Pervasive Spectrum Sharing for Improved Wireless Experience

Mostafizur Rahman
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PERVASIVE SPECTRUM SHARING FOR IMPROVED WIRELESS EXPERIENCE

by

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A dissertation submitted in partial fulfilment of the requirements
for the degree of Doctor of Philosophy
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Major Professor: Murat Yuksel
ABSTRACT

Spectrum sharing among cellular users has been a promising approach to attain better efficiency in the use of the limited spectral bands. The existing dynamic spectrum access techniques include sharing of the licensed spectrum bands by allowing other ‘secondary’ users to use the bands if the licensee ‘primary’ user is idle. This primary-secondary spectrum sharing is limited in terms of design space, and may not be sufficient to meet the ever-increasing demand of connectivity and high signal quality to improve the end-users’ wireless experience. The next step to increase spectrum efficiency is to design markets where sharing takes place pervasively among primary providers rather than leaving it to the limited case of when the primary licensee is idle. Attaining contractual pervasive spectrum sharing among primary providers, a.k.a. co-primary spectrum sharing (Co-PSS), involves additional costs for the users, e.g., roaming fee. Co-PSS without additional charge to the users poses two major challenges: 1) regulatory approaches must be introduced to incentivize and encourage providers for sharing spectrum resources, and 2) small providers in Co-PSS markets may freeride on large providers’ networks as the customers of the small providers may be using the spectrum and infrastructure resources of large providers. Such freeriding opportunities in Co-PSS markets must be minimized to realize the benefits of primary-level sharing.

This dissertation considers a subsidy-based spectrum sharing (SBSS) market to facilitate Co-PSS where providers are explicitly incentivized to share spectrum resources. It focuses on minimizing freeriding in SBSS markets by introducing a novel game-theoretic and heuristic algorithm. It proposes “Proof of Sharing (PoS)”, an architecture to account spectrum sharing. It also demonstrates how to utilize PoS-like crowdsourced data to predict cellular tower locations which help to generate a truthful coverage map. Finally, this dissertation extends Co-PSS to two new models with government infrastructure and spectrum as rewards.
I dedicate this dissertation to my parents Azharur Rahman and Nargis Akhter.

Without their support, it would not be possible to fulfill my dream.

They were always with me to support until the end while fighting against all the odds.
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Completing a dissertation toward a Ph.D. is always a challenging milestone to achieve. It requires immense support from the nearest and dearest ones. I am lucky to have such encouraging family
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CHAPTER 1: INTRODUCTION

Easier availability and mobility of wireless devices has increased the demand for spectrum use [6]. More mobile devices are being admitted to the wireless networking environment which has raised a concern on the long-term availability of the already-scarce spectrum resources, e.g., spectrum allocation in the US, Fig. 1.1. From the early days of government-controlled fully regulated market to today’s semi-regulated spectrum market, various models have been considered to meet the growing need for wireless use [7, 8]. Existing static allocation of cellular spectrum has seen sharing schemes between providers over the recent years. However, such spectrum sharing usually occurred in a way that prevents the providers from having significant business dominance. In such cases, small providers may participate in spectrum sharing with the leading provider on a secondary basis. Such sharing seems unlikely to meet the actual need of users on a large scale. To meet the growing demand for cellular use, the market needs a pervasive mode of spectrum sharing among primary licensee providers [9, 10]. However, for business purposes, no primary provider will be interested to participate in pervasive spectrum sharing unless they are incentivized. This incentive can come in two different ways: a) incentive from mutual benefits, and/or b) external incentive, e.g., government subsidy [11, 12, 13].

Spectrum utilization via sharing has exploited several approaches over time, e.g., dynamic spectrum allocation to secondary users [14], roaming [15], and offloading data to neighboring networks [16]. However, most of these techniques focus on spectrum sharing at primary-secondary basis, i.e., a secondary user can use a band when the primary user is idle. Such sharing schemes increase spectrum utilization, but the underlying techniques emphasize on providers’ incentive rather than end users’ experience. Further, the potential of such secondary-level spectrum sharing is limited to utilizing whatever is leftover from the primary users. Recently, multiple attempts have aimed to take this sharing to primary level (e.g., co-primary [17], inter-operator [18], multi-operator [19]
or bi-directional [20] spectrum sharing) where sharing takes place even though the primary user may be busy. Spectrum sharing at primary-level seems necessary to maximize end users’ overall wireless experience and optimize “micro-opportunities” arising in radio propagation [21]. For example, in urban areas, a user might go into dark spots (e.g., no coverage or low signal quality) even though his provider has overall the largest coverage or the highest average signal quality. The user located in a dark spot could be served by other providers if there exists an extensive spectrum sharing among providers [22] and users [18] at the primary level.

Cellular providers usually claim exaggerated coverage ability. Most of the time they don’t give us the actually picture. From Fig. 1.2 and Fig. 1.3, we see both Verizon and Sprint have covered almost entire US. However, it is not the actual representation of reality. Consider a real-world ex-
ample as shown in Fig. 1.4 which illustrates an overlapping coverage map of two primary cellular providers Sprint and Verizon. If both providers have any difference in coverage signal strength within the operating region, it appears as dark black area in the coverage difference map. In some places of the map, a Sprint customer may find himself out of coverage or get weak coverage while a Verizon customer is expected to enjoy seamless connectivity because of Verizon’s better coverage.
On the other hand, a Verizon customer may still find himself in a spot with a weak signal due to complex radio propagation. We call these situations as “micro-opportunities” for sharing at the primary level. In another case, a Sprint customer will get better service than a Verizon customer as the existence of Verizon coverage was not reported in an area according to the map of Fig. 1.5. Note that radio propagation may be presenting many more micro-opportunities in overlapping coverage areas as Fig. 1.4 only shows the radio coverage difference. If providers (Verizon and Spring in this
example) are incentivized to serve each other’s customers, the end user’s experience could notably be improved. Only available economic framework for co-primary spectrum-shared market is cellular roaming [15]. An interesting feature of roaming is that it does not require any governmental regulation. However, it works well when participating providers have significant non-overlapping coverage since this motivates the providers to make roaming agreements with each other. To reap the benefits of spectrum sharing in physically smaller markets, and utilize micro-opportunities for improving user experience, we need schemes to incentivize providers that may be competing with each other in overlapping regions of coverage.

Regulatory authorities around the world are aligning with the recent trends of spectrum sharing. FCC’s vision of the U.S. National Broadband Plan [23] and the wireless community (i.e., industry and academic researchers) are taking direction to explore regimes where sharing is pervasive and even the norm [24]. However, due to the expenditures associated with the licensed bands, a provider is reluctant to share its spectrum resources with other providers unless the sharing brings financial benefit. Incentivizing providers to share their spectrum resources has picked up attention recently [25]. Such cooperation can also be done by injecting some governmental or semi-governmental regulation, although other motivations to improve the “larger good” (e.g., public safety) do exist. As providers get incentive to share their licensed bands, they get more freedom to improve infrastructure and can provide better service without charging more fees to end-users which contributes to maximize users’ welfare. Yet, such pervasive sharing introduces the problem of freeriding. If strong providers (i.e., large providers in terms of coverage areas, signal strengths and service rates) get incentive to share their spectrum bands with the users of weak providers, there may arise a tendency for the weak providers to freeride. In particular, if the incentive is given externally/explicitly (e.g., government subsidy in energy and power markets [26]), weak providers will have incentive to freeride in the shared spectrum markets. In this dissertation, I outline the emergence of freeriders in pervasively shared inter-provider spectrum markets where
sharing takes place at the primary-level aiming to improve connectivity and wireless experience of end-users, and tackle this issue by introducing a game-theoretic model considering head-to-head competitions between providers and exploring regimes where freeriding can be minimized.

In an open market, all participating providers prefer fewer government regulations. So, I try to involve the government as less as possible and focus to find market equilibrium involving activities of the providers. A government uses collected license fees to operate spectrum regulatory authority and a significant portion of surplus goes to national reserve for serving other purposes [27]. A question now arises: why does not the government use this money to improve users wireless experience? Incentivizing providers from this surplus dollars can motivate them to share spectrum resources and reduce additional fees, e.g., roaming fees, from the users. In prior work [28], the government’s role in giving a performance-based subsidy to the service providers was introduced with the goal of maximizing social welfare. In this dissertation, I focus on the issues arising with the subsidy-based spectrum sharing (SBSS) model and solving them, and involve the government to providing a performance-based subsidy, determining the amount of subsidy to avoid freeriding and applying a penalty when it is required. In a game-theoretic framework [29], I show the emergence of freeriding in the SBSS market. This framework focuses on regulating freeriders using the concept of a Nash equilibrium (NE) in a static market environment where all necessary market conditions are known. However, consideration of dynamics of the SBSS market is needed for sustainability and plausibility for participating providers. Usually a subsidy distribution interval is longer than a provider’s revenue assessment interval. One may pose the following question: What will happen if the market conditions change on a regular basis? Due to these dynamics, a provider may find significant revenue loss due to freeriding effects in the SBSS market. It may prefer to leave the market before next subsidy distribution which indicates unstable market situation. If most of the participating providers face a similar issue, an SBSS market will not last for a long period. Our game framework [29] does not address market healthiness under frequent changes. Hence,
there is a need for new dynamic solutions to address the freeriding problem and establish a stable SBSS market. In this context, here, our goal is to eliminate freeriding by providing necessary adaptive strategies to the providers and regulatory policies to the government. Considering the dynamic environment of the SBSS market, in this dissertation, I propose a novel heuristic algorithm to address strategies for providers and government regulations against freeriders.

