to access the spectrum.

In this thesis, we look to solve these challenges by proposing a novel framework that offers a convenient way for sharing the licensed layer spectrum. We form multiple GAA clusters that act as a single entity when requesting access to the PAL spectrum, while operating collaboratively when accessing the spectrum, allowing users outside the PAL service region to gain wireless access through the clusters. To ensure effective communication between the clusters and PAL operators, each cluster will nominate a leader to accumulate and submit the access requests to PAL, and convey their response to the rest of the cluster. We formulate a distributed leader election algorithm called

LSA to nominate this leader from the user pool of the clusters. In order to encourage PAL operators to share their spectrum more frequently, we propose a government reward scheme that compensates PALs based on their level of sharing, by giving them access to additional spectrum for limited periods. We tested our framework in a two PAL-two cluster CBRS environment and it effectively managed to beat the current CBRS approach, both in terms of offering superior revenue to PAL operators, and increased service utility to the GAA users of the clusters.

In the future, we would like to make further improvements to the model and explore the following:

1. Expand our simulation to a n-PAL, n-cluster CBRS environment and develop a more efficient bandwidth sharing algorithm, as the computational complexity for the current algorithm in such a set up will be too high.

2. Incorporate the number of access points made available to the GAA clusters as a decision parameter and obtain the access point sharing strategies of operators. In the thesis, that number was kept constant for simplicity, but PAL operators may choose to make certain access points unavailable to the cluster, if a high number of PAL customers are using those particular access points.

3. Develop a framework to obtain the optimum value of the tuning parameter, β in the government reward. Currently, there are not enough data about the PAL business models to partake such a task in this thesis.

4. Observe the effects of cluster node inactivity in the leader election process. In the current work, we considered all the GAA nodes were active which may not be the case in practical.

5. Illustrate the effects of the link capacities used to communicate among GAA nodes within the cluster. In the thesis, we considered all the links with same capacity for computational simplicity, but that would not be the case in real life, as nodes with different number of GAA users will deploy different link capacities owing to the difference in data transfer demand.

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BIOGRAPHICAL SKETCH

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