With the goal of fulfilling truthfulness of pervasive spectrum sharing, I propose a concept, proof of sharing (PoS) [30, 31], where a module keeps sharing information and periodically reports to the government for incentivizing providers. In an SBSS market, providers get subsidy on the basis of PoS, which quantifies how much a provider has shared its resources with another provider’s customers with a weaker signal/coverage at a certain time and location. This subsidy goes for a certain time period. After each period, the provider’s sharing information gets assessed and the provider gets penalized based on its service record. Thus, effectively, the providers get a varying subsidy after each assessment period. I consider two major architectures for accounting PoS. One is a centralized spectrum manager and another one is a cloud-based spectrum manager. In the centralized spectrum manager scheme, each provider shares its sharing information to the spectrum manager, which is transparent to other providers as well as the government. In the cloud-based model, a system application will be located in each cellular device, User Equipment (UE), to keep track of the usage information, and later on, the application transfers the spectrum usage information to a trusted cloud from where the government can fetch the exact sharing information to be used later for incentivizing providers accordingly. Cloud-based PoS data can also contribute to generating a truthful coverage map. As the users are going to share their network service status, it can assist to draw an actual perceived coverage map. To get a better understanding of the coverage area, I utilize crowdsourced data [5] to predict cell tower locations. This data contains some necessary attributes similar to PoS messages. Later, I develop a mapping algorithm to map our predicted towers with publicly available tower locations to find the accuracy of the mapping.
Effective integration of the PoS module in the cellular system is an important and open issue. In order for the PoS module to properly and accurately account the amount of sharing during a call by a UE, frequent UE movement among different all evolved node bases (eNodeBs) may have to generate significant number of control messages in the core of a long term evolution (LTE) network [32]. If eNodeBs belong to a particular provider, the provider can manage such movement records through its mobility management entity (MME). However, in case of UE movement among eNodeBs from different providers, a shared MME [33] would be needed for tracking users. To this end, a UE movement can cause different origins for the PoS report messages. Accordingly, I extend our PoS architecture by focusing on integrating PoS module with the shared and non-shared MMEs in a cellular system. I propose three different architectures for the placement of a PoS report initiator in the system. Those are: (1) An MME-generated PoS report, (2) An eNodeB-generated PoS report, and (3) A UE-generated PoS report. Further, I consider UE movement among different types of cells such as macro and small cells, and the feasibility of integrating each PoS architecture in these cells.

A lot of geographical areas are still out of coverage as they are not attractive to the commercial interest of the providers or the providers are not allowed to establish infrastructure for cellular services. For instance, we see in the US where a significant portion of the national parks or sea shores have coverage issues [34]. Very few providers have limited to no coverage in those areas. Millions of visitors seasonally visit these areas each year. Beyond a certain area, they feel adrift without the reception of cellular signal. The visitors come from different regions where they get subscription from a provider. With the lack of a steady pool of customers, cellular providers have less interest to improve their coverage in these areas. To improve the wireless experience for the users, the government could come forward for such cases. The government can act as a micro-provider to accommodate these customers [35]. It will serve two purposes simultaneously: a) the customers will get cellular reception, and b) it will resolve the issues of establishing cellular
infrastructure inside a protected or seasonally attended region. The providers, who have coverage inside these regions, do not share spectrum resources with the customers of other providers unless a business agreement has already been made, even though the demand of their own customers are not high enough to utilize all of their resources. In this dissertation, apart from the SBSS market, to make the inter-provider sharing pervasive, where a customer can always get better wireless service irrespective of its subscribed provider, I devise two different reward models for the government to improve wireless coverage: a) government spectrum, and b) government cells. I argue that a reward model maintained by the government (or a similar entity with regulatory power) can make it possible where both customers and providers are motivated to share.

1.1 Motivations

Spectrum is already scarce for increasing wireless demand, and, federal and commercial cellular bands are frequently remain under-utilized because of their exclusive and non-shared use. A licensed access to spectrum refrain providers to share each other’s resources because of business competitions. Besides, a customer feels adrift in protected regions because of no signal reception. If all of these issues get addressed, a customer could enjoy higher utility from the cellular system. To ensure higher utility, the providers need incentives to share spectrum resources and serve each others’ customers. In this dissertation, I only consider licensed spectrum bands as unlicensed bands are already open in the form of a common pool of spectrum resources. No provider needs to pay money for it, thus, no additional incentives are required. Also, these unlicensed bands can be used as a reward for sharing licensed bands on which I made our initial observation in Chapter 8. For simplicity, I left further exploration of unlicensed bands to increase spectrum sharing as future work.

Existing cellular roaming or DSA is inadequate to provide the full benefits of spectrum sharing where a cellular user goes temporarily out of coverage or experiences weak coverage. We have
already seen examples, Fig. 1.4 and Fig. 1.5, where current spectrum allocations cannot provide the service to the customers of different primary providers to get the advantages of spectrum sharing. Hence, we need a spectrum sharing market where the providers are motivated to share and the customers enjoy maximum services from the sharing. We need to design a system that allows providers to trust the overall market norms that their customers will not be affected both in terms of numbers and services. Since different providers have various types of investments on the infrastructure, there should be an attractive way of incentivizing them for sharing the spectrum. Without any incentive, no provider will be motivated to share their valuable spectrum. Roaming-like pay-per-use framework may work for such pervasive spectrum sharing markets. However, customers have to pay for it (either explicitly or implicitly as part of their regular subscription fee) which is an undesired situation as the service they receive is typically lower quality even though they have to pay more. Also, in the dense areas where significant number of customers are located, some customers from different providers may get bad signal to establish a call or getting data service, which is a case not addressed by traditional roaming. If there exists any scheme similar to roaming without additional charges on the customers, the customers would enjoy a better network while spectrum efficiency is kept high due to inter-provider cooperation. A favor-based model, where providers favor each other in return of a favor from the other, can be a good example to facilitate inter-provider cooperation to cover each other’s customers. However, if their size difference is significantly large, a small provider’s customers are expected to get more favors from a large provider, which will demotivate the large provider to participate in such sharing. In roaming, providers are interested to share, but the customers may not find interest in this framework for the long run if they have to pay roaming charges for their daily cellular use. So, we need a framework where cellular users will get the advantage of pervasive spectrum sharing without any additional fees and providers are motivated to share spectrum resources.
I choose government subsidized spectrum shared market where providers are incentivized based on their sharing. As the subsidy money is coming from the taxpayers, there may arise some questions among taxpayers, e.g., why their tax should be given to the providers? The answer lies in the case where the government will give subsidy only to the providers who have actually shared their spectrum resources with other providers’ customers. If a provider does not participate in sharing then it should not get any subsidy. If no such regulation exists, providers may charge higher pay-per-use fees and customers are obliged to pay for such services. If the government takes care of giving the incentive of the providers, customers do not need to worry about additional charges. However, as briefly discussed earlier, this subsidy may create a situation where smaller providers may not find interest to invest in infrastructure improvement as they already know other strong providers will take care of their customers. Also, they may ask lower subscription fees to attract new customers, which is legal and valid in any free market. So, we need an effective framework to control such freeriders while maximizing spectrum sharing. These opportunities and challenges motivate our work. I choose a game-theoretic framework to suggest to the providers’ how much sharing should be done for any particular circumstance to avoid the adverse effect of freeriding, a novel heuristic approach to provide sharing strategies and minimum fees in a dynamic spectrum sharing environment, introduce a verification architecture called “Proof-of-Sharing” for maintaining truthfulness, and propose two new reward models for further study. I suggest how much subsidy should be given to the provider who is sharing to avoid freeriding. I aim to maintain market healthiness with maximizing user welfare while minimizing freeriding to motivate providers for spectrum sharing.

1.2 Contributions

I first consider a non-SBSS market as the base, and then make a transition towards an SBSS market. The major contributions of this dissertation are to minimize freeriding in a co-primary SBSS market, propose spectrum sharing verification approaches, and new models for pervasive spectrum
sharing markets. Specific contributions of the thesis are as follows:

- A Game-Theoretic Framework to Model Freeriding in An Asymmetric Spectrum Sharing Market
  - I develop a game-theoretic framework to minimize freeriding while maintaining spectrum sharing at the primary level.
  - I formulate a two-player non-cooperative game considering head-to-head competition in the market with one large provider (a.k.a. spectrum sharing provider) and one small provider (a.k.a. probable freeriding provider), calculate revenue (i.e., payoff) of each provider, and find NE of the game.
  - Our game-theoretic model is able to determine the maximum possible sharing by the large provider while it can successfully avoid freeriding considering other conditions remain unchanged. This model can prevent or reduce the small providers’ freeriding opportunities by adjusting the large provider’s subsidy amount. It sheds light on regulating providers’ subscription fees (i.e., service prices) to minimize freeriding, with respect to fair market fees.
  - The game-framework identifies operational regimes where the large provider earns at least the earnings of a non-shared market irrespective of its willingness to share (i.e., percentage of accepting incoming calls/service requests from the customers of the small provider) and the small provider’s strategies to steal customers and freeride.
  - I show the existence of operational regimes without freeriding in a two-provider market with the exception where both providers enter into the freeriding Pure Strategy Nash Equilibrium (PSNE) region (explained later in Section 4.4) due to the excessive subsidy which was given to the large provider. Before reaching this condition, the large
provider gets at least the earnings of non-shared market by playing a mixed strategy or
a freeriding-free pure strategy.

• Heuristic Approach to Minimize Freeriding in A Dynamic and Symmetric Spectrum Sharing
  Market

  – I develop a novel heuristic algorithm that allows one to determine a provider’s most
    suitable fee and willingness to share to participate in an SBSS market.

  – I introduce a government-regulated minimum fee for each provider to take part in
    an SBSS market. I show that the government-regulated minimum fee and providers’
    strategies resulting from the proposed algorithm help mitigating freeriders.

  – I show that providers are highly interested to charge a price that lies between the gov-
    ernment regulated minimum fees and the fair market fees because of higher revenue.

  – I analyze each provider’s revenue from an SBSS market and show that each provider
    earns higher than non-SBSS market revenue.

  – I determine the subsidy amount that must be given to each provider for ensuring maxi-
    mum sharing by observing all providers’ charging fees.

• Proof of Sharing (PoS) Architectures to Verify Spectrum Sharing

  – I propose the notion of PoS as a representation of verified sharing of spectrum resources
    with another provider.

  – A centralized architecture for accounting how much sharing was done by which provider.

  – A cloud-based architecture using a monitor at the UE for accounting how much sharing
    was done by which provider.

  – Placement of PoS reporting module that handles mobility in a cellular system.
– A cell location tower prediction from PoS-like crowdsourced data [5] to get better understanding on truthfulness of coverage maps.

- Government Reward Models to Enable Pervasive Spectrum Sharing
  – A model of unlicensed access in the under-utilized federal bands as reward to the providers for serving each other’s customers.
  – A model of granting access in government eNodeB within the government controlled areas to the providers for taking care of each other’s customers.

1.3 Key Insights

I run simulations based on our game-theoretic framework and heuristic approach on an SBSS market where two providers (one large provider and one small provider) are competing in a region to attract customers from a common pool of 1000 participants who have high averseness to the price. Each customer makes two types of calls: a) home calls and foreign calls. Initially, in the game framework, the large provider enters with a high interest to share its spectrum resources and the small provider does not share (all detailed in Section 4.4). However, in the heuristic approach, both providers participate in sharing. As our goal is to maintain better connectivity to improve end-users’ wireless experience irrespective of their choice of provider, I only consider call service to evaluate our model. From this market, our findings are as follows:

- Observations from Game Framework
  – If the large provider’s willingness to share is at most 69%, it can maintain this sharing for entire subsidy period regardless of subsidy amount by playing a pure strategy without incurring any revenue loss irrespective of the small provider’s charging fee. If the
willingness to share is more than 69%, the large provider plays a mixed strategy where it can only maintain this willingness to share for a certain duration of subsidy period to ensure no revenue loss from freeriding.

- If the ratio of the small provider’s charging fee to the fair market fee is at most 41%, the large provider can operate with sharing its infrastructure at any level, i.e., willingness to share being 100%. If the fees ratio is greater than 41%, the game follows a mixed strategy.

- A small amount of subsidy can motivate a provider for more sharing if both providers get the chance to improve signal strengths (described in Section 4.4).

- If a participating provider is too large compared to the other provider, we observe a non-freeriding regime. It happens because the customers of the small provider perceive low quality signal compared the large provider. Again, if the participating providers are similar in size, no freeriding takes place.

- A spectrum sharing provider is more interested to play mixed strategy due to customers’ high averseness to price.

- By considering all head-to-head competitions, a spectrum sharing provider gets necessary strategies from the game NEs to tackle each of its competitors’ freeriding strategies in the market. Thus, our model provides effective solutions in a multi-provider environment.

- Observations from Heuristic Approach

  - We observe that, in a dynamic environment, all providers can earn more revenue if they charge a price that lies between the fair market fees and the regulated minimum fees which indicates the stability of the SBSS market.

  - In a highly competitive market, a subsidy of 4% of the total market value, which is the
aggregate market share of all participating providers, can ensure that an SBSS provider will opt for full sharing, e.g., accepting 100% foreign customers as long as the freeriding provider charges higher than or equal to 90% of its fair market fees.

- If the government provides a subsidy to the resource sharing provider equal to 16% of total market value, the freedom of lowering fees for the freeriding provider can go down to 50% of its fair market fees.

- When the subsidy amount reaches about 36% of the total market value, the freeriding provider actually has no regulations on fees. It can charge any fee it wants.

1.4 Organization of This Dissertation

The rest of this dissertation is organized as follows: In Chapter 2, I explore existing literature on spectrum sharing. Here, I cover related works on Dynamic Spectrum Access (DSA) for secondary spectrum sharing and auctioning procedures for such spectrum sharing, freeriding behaviors in networks, roaming models and associated regulatory policies to increase spectrum utilization, accounting and verification of spectrum sharing. How government subsidy can contribute to increase sharing among primary providers without asking additional fees from customers was described in Chapter 3. It shows how a provider can behave maliciously, freeride on other providers infrastructure and trigger unfair customer switching. It also outlines a baseline model of an SBSS market and spectrum sharing among primary providers. Chapter 4 illustrates a game-theoretic model of two providers in an SBSS market. It also describes different scenarios of the game depending on small providers’ subscription fees, large providers’ willingness to share and associated equilibrium strategies for both providers to control unfair customer switching. It illustrated the equilibrium strategies of both providers based on different subsidy amount. I have differentiated the game regions between freeriding and non-freeriding. I also show, how additional subsidy can
restart freeriding game regions. In this chapter, customers price averseness effect on market was also examined in details. Considering dynamic environment and symmetric mode of spectrum sharing, I proposed a novel heuristic model in Chapter 5. It discusses government regulations on fees, sharing strategies for participating providers while minimizing freeriding. It shows suitable fees and willingness to share for different operating regions with higher revenues, a comparison between shared and non-shared revenues. It also illustrated the optimality gap between observed fees and willingness to share with the results obtained from game model. In Chapter 6, I demonstrate “Proof of Sharing” architecture and qualitative comparison between all models to show the feasibility of each model. I also developed a cell tower prediction and mapping algorithm by utilizing PoS-like crowdsourced data in Chapter 7. I propose two new reward-based models for pervasive spectrum sharing in Chapter 8. Here, I describe how these models can improve end-users’ wireless experience beyond the SBSS market. I also make a qualitative analysis between two models and average utility gain from them. I kept further study on this models as future work. Finally, in Chapter 9, I have summarized this dissertation and indicated future improvements on this work.
CHAPTER 2: LITERATURE REVIEW

Wireless spectrum utilization has been a national priority as the demand for this natural resource has been increasing. Improving users’ wireless experience via spectrum efficiency has also become a key concern due to its increasing scarcity. Dynamic spectrum access, dynamic pricing, spectrum auction, primary-secondary sharing, inter-primary spectrum sharing, etc. have already been introduced to improve spectrum utilization and efficiency of sharing. Accounting of sharing is also important to increase utilization along with spectrum sharing technologies. Better spectrum allocation and sharing of spectrum resources eventually contribute to improving end-users’ wireless experience.

2.1 Dynamic Spectrum Access

Secondary providers in a dynamic spectrum access (DSA) environment get spectrum in a form of fine-grained space-time unit via a truthful auction was proposed in [36]. Such spectrum access enables secondary providers to introduce new services as well as improve existing wireless services to meet demands. The authors also utilized Vickrey-Clarke-Grove’s truthful auctioning procedures to motivate primary providers by maximizing revenues from the auctions. It is a polynomial-time suboptimal auction where monotone allocations and critical value payment was considered for enforcing truthfulness. The strength of this work was providing high revenue to the sellers which motivates a primary provider to share its spectrum and high spectrum utilization within the whole system.

Truthful auctions can become challenging due to location-constrained interference. It may even fail to address truthfulness and spectrum utilization in cases. To improve spectrum utilization
in such cases and reduce computational complexity, [37] proposed an approximate truthfulness mechanism, ETEX, which exploits seal-bid auction mechanism to ensure approximate truthfulness. The polynomial solution of ETEX outperforms some existing auction procedures in terms of user satisfaction, spectrum utilization.

A sealed-bid knapsack auction was illustrated in [38] for dynamic spectrum allocation. It offers a common pool of spectrum resources to the service providers and the providers bid based on the demands. This work developed a two-tier trading system where providers get spectrum bands from spectrum owners and provide spectrum services to users. A paradigm shift from static to dynamic spectrum allocation using sealed-bid knapsack auction from a common pool of spectrum resources with the help of a spectrum broker strengthened this work from the rest.

Cooperative and coexistence of spectrum sharing among primary and secondary operators while withstanding interference were addressed in [39]. In the coexisting phase, a secondary provider transmits power without creating interference in the primary provider’s network by making queries to a sensor node. The sensor node is responsible for monitoring the primary provider’s downstream communication and estimating upstream communications. Based on the observation, the sensor network adjusts the interference tolerance level and shares this information with the secondary network when asked for.

A spot pricing for spectrum use was discussed in [40] with the presence of nonelastic primary users, and elastic secondary users. It views the horizon reward problem and forms a stochastic dynamic solution for efficient pricing policy. It differentiates operating regions for different pricing policies based on customer arrival rates. In the work, the single-price deterministic optimal threshold pricing uses a unimodal profit function that can reach near to the globally optimal price. This single-pricing policy is also the weakness of this work as the optimal price can change over time depending on the channel occupancy which makes the spectrum access less predictable.
A user’s selection of a provider based on the sum of congestion and price announcement by both primary and secondary providers was proposed in [41]. It assumes the primary provider’s customers are responsible for causing congestions in the primary provider’s network and both providers’ customers are responsible to create congestions in the secondary provider’s network.

2.2 Regulating Freeriding in Networks

Controlling freeriding based on utility and extended point-based models have been introduced in [42, 43]. Both works considered the negative impact of freeriding in P2P file sharing. They developed a model to study different patterns of file-sharers behavior and its impacts on the community. According to these utility-based freeriding controlling works, users get incentives based on sharing interesting and popular files. They considered the total number of files shared, the total size of the data, and the popularity of the data. Finally, they penalize users based on this information. These works differ from the rest of the incentive-based models because of the parameters used to calculate incentives. They determine incentive points after taking care of how much time a user spends in the network, his/her upload speed, how many simultaneous uploads are done by a user.

An EigenTrust score-based [44, 45] freeriding minimization approach was introduced in [46] for P2P networks. EigenTrust is a reputation-based metric that assigns scores to each participating peer. High EigenTrust score provides additional benefits to the peers, e.g., more bandwidth, and more connection time while downloading or uploading data. If a peer with the zero EigenTrust scores arrives in the network, the system detects it as a freerider. This model will restrict freeriders to access shared data from the network. The strength of EigenTrust lies in determining different types of malicious freeriders who can act alone or collective manner. EigenTrust also determines malicious spies and camouflaged freeriders with high probability. It is also effective against Sybil attack and virus-disseminators.
Passive monitoring on neighbor nodes in P2P networks to control freeriders was proposed in [47]. A peer can be both, a ‘monitor’ as well as ‘controlled’. In the role of a monitor, the peer observes its neighbor’s incoming and outgoing messages and keeps statistical records of the data. During this period, the observing neighbor is a controlled peer. At the same time, the monitoring peer can also be controlled by its neighbor. Thus, monitoring each other’s sharing information and messaging records, a peer can determine the freeriding characteristic of its neighbors and take countermeasures to reduce freeriding effect in the network.

The payment-based scheme is another way to prevent freeriding in P2P systems. Two decentralized payment methods were delineated in [48]. Those are: (1) a sender uploads the required payments and each intermediate node earns a portion of it when the packet traverses through the node, and (2) each node buys a packet from the previous node and sells to the next node, finally, the receiver pays the total cost.

An agent-based dynamic freeriding control mechanism was well investigated in [49, 50]. According to this model, one agent’s contribution decreases with the increase of other agents’ contributions. If equilibrium forces one agent to contribute more, then others reduce their contribution by the same amount in the aggregate.

2.3 Regulations to Increase Spectrum Efficiency and Utilization

Regulatory authorities around the world, e.g., Federal Communications Commission (FCC) in the US, European Telecommunications Standards Institute (ETSI) in Europe, are working and revising spectrum use policies regularly to meet the growing demand for spectrum utilization and efficiency. Researchers in academia are also working actively to propose new sharing policies and assist regulatory bodies in implementing effective regulation while maintaining all network providers’ participation.
In Europe, the European Parliament and Council approved the first Radio Spectrum Policy Program (RSSP) in March 2012, [51, 52]. It aimed at implementing two actions: 1) identifying potential beneficial sharing opportunities (BSOs) where net socio-economic benefits of sharing a band to multiple applications surpass the benefits of a single application, and (2) authorizing Licensed Shared spectrum Access (LSA) through spectrum sharing contracts with regulators handing out. A new commission was involved to implement the actions within the European Union (EU) boundary. It also acted as impartial technical advisers and registrars of the contract terms. In LSA, users will have temporary exclusive rights and roles to use available unused cellular spectrum within a specific area.

Almost all Mobile Network Operators (MNOs) around the world support International roaming. In Europe, the Body of European Regulators for Electronic Communications has launched some regulatory proposals to make data and voice roaming services easier for cellular users [53, 54, 55]. In this proposal, the charging overhead of mobile data roaming on traveling cellular users within the European Union was analyzed. It also analyzed the applicability of flat-rate pricing for roaming to reduce the burden of excessive charging on users and evaluate three structural measurements proposed by the European Commission. It considered the impact of competition, wholesale prices, retail prices, operators’ investment for network infrastructure, and finally, increasing spectrum utilization.

In the US, the President’s Council of Advisors on Science and Technology (PCAST) has proposed three-tier interference protection to utilize spectrum allocations and obtain incentives from the spectrum market. The three-tiers of spectrum users are 1) Incumbent, 2) Priority Access License (PAL), and 3) General Authorized Access (GAA). It will allow commercial access at the federal spectrum band, e.g., 3550 - 3700 MHz band, while protecting federal operations from interference. It will also make a way for commercial users to upgrade their own technology according to their business models. A Spectrum Access System (SAS) will monitor spectrum use and coordinate to
assign the available spectrum among multiple tiers of users. The incumbent users, e.g., federal ship-borne, radar operations, and fixed satellite service, are top in the hierarchy and they are protected from interference due to other users. Any non-federal incumbents are required to register their operation details with FCC or a SAS. PAL and GAA users will be allowed to use the federal spectrum in specific locations only with the authorization of SAS. It ensures that the PAL users are protected from the interference created by GAA users. A PAL user can have access up-to 70MHz from 3550 - 3650 MHz bands. A GAA user can only use the band which is not assigned to any PAL user between this range.

A two-stage pricing policy based on PCAST’s 3-tiers interference protection policy was introduced in [56]. At the first stage, it considers a static pricing policy for the specific level of commercial usage, and in the last stage, it takes an optimal dynamic policy for controlling new admissions. Such combination works efficiently to share spectrum and increase efficiency without requiring an additional spectrum. It also makes stable revenues for network providers and provides the ability to adopt any change in the network.

To regulating Mobile Network Operators (MNOs) in the cognitive radio spectrum sharing environment, a simple rule-based framework consisting of six themes was proposed in [57]. The themes are: (1) The nature of the opportunity rule, (2) rules for conducting cellular business, (3) boundary rules to identify boundaries of the business, (4) priority ranking rules to differentiate critical to general decisions. (5) timing rules to identify, synchronize and pace things, and (6) exits rules to make the decision for exit or selecting things which should be stopped or given up. These rules will help dominating and challenger MNOs to reform their business policies according to the demands. A dominator can enhance small cell deployments to provide good QoS with better traffic offloading and act as a cognitive platform provider for other providers. A challenger can focus on specializing in governmental, enterprise customers, special mobile devices, Internet of Things (IoT) based operations to increase spectrum utilization.
Mobile service, technology, network value provisions were illustrated in [58]. To meet the best-effort service delivery, the operators should have the infrastructure for next-generation communication services such as real-time video. It argues that certain regulatory and operating restrictions should be taken into consideration while allocating additional spectrum to the mobile network operators (MNO). In technology provision, LTE Time Division Duplex is well suited for DL/UL asymmetric traffic with small applications though LTE Frequency Division Duplex is used as the mainstream cellular networks. For value provisioning, a mobile business model should have the value proposition, revenue model, and architectural value provisioning.

2.4 Spectrum Sharing at Primary Level

A Gibbs sampling-based learning techniques was proposed in [19] for a decentralized Co-primary spectrum sharing which aimed at a long-term spectrum sharing among small cell base stations from a common pool of spectrum resources. The benefits of Gibbs sampling-based learning algorithm is that it provides tenfold throughput gain compared to greedy or equal spectrum sharing algorithms.

A non-orthogonal spectrum allocation in a form of a combinatorial optimization problem was proposed in [22] to maximize social welfare in multi-operator spectrum sharing environment. It adopted a many-to-one form of a matching game to find a stable matching equilibrium which correspondence to local optima. To obtain global optima and maximize social welfare, it has used generic Markov Chain Monte Carlo method. Using simulation, the authors also showed the significance of effective spectrum resource allocation over power allocation for social welfare system.

Inter-operator spectrum sharing with device-to-device (D2D) communications capability was discussed in [18]. It has proposed to form a common pool of spectrum resources from all operators’ underutilized spectrums and play a non-cooperative game among providers to share spectrum. To
implement this policy, the authors used Jacobi-play strategy instead of the best response for ensuring game equilibrium.

Acquiring spectrum resources in the forms of favor, the authors of [59] constructed a protocol. According to this protocol, a provider with the high load of users can ask favors from providers with low loads. Each of these providers keeps track of such favors. One favor gainer is expected to return the favor when others needed help and balances the favor counts. The authors also proposed a repeated game framework to keep tracking of favors for granting future favors. This work does not require monetary transaction to share spectrum resources. It also does not reveal any operator specific information, which is the strength of this work.

Bidirectional spectrum sharing in the forms of multiplexing secondary users’ communication channels with the presence of both primary and secondary users are described in [20]. The transmission times are divided into two time slots to enable uninterrupted communication for primary users’ (PUs). In one time slot, a secondary user acts as a relay for primary users’ transmission if the destination primary users are out of reach for the sender. On another time slot, the SU can communicate with another SU device as well as with a PU using two different links. Such simultaneous bidirectional communication protocol allows an SU to utilize spectrum more efficiently compared to the existing one-directional scheme without interfering PUs link.

Spectrum sharing at millimeter-wave (mmWave) cellular networks was discussed in [60, 61]. In the model, the authors used cell association, coordination, beam forming, and bandwidth to analyze the effectiveness of such sharing as an alternate of traditional spectrum sharing. To maximize throughput with a guaranteed load balancing, it applies a mathematical framework to integrate beam formation with the base stations. Regardless of coordination types in inter-operator spectrum sharing, this work identified and discussed five key points. It shows (1) the feasibility of inter-operator spectrum sharing with light on-demand intra- and inter-operator coordination at higher
mmWave frequencies, e.g., 73 GHz, (2) issues with directional communication such as multiuser interference, (3) how a large number of antenna elements can help coordinate and simplify spectrum sharing implementation, (4) how fair load balancing can be done in intra-operator coordination while neglecting inter-operator coordination in large antenna regimes, and finally, (5) how to protect critical information from the adverse effects of spectrum sharing by implementing critical control messages.

Addressing user throughput, MNO markets, coalition cost and mobile data pricing, [62] proposed two cooperative game models. It introduced a cooperative game among MNOs to share unique RAN for gaining spectrum aggregation and reducing operational costs. The MNOs with larger customer bases are responsible for larger fractions of the network costs and the MNOs with larger spectrum resources shares lower costs. In market share-based cost divisions, stability is not always guaranteed. Due to the instability, cost division-based contribution of spectrum resources from each MNO makes this work as a better candidate for cost division policies.

2.5 Accounting of Spectrum Sharing

Accounting of service details (e.g., call duration, data services) is one of the basic criteria of a cellular communications network. If there exists a mutual agreement of serving each other’s customers, e.g., in roaming agreements, all operators need to maintain truthfulness on detailed service. In the case of roaming, each operator maintains detailed call records of a customer in a file known as transferred account procedure (TAP) for billing purposes [63, 64]. Later, this TAP file gets exchanged between operators by a trusted third party or direct communication between operators.

Spectrum and infrastructure sharing between a mobile network operator (MNO) and a mobile virtual network operator (MVNO) is an existing way of inter-operator spectrum sharing. However,
it works statically. An MNO sells its leftover cellular capacity to an MVNO on a bulk rate after assessing demands from its own customers [65]. An MVNO does not get any licensed band. However, it may or may not have infrastructure. As a result, the MVNO has to use an MNO’s spectrum based on the agreement between them. An MVNO periodically checks its users’ service records and verifies the sharing agreement with the MNO [66].

A three-tier interference protection plan was taken in the US to facilitate spectrum sharing with commercial operators at the federal band [9]. Spectrum access system (SAS) is an entity which monitors the band, coordinates between users, allocates spectrum to the users, and reduces interference. Thus, SAS performs the accounting of spectrum use in this spectrum shared environment. Similar to the three-tier model, European regulatory authority also initiated a scheme known as licensed shared access (LSA) to share government bands with the commercial operators [67].

Radio resource sharing among operators has been standardized in 3rd generation partnership project (3GPP) [68]. This sharing can take place at radio access network (RAN) level or along with RAN, a mobile switching center (MSC) and a serving general packet radio service (GPRS) support node (SGSN) are shared. A shared RAN broadcasts all participating operators’ public land mobile network (PLMN-id) id. Based-on subscription type a UE gets service through a PLMN. This PLMN id is stored in MSC/SGSN serving gateway (SGW) node of the network core. A function known as global system for mobile communications (GSM) service control function (gsmSCF) fetches PLMN-ids from the SGW to determine the serving operator for accounting usage details and creating bills. In this way, a gsmSCF performs the accounting of radio resource sharing and maintains truthfulness.

TAP files in roaming maintain detailed call records and SAS in three-tier system monitors spectrum sharing information. However, both of these models work in limited areas and focus on specific use-cases. An MNO-MVNO spectrum sharing takes place in static mode. A PoS concept
shows the necessity of placing the PoS node in a pervasively shared cellular market. It does not consider the overhead of integration and messaging burden on the core of a cellular network. To our best knowledge, our proposed architectures on PoS module involving PoS report initiator and considering message overhead due to mobility is the first work of this type.
An SBSS market operating within a region is visualized in Fig. 3.1. It is built on existing cellular market with the inclusion of the government as an incentivizing organization. Initially, the customers choose providers based on the utility of the offered services. The government subsidizes the providers to share their spectrum with foreign customers (i.e., ones subscribed to another

Most of the content of this Chapter have appeared in the Proceedings of [29]
provider) and penalizes based on proof-of-sharing [30]. The providers try to maximize revenue earnings by serving as many foreign calls as they can without hurting their service quality.

In the SBSS markets [28], a subsidy from the government to providers can contribute to increasing user welfare. In this case, the end users will not need to pay more subscription fees for service when they are in suburban areas or out of their provider’s coverage. Further, they will receive a better quality of experience due to micro-opportunities arising in urban settings. Thus, putting the end user’s received quality of experience as the top priority is one of the main motivations for our work on SBSS markets.

3.1 Freeriding in Subsidy-Based Spectrum Sharing (SBSS)

In [28], we considered the benefits of an SBSS market. However, we did not analyze the potential risks of this market. It can result in a situation that provides an opportunity to the weak provider a.k.a small provider, i.e., a provider with weak signal strength, small coverage area or low service rate, to freeride on the strong provider’s a.k.a large provider’s infrastructure. When a weak provider advertise relatively smaller subscription fees compared to it’s fair market fees and the strong providers fees, it can unfairly attract customers who would normally go to the strong providers in a fair market. Since strong providers are motivated to serve the users of the weak providers because of the extra subsidy, the weak providers may exploit this situation and tend to freeride on the strong providers’ network infrastructure. Further, strong providers will not be able to drop subscription fees below a certain level due to high maintenance costs, and may not retain their customers who eventually switch to other providers offering lower fees.

Assume an SBSS cellular market with Providers 1 and 2 as shown in Fig. 3.2. The dashed circles encapsulate each of the providers’ coverage domination. Some regions are equally dominated by
both providers while others are dominated by one of them. Provider 1 is, overall, stronger as it has more base station (BS) support than 2. Also, due to higher infrastructure costs, Provider 1’s subscription fees are expected to be higher in an existing market. Consider a region where Provider 1 has better network coverage. If a customer wants to get a strong connection, he should subscribe to Provider 1 in an existing market. In fact, if there was no subsidy, Provider 1 would retain these customers. However, under the SBSS market, the weak one, Provider 2, can offer cheap subscription fees due to its small infrastructure costs. Further, Provider 1 is incentivized to serve Provider 2’s customers. Thus, if Provider 1 shares its BSes with Provider 2’s customers too much, the overall quality of the network service will appear to be similar for both Provider 1’s and 2’s subscribers. Then, for the customers, the only perceived difference between two providers will be the subscription fees. As the customers are highly averse with price, these fees differences will
cause unfair customer switching (UCS) in favor of Provider 2. To make it fair, Provider 2 should increase its fees to fair market levels (i.e., similar to Provider 1’s fees), but it has no motivation to do so in the SBSS market. Due to the potential revenue loss from freeriding, no strong providers will agree to join the SBSS market. To ensure their participation, we address freeriding and UCS issues in the SBSS markets, and minimize them using spectrum sharing strategies obtained from our proposed game-theoretic framework.

3.2 A Baseline Model for SBSS Market

Assume a set of $J$ network providers, denoted by $\mathcal{J}$, that are competing within same region in an SBSS market. A customer $i$ will choose $j$ as “home provider” based on the overall signal strength/quality, $\psi_j$, and the subscription fee, $f_j$, of provider $j$, and treats any other provider $k \in \mathcal{J} \setminus \{j\}$ as a “foreign provider”. The SBSS market may result in a customer being served by a foreign provider in addition to its subscribed home provider, depending on the received signal quality from these providers as well as the providers’ willingness to share their infrastructure. A provider treats all customers as “foreign customer” if the customers are subscribed to other providers. Based on these selections (to be detailed next), the number of customers subscribing to provider $j$ can be expressed as:

$$n_j = N(f_j, \psi_j)$$

where the demand function $N(\cdot)$ is a decreasing convex function with respect to (w.r.t.) $f_j$ and an increasing concave function w.r.t. $\psi_j$. The shape of a demand function w.r.t to price is usually a decreasing convex function [69], which we follow in our model. Further, the utility from a service diminishes with the increase of service consumption [70]. If we continuously increase the signal strength of a provider, after a certain limit, the marginal improvement of perceived signal strength will saturate and become insignificant. To model this, we shape the demand function as increasing concave form w.r.t. the provider’s signal strength.
3.2.1 Customer i’s Provider Selection

Assume each customer $i$, on average, makes $\mu$ calls during a fixed time period. Among them, he makes $\beta_{i,j} = \sigma(X_j)$ home calls where $\sigma(\cdot)$ is an increasing concave function w.r.t. the number of BS, $X_j$, of his home provider $j$. The probability to find customer $i$’s home BS during making a call increases with the increase of home BS count. Since the marginal benefit of adding more BSes diminishes in terms of covering calls from subscribed customers [71], we assume $\sigma(\cdot)$ as a concave function. The customer $i$ also makes $\alpha_{i,j} = \mu - \beta_{i,j}$ foreign calls.

We model a customer’s selection of a home provider via its utility of the service quality. Let a customer’s utility function, $u(\cdot)$, be an increasing concave function of the signal intensity/quality of service available to that customer. Then, customer $i$’s overall utility from subscribing to provider $j$ can be expressed as:

$$U(i, j) = \beta_{i,j} u(\psi_j) - f_j.$$  \hspace{1cm} (3.2)

Based on (3.2), customer $i$ will select provider $j$ as his home provider with the following probability:

$$P_{i,j} = \frac{U(i, j)}{\sum_{j=1}^{J} U(i, j)}. \hspace{1cm} (3.3)$$

We get this probabilistic provider selection from Contest Theory, [72], where a customer will most likely choose a provider which offers best utility.

3.2.2 Provider j’s Revenue Earnings

Provider $j$ receives subsidy in addition to its regular subscription fees. Further, it can generate revenue by freeriding on other providers’ networks. If a regular non-subsidized market consists of $n$ customers among which $n_j$ are subscribed to provider $j$, we can suppose that provider $j$ earns
subscription revenue. However, after joining in the SBSS market, provider \( j \) gets the subsidy \( \epsilon_j \), some of which it can spend to improve its infrastructure, e.g., by increasing the number of base stations, \( X_j \). It also has licensed bandwidth, \( b_j \), divided equally among all of its BSes, in order to run cellular operations. Available bandwidth and the number of BSs determine the signal strength of provider \( j \), which can be expressed as \( \psi_j = Q(X_j, b_j) \) where \( Q(\cdot) \) is an increasing concave function w.r.t. \( X_j \) and \( b_j \), since marginal signal improvement diminishes with the increase of \( X_j \) and \( b_j \).

In a multi-provider environment, the government can split subsidy \( \epsilon_1 \) further in a way where the provider \( j \) earns \( \epsilon^k_j \), a portion of \( \epsilon_j \) by serving the customers’ of provider \( k \) only. However, such a split is beyond the scope of this work. We assume, the government will maintain a suitable policy to split \( \epsilon_1 \) and penalize separately on the components where \( \epsilon_j = \sum_{k \in J \setminus \{j\}} \epsilon^k_j \). Assume that provider \( j \) serves \( F^k_j \) foreign calls generated by the customers of provider \( k \), which is the proof of sharing of provider \( j \)’s BSes with other provider’s customers. A provider is penalized on it’s subsidy based on the number of foreign calls it serves. We call this a performance-based subsidy scheme. The higher \( F^k_j \), the lower the penalty. We model the penalty function \( p(\cdot) \) which determines the percentage of the subsidy given to provider \( j \) for serving customers’ of provider \( k \) needs to return to the government as: \( P^k_j = p(F^k_j) \) where \( p(\cdot) \) is a linear function w.r.t. \( F^k_j \). If provider \( j \) serves all foreign calls, \( P^k_j \) becomes 0. Contrary, \( P^k_j = 1 \), when provider \( j \) does not serve any foreign customer.

Based on the provider selection problem (3.3), a customer \( i \) of provider \( j \) is more likely to choose another provider \( k \) if \( U(i, k) > U(i, j) \). Also, any change of subscription fees can change provider selection criteria along with the signal strength, which is the main driving factor behind \( U(\cdot) \). In an SBSS market, the service utility received from providers \( j \) and \( k \) can be the same (or similar in a more general sense) due to the subsidy for sharing, i.e., \( U(i, j) = U(i, k) \). In such a case, if \( f_j < f_k \), customer \( i \) of provider \( k \) will more likely subscribe to provider \( j \). Assume, by advertising
lower-than-fair subscription fees, i.e., \( f_j < f_k \), provider \( j \) can unfairly attract \( n_k \tau_{kj} \) subscribed customers of \( k \), where \( \tau_{kj} = 1 - e^{-C f_k/f_j} \) is the probability of UCS from provider \( k \) to provider \( j \).

Here, \( C \) is customers’ averseness to price. A high value of \( C \) indicates a high fees difference and a high customers’ averseness to price. The value of \( C \) can be any number where \( C \geq 0 \). When \( f_k/f_j \approx \infty \), we get \( \tau_{kj} \approx 1 \) and if \( f_k/f_j \approx 0 \), we have \( \tau_{kj} \approx 0 \). Now, provider \( j \)’s revenue, \( R_j \), becomes

\[
R_j = n_j f_j + \sum_{k \in J \setminus \{j\}} (1 - P^k_j) \epsilon_j^k + \sum_{k \in J \setminus \{j\}} (n_k \tau_{kj} - n_j \tau_{jk}) f_j
\]

(3.4)

where \( \sum_{k \in J \setminus \{j\}} \epsilon^k_j = \epsilon_j \) and \( f_j, b_j, X_j > 0, \forall j \).

The first term of (3.4) denotes the earnings of provider \( j \) from its subscribed customers. The second term describes the leftover subsidy money. If provider \( j \) does not serve a satisfactory number of foreign calls, it has to return some or all of \( \epsilon_j \). The third term delineates the earnings from net switching customers.

In an SBSS market, provider \( j \) may lose significant number of customers due to freeriding which eventually generates less revenue for \( j \) compared to a non-shared market. To make sure \( j \)’s participation in the SBSS market, \( j \)’s overall earnings must be at least as much as the revenue of the non-shared market. Thus, the following condition must be met to motivate \( j \) for sharing.

\[
\sum_{k \in J \setminus \{j\}} (1 - P^k_j) \epsilon_j^k + \sum_{k \in J \setminus \{j\}} (n_k \tau_{kj} - n_j \tau_{jk}) f_j \geq 0
\]

(3.6)
CHAPTER 4: GAME-THEORETIC MODEL OF AN SBSS MARKET

We mitigate freeriding issue in an SBSS market by developing a non-cooperative game to hold the condition of (3.6) by generate at least the earnings of a non-shared market. Initially, we consider a two-provider SBSS market, form a 2x2 non-cooperative game and determine the Nash equilibrium (NE) of the game. Later, we extend the game to a multi-provider market by applying the two-provider game among all providers considering head-to-head competitions.

4.1 Two-Provider SBSS Market

Consider two providers, Provider I and Provider II, are competing in an SBSS cellular market with willingness to shares, \( \omega_1 \) and \( \omega_2 \), respectively. The maximum number of foreign calls I and II can get from the market is \( \sum_{i=1}^{n_2} \alpha_{i,2} \) and \( \sum_{i=1}^{n_1} \alpha_{i,1} \) respectively, and are willing to serve \( F^2_1 \) and \( F^1_2 \) incoming foreign calls, respectively, where \( 0 \leq F^2_1 \leq \sum_{i=1}^{n_2} \alpha_{i,2}, \quad 0 \leq F^1_2 \leq \sum_{i=1}^{n_1} \alpha_{i,1} \), \( F^2_1 = \omega_1 \sum_{i=1}^{n_2} \alpha_{i,2} \), and \( F^1_2 = \omega_2 \sum_{i=1}^{n_1} \alpha_{i,1} \).

A customer’s perceived signal strength of home provider depends on the distance between his location and the nearest home BS. So, perceived home signal strength can vary from customer to customer. Similarly, perceived signal strength for the foreign calls the customer makes can vary. Thus, the choice of BS selection to make a call varies from customer to customer which eventually generates different numbers of home and foreign calls for different customers. Suppose \( \theta_1 \) denotes the probability that a customer of Provider I chooses Provider I’s BS to make call (i.e. home call), and \( \theta_2 \) denotes the probability that a customer of Provider II chooses Provider II’s BS for a

Most of the content of this Chapter have appeared in the Proceedings of [29]
home call. Then $\theta_1$ and $\theta_2$ are given by the expressions

$$\begin{align*}
\theta_1 &= \text{Probability}[\psi_1 \geq \psi_2] + (1 - \text{Probability}[\psi_1 \geq \psi_2])(1 - \omega_2) \\
\theta_2 &= \text{Probability}[\psi_2 \geq \psi_1] + (1 - \text{Probability}[\psi_2 \geq \psi_1])(1 - \omega_1)
\end{align*} \tag{4.1}$$

where $\psi_1$ and $\psi_2$ are the signal strengths of Provider I and II, respectively. Now, the overall perceived signal strengths for customers of I and II will be

$$\begin{align*}
\psi_1^* &= \theta_1 \psi_1 + (1 - \theta_1) \psi_2 \\
\psi_2^* &= \theta_2 \psi_2 + (1 - \theta_2) \psi_1
\end{align*} \tag{4.2}$$

Consider Provider I has more BSes than II, i.e., $X_1 > X_2$. According to the discussions of Section 3.2.1, $\beta_{i,1}, \beta_{i,2}$ are increasing concave functions of the BS counts of the providers. Likewise, according to Section 3.2.2, $\psi_1, \psi_2$ are increasing concave functions of the BS counts and bandwidths of the providers. As $X_1 > X_2$, comparing the first terms of (3.2), $\beta_{i,1} \ast u(\psi_1) > \beta_{i,2} \ast u(\psi_2)$ holds. So, if $f_1 \leq f_2$, we can infer that $U(i, 1) > U(i, 2)$. If $f_1 > f_2$, we can write that $U(i, 1) > U(i, 2)$ holds as long as the subscription fees are at their fair market values. We model an SBSS market which transforms from the existing market where both providers were charging fair market fees $f^*_1$ and $f^*_2$. Thus, considering different cases of both providers’ fees, we can say, Provider I offers better utility than II before the effects of subsidy take place.

The SBSS cellular market makes a tunnel for the weak (i.e., small) provider to make extra earnings by freeriding on the strong (i.e., large) provider. Under the subsidized market, each provider’s offered cellular utility, $U(\cdot)$, could become almost equal, and there may remain only a small perceived difference between cellular providers’ service quality. Assuming no changes of previously subscribed customers’ fees and considering the possibility of UCS, the revenues under the subsi-

---

We show the calculation of the fair market fee from marginal signal utility in Section 4.4.1.1.
dized market becomes

\[ R_1 = n_1 f_1 + (1 - \mathcal{P}_1^2) \epsilon_1 + f_1 (n_2 \tau_{21} - n_1 \tau_{12}) \]  

(4.3)

and \[ R_2 = n_2 f_2 + (1 - \mathcal{P}_2^2) \epsilon_2 + f_2 (n_1 \tau_{12} - n_2 \tau_{21}) \].

(4.4)

In a two-provider SBSS market, we can say \( \epsilon_1^2 = \epsilon_1, \epsilon_2^1 = \epsilon_2, \mathcal{P}_2^1 = \mathcal{P}_2, \mathcal{P}_1^2 = \mathcal{P}_1 \), and will use these notations in the following sections. If \( f_1 \leq f_2 \), most of the potential customers will go for Provider I’s service in those areas where I has better coverage. Because, Provider II may offer the same service utility, i.e., \( U(i, 1) = U(i, 2) \), it charges higher subscription fees. Thus, no UCS and freeriding take place, which is aligned with the existing market equilibrium. If Provider II aims to initiate UCS by lowering fees, i.e., \( f_1 > f_2 \), then the market equilibrium changes. Now, Provider II may offer the same utility with lower fees, which will attract the customers of Provider I. As a result, Provider I will lose customers, even though it has a stronger signal and better coverage. If no subsidy agreement exists, Provider I could retain these customers. Also, depending on the government’s offerings, the subsidy money can be less than the subscription revenue lost due to Provider II’s freeriding, which will demotivate Provider I to continue participating in the SBSS market.

4.2 Game for a Two-Provider SBSS Market

To model the freeriding problem, we envision a simple 2x2 non-cooperative strategic form game. The two players are a large provider a.k.a Provider I and a small provider a.k.a Provider II. They are competing in an area where the large provider is able to offer better service than the small provider. Now, consider customers not subscribed to the large provider, who venture into this area and wish to make calls. The large provider then has a decision to make: It can either cover such
calls or else not cover them. Covering them has the benefit of earning subsidy profit from the government, but runs the risk of the freeriding problem described below.

At the same time, the small provider decides whether to “undercut” the large provider, by offering low-fee service to these customers. If the large provider is “covering” these customers’ calls, the small provider can freeride, i.e., it attracts the customers by offering the low-fee service, collects the fees, but does not have to provide any better service because the large provider is doing so by sharing its BSes with these customers.

The situation outlined above is modelled by the simple 2x2 non-cooperative strategic form game in Fig. 4.1. The two strategies for the large provider (or “Player I” or “The Row Player”) are listed on the left, while those for the small provider (“Player II” or “The Column Player”) are across the top. The four possible outcomes are represented by the four cells. Of concern here is the freeriding outcome in the top left i.e., if the large provider “covers calls” and the small provider charges “low fees”. Also note that there is another outcome which the government would prefer over the freeriding outcome; namely, the large provider to cover foreign calls while the small provider to charge fair market fees so that no freeriding occurs. This is the top right cell of the bimatrix.

The two entries in each cell represent the payoffs a.k.a revenues for Player I (large provider) and Player II (small provider), respectively, if the players play the corresponding strategies. For exam-
ple, if the large provider does not cover calls while the small provider charges low fees, the payoff is $e$ for the large provider and $f$ for the small provider.

Table 4.1: Payoffs

<table>
<thead>
<tr>
<th>Payoff</th>
<th>Value</th>
<th>Payoff</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$a$</td>
<td>$n_1 f_1 + (1 - \mathcal{P}<em>1^2)\epsilon_1 - n_1 \tau</em>{12} f_1$</td>
<td>$b$</td>
<td>$n_2 f_2 + n_1 \tau_{12} f_2$</td>
</tr>
<tr>
<td>$c$</td>
<td>$n_1 f_1 + (1 - \mathcal{P}_1^2)\epsilon_1$</td>
<td>$d$</td>
<td>$n_2 f_2^*$</td>
</tr>
<tr>
<td>$e$</td>
<td>$n_1 f_1$</td>
<td>$f$</td>
<td>$n_2 f_2$</td>
</tr>
<tr>
<td>$g$</td>
<td>$n_1 f_1$</td>
<td>$h$</td>
<td>$n_2 f_2^*$</td>
</tr>
</tbody>
</table>

We derive expressions for the payoff quantities $a, b, ..., h$ by simplifying (4.3) and (4.4) and present in Table 4.1. We assume that a provider knows its customer count and gets the other provider’s customer count from the government report or the annual report released by the other provider. If such reporting is not possible, a provider can predict the customer count of other providers by inspecting public data about other providers such as the coverage of their network and their market value. The fees of both providers are publicly available. In the same way, subsidy allocation from the government is also assumed public information. From the customer switching function which involves both providers’ fees, a provider can predict the net customer switching. Now, the only unavailable parameter of (4.3) and (4.4) is the penalty on subsidy which depends on the amount of sharing the large provider does. A provider can get the information related to serving foreign calls from the “proof-of-sharing” module [30] where the accounting of serving foreign calls are conducted. It helps all providers to predict/compute applied penalty on each other’s subsidy amount. By utilizing all of this information, a provider can measure game payoffs of Fig. 4.1. We assume only Provider I is losing customers to Provider II, where $n_1 \tau_{12} > 0$ and $n_2 \tau_{21} = 0$, and Provider II cannot earn subsidy (i.e., $0 \leq \mathcal{P}_2^2 \leq 1$, $\mathcal{P}_2^1 = 1$) as it is not sharing the spectrum. In reality, this sharing and customer losing could happen in both ways. However, we focus on the simplified case of one provider being larger than the other, so we consider it happens in one way which is sufficient to observe the freeriding effects in SBSS markets.
We have denoted the fair market fee or reservation price as $f^*_2$ for Provider II. Alternatively, $f_2 < f^*_2$ is the undercutting low fee Provider II could charge. From Table 4.1, we see that the following relationships necessarily hold: $e = g$, $g < c$, $a < c$, $f < h$, $h = d$, and $f < b$. These relationships are used in all states of the game detailed next.

We analyze this game using non-cooperative game theory. A mixed strategy for Player I is a two component vector $(p, 1 - p)$ in which $p \geq 0$ represents the probability that it will cover all calls and $1 - p$ is the probability it does not. Similarly, a mixed strategy for Player II is given by $(q, 1 - q)$, in which $q$ is the probability that it charges low fees. Given mixed strategies of each player, it is easy to calculate the expected payoff for each player: $pq + p(1 - q)c + (1 - p)qe + (1 - p)(1 - q)g$ for Player I and $pqb + p(1 - q)d + (1 - p)qf + (1 - p)(1 - q)h$ for Player II.

A Nash equilibrium (NE) is a pair of mixed strategies, one for each player, in which both players are maximizing their expected payoff given what the other is doing. It is the most used solution concept in non-cooperative game theory, and we use it here to analyze the game above.

Considering uncertain relationships between $a$, $e$, and $b$, $d$, we get four different states for the game. They are:

**Scenario I** ($a < e \text{ AND } d < b$). This is the interesting case, with no dominating strategies. The unique NE is for Player I to play $(p^*, 1 - p^*)$ and Player II to play $(q^*, 1 - q^*)$, where $p^* = (h - f) / (b - f)$ and $q^* = (c - g) / (c - a)$.

Now observe what happens if the government raises the subsidy to the large provider for covering calls. This raises both $a$ and $c$ by the same amount, say $x$. For small $x$, the effect is to raise $q^*$, i.e., to make the small provider more likely to undersell. If $x = e - a$, there is a continuum of NEs, all with $q^* = 1$, i.e., all with small provider underselling. Finally, if $x > e - a$, the unique NE

---

$(p^*, 1 - p^*)$ and $(q^*, 1 - q^*)$ denote Provider I and II’s NE strategies respectively.
outcome is the freeriding outcome of \( p^* = q^* = 1 \). Hence, we see how the government raising the subsidy triggers the freeriding problem.

So, how can the government encourage its desired outcome? It merely needs to raise the payoffs (to small provider) for not underselling. In terms of our bimatrix, this would raise the quantities \( d \) and \( h \). If done in conjunction with the subsidy idea above, it could force the NE to be the desired outcome, i.e., \( p^* = 1 \) and \( q^* = 0 \). In practice, this can be done by either imposing a price floor for the service subscription fee (so that charging too small a fee is a crime), or perhaps by allowing providers to keep more of their fees via lowering particular penalties on the subsidy benefits by the government.

**Scenario II** \((a \geq e \text{ AND } d < b)\). In this state covering calls is a dominating strategy for the large provider, i.e. it is in the best interest of the large provider to cover calls, no matter what the small provider does. Since \( d < b \), the small provider’s best response to this is to charge low fees. Hence, the unique NE is the freeriding outcome.

**Scenario III** \(((d > b) \text{ OR } (a < e \text{ AND } d = b))\). In this case, charging high fees is a dominating strategy for the small provider. Since \( c > g \), the large provider’s best response to this is to cover calls. Hence, the unique NE is the desired freeriding-free outcome.

**Scenario IV** \((a \geq e \text{ AND } d = b)\). When a game forms like this, we get a continuum of NEs. For all NEs, Player I covers calls. Player II can play any mixed strategy.

### 4.2.1 Observations

If we closely observe the game NEs, we see that Provider I’s strategies ensure it to earn at least the earnings of a non-shared spectrum market which can be found at the bottom-right cell of the game matrix. In case of PSNEs, it is obvious from the payoffs, e.g., in **Scenario II**, the game
NE at the top-left cell ensures Provider I to get as much as the earnings of a non-shared market. Similarly, Provider I gets guarantees from the freeriding-free outcome at Scenario III. In case of mixed strategy NEs, we can not directly observe such guarantees just looking into the game matrix. However, if we compute the total revenue by applying NE strategies, the game guarantees Provider I no revenue loss. Let analyze this scenario with an example where the game follows mixed strategies as described in Scenario I. If \( a = 8, b = 6, c = 15, d = 5, e = 10, f = 3, g = 10, \) and \( h = 5, \) the game has an NE with the mixed strategies \((0.67, 0.33)\) and \((0.71, 0.29)\) for Provider I and II respectively. Provider I’s expected payoff becomes 10.02, which is higher than the non-shared payoff 10. Similarly, we will get a higher payoff for all mixed strategy NEs. In this way, our proposed two-provider game holds the condition of (3.6).

### 4.3 Game in a Multi-Provider SBSS Market

A provider \( j \) can apply strategic decision of sharing with the presence of a freeriding provider \( k \) by following the two-provider game settings described in earlier section, which holds the condition of (3.6), where \((1 - P^k_j)\epsilon^k_j - n_j\tau_{jk}f_j \geq 0.\) It ensures no revenue loss for provider \( j.\) Similarly, in a \( J \)-provider market, provider \( j \) can play the two-player game against each of the \( J - 1 \) providers and apply appropriate sharing strategies to overcome overall revenue loss where \( \sum_{k \in J \setminus \{j\}} (1 - P^k_j)\epsilon^k_j - \sum_{k \in J \setminus \{j\}} n_j\tau_{jk}f_j \geq 0. \) Now, the revenue of provider \( j \) becomes:

\[
R_j = n_jf_j + \sum_{k \in J \setminus \{j\}} (1 - P^k_j)\epsilon^k_j - \sum_{k \in J \setminus \{j\}} n_j\tau_{jk}f_j
\]  

(4.5)

which is at least the earnings of a non-shared market. Thus, provider \( j \) can apply different strategic decisions of sharing against each of the competitor providers’ freeriding strategies and continue participation in the SBSS market without losing revenue.
Table 4.2: Parameters & values in game framework

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\eta$</td>
<td>1000</td>
<td>$n_1, n_2$</td>
<td>$\frac{\eta X_1}{X_1 + X_2}$, $\frac{\eta X_2}{X_1 + X_2}$</td>
</tr>
<tr>
<td>$\omega_1, \omega_2$</td>
<td>(0.3, 0.8, 0.96), 0</td>
<td>$f_1^<em>, f_2^</em>$</td>
<td>$\frac{n_1 f_1^<em>}{X_1}$, $\frac{n_2 f_2^</em>}{X_2}$</td>
</tr>
<tr>
<td>$\mu$</td>
<td>100</td>
<td>$V_1, V_2$</td>
<td>$n_1 f_1^<em>, n_2 f_2^</em>$</td>
</tr>
<tr>
<td>$\pi$</td>
<td>0.05, 0.5, 0.8, 0.95</td>
<td>$T_{mv}$</td>
<td>$V_1 + V_2$</td>
</tr>
<tr>
<td>$(X_1, X_2)$</td>
<td>(70, 30), (100, 1–100)</td>
<td>$\epsilon_1, \epsilon_2$</td>
<td>$(4.49, (0–45))%$ of $T_{mv}$, 0</td>
</tr>
</tbody>
</table>

4.4 Experimental Evaluation

In previous Section, we observed a two-provider game NEs based on different scenarios. In this section, we will perform quantitative analysis of these NEs using simulation. To analyze the providers’ problem in an SBSS market, we consider two providers are competing within a single region where Providers I and II are the large and small providers, respectively. We use the parameters and initial settings outlined in Table 4.2. If we look at the functions to determine the number of customers and fair market fees in Table 4.2 and Section 4.4.1.1, we can see that similar sized providers will have a similar customer counts and subscription fees. If both providers are exactly the same, then both will have an equal customer count and charge equal fees.

In our model, one provider shares spectrum resources and the other does not. Because of UCS, some customers may move from one provider to other. If both providers are similar in size and both are sharing, then the probability of UCS will be small and similar in both directions. If one of them takes new strategies on fees or willingness to share spectrum resources, the other provider will be forced to follow similar strategies to keep its subscribers. As fee difference is a key factor for freeriding, similar fees will overcome the freeriding issues. Our objective in this work is to identify potential freeriding possibilities and take countermeasures against them. Hence, we mostly focus on the harmful conditions where fees differences are significantly high. We can
obtain such market conditions when the difference between the size of two providers is high. For this reason, we focus on a large and a small provider market to evaluate our model. We start with customer utility, demand and call quality. Later, we analyze customers’ price averseness and UCS. Finally, we illustrate the strategies associated with each game NE.

### 4.4.1 Experimental Setup

We enlist the simulation parameters in Table 5.1 where \( \eta \) and \( \mu \) denote the number of customers within the experimental region and the total number of calls each customer makes, respectively. The large Provider I has better area coverage than II and is more willing to share its spectrum resources. These willingness to shares, \( \omega_1 \) and \( \omega_2 \), represent the initial agreement between providers indicating the percentage of incoming foreign calls they will serve. Initially, we set Providers I and II’s BS count to 70 and 30 respectively, a high value 0.8 for \( \omega_1 \) to observe freeriding scenarios, and 0 for \( \omega_2 \) as Provider II does not share spectrum resources. Except Section 4.4.2.3, we use this count of BSes throughout the experiments. We randomly set up each provider’s BSes in a 35 × 35 square grid and calculate the number of customers, \( n_1, n_2 \), subscribed to the providers based on the BS counts as shown in Table 5.1. Also, we position all customers in the experimental region randomly. We apply a linear penalty, \( P^2 = 1 - F^2_i / F_t \), to Provider I on given subsidy where \( F_t \) is the total incoming foreign calls to Provider I.

#### 4.4.1.1 Customer Utility and Demand

We model a customer’s perceived signal utility from Providers I and II as \( u_1 = u(\psi_1) \) and \( u_2 = u(\psi_2) \) where \( u(\psi_1) = \log(Q_1) \) and \( u(\psi_2) = \log(Q_2) \), respectively, and formulate the signal quality offered by a provider as an increasing concave function of BS count, and decreasing convex function of the number of customers. In particular, we use \( Q_1 = X_1^\pi / n_1 \) and \( Q_2 = X_2^\pi / n_2 \).
to represent the offered signal quality to the customers of Providers I and II where $\pi$ is a constant expressing the benefit of having more BSes to the signal strength. It describes, within a fixed size region, how the marginal improvement on the offered signal quality will diminish w.r.t. the BS count. To assure concavity, $\pi$ must be in $(0, 1)$, and we chose $\pi = 0.8$ for rest of the experiments except Section 4.4.2.5. With same $\pi$, the small provider’s offered signal quality and utility will improve more than the large providers’ if we increase their base station counts by the same amount.

$\pi$ also helps to determine fair market fees for both providers. Using the marginal utilities, $u'_1$ and $u'_2$, we define the fair market fees as: $f^*_1 = u'_1 = 1/Q_1 = n_1/X_1^\pi$ and $f^*_2 = u'_2 = 1/Q_2 = n_2/X_2^\pi$. For $\pi < 1$, we get $f^*_1 > f^*_2$ which is expected in a normal market where market leader charges higher than the followers [73]. We determine both providers’ market values, $V_1$, $V_2$, and the total market value, $T_{mv}$, using fair market fees as shown in Table 5.1. Based on $T_{mv}$, we start with subsidies, $\epsilon_1 = 4.49\%$ of $T_{mv}$, and $\epsilon_2 = 0$, as Provider II does not share spectrum resources. Later, we vary $\epsilon_1$ between 0–45\% of $T_{mv}$ and observe market equilibrium. 45\% of $T_{mv}$ is already too much subsidy considering real markets. As a result, we do not consider higher subsidy amounts because they almost certainly cause freeriding.

4.4.1.2 Overall Perceived Quality

To measure the signal strength of each provider, we consider the received power at free space. For simplicity, we only consider the distance from a caller to the BS for the main beam and ignore any multi-path beams. We define $\psi_1 = 1/d_1^2$ and $\psi_2 = 1/d_2^2$ where $d_1$ and $d_2$ represent the distance from a customer to the nearest BS of Provider I and Provider II, respectively. As we consider a simplified game model where only Provider I is willing to share (i.e., $\omega_1 > 0$, $\omega_2 = 0$), all calls of Provider I’s customers are considered as home calls. However, for Provider II, it depends on
the signal strength of both providers. If the nearest BS is one of Provider I’s, then the decision to
serve as a foreign call is made based on a random number ranged between 0 to 1. If the number is
at most $\omega_1$, then Provider I serves it as a foreign call. Thus, the number of home and foreign calls
may vary for all customers of Provider II. Considering the randomness of the locations of BSes, 
customers, and determination of foreign vs. home calls, we have run our experiments 7 times and
took the average of them to calculate the signal qualities $\psi_1$ and $\psi_2$, and overall perceived qualities
$\psi_1^*$ and $\psi_2^*$.

4.4.1.3 Price Averseness and Unfair Customer Switching (UCS)

The probability of UCS is one of the key factors of freeriding. If $\psi_2^* \geq \psi_1^*$, and $f_1^* > f_2$, then the
probability of the UCS initiated by Provider II becomes: $\tau_{12} = 1 - e^{-Cf_1^* / f_2}$. The probability of
the UCS is high when the price averseness, $C$, is high. In a normal market, we believe customers
are very averse with price. Hence, we use a moderate high value for $C$ which is 0.9, except Section
4.4.2.6. Due to UCS, Provider I’s lost customers $n_1 \tau_{12}$, can range between 0 to $n_1$ depending on
$\tau_{12}$.

4.4.2 Results

In this section, we illustrate observed NEs and both providers’ strategies. We find the effects
of different subsidies on game NEs, e.g., a large subsidy, study how the NE changes with the
change of small provider’s BS count, and the contribution of marginal signal improvement. We
also analyze how an NE can shift from one state to another due to the small provider’s UCS strategy
as well as for the large provider’s willingness to share.
4.4.2.1 Strategies of Large and Small Providers at Equilibrium

We have observed the NE strategies taken by Provider I, $p^*$, and Provider II, $q^*$, against Provider II’s low fee, $f_2$, to fair market fee, $f_2^*$, ratio, $r$. We have taken 30, 50 and 70 different data points between the ranges $0 \leq r \leq 0.199$, $0.2 \leq r \leq 0.4$ and $0.41 \leq r \leq 1$ respectively to evaluate.

We consider Provider I’s three reference willingness to shares ($\omega_1 = 0.3, 0.8$ and $0.96$) and draw the graphs, Fig. 4.2a. If we continue increasing Provider II’s fees towards the fair market fee, i.e., $r \rightarrow 1$, Provider I plays a less sharing strategy (lowering $p^*$), and Provider II undersells more (higher $q^*$) at high $\omega_1$. It happens because of increasing fees nearer to the fair market fee causes less revenue loss for Provider II compared to the earnings from UCS, and high revenue loss for Provider I due to freeriding. We observe a transition of $p^*$ from pure strategy, $p^* = 1$, to a mixed strategy between fees ratio, $r = 0.41$ to $r = 0.42$. This, $r = 0.41$, is the terminal fees ratio up-to which Provider I can always maintain agreed sharing without facing any loss. At low willingness to share, $\omega_1 = 0.3$, we observe no freeriding and it takes place at high willingness to share, $\omega_1 = 0.8$ or 0.96. Once Provider I starts losing revenue due to UCS, it chooses mixed strategy over pure strategy to overcome the loss.

Figure 4.2: Equilibrium strategies
We have observed the NE strategies $p^*$ and $q^*$ for Provider I’s all possible willingness to shares, $\omega_1$. We have considered 50, 90 and 10 different data points between the ranges $0 \leq \omega_1 \leq 0.599$, $0.6 \leq \omega_1 \leq 0.9$ and $0.91 \leq \omega_1 \leq 1$ respectively, and plotted the graphs for three different $r$ where the values are 0.3, 0.8 and 0.96, Fig. 4.2b. At same $\omega_1$, Provider I is more interested for less sharing with the increase of Provider II’s fees towards the fair market fee. We observe both providers play freeriding-free pure strategies, $p^* = 1$, $q^* = 0$, at low fees ratio, $r = 0.3$. In case of high fees ratio, $r = 0.8$ or 0.96, both starts playing mixed strategies above a certain $\omega_1$. We have seen a transition phase of $p^*$ (from 1 to a proper fraction) when $\omega_1$ is 0.69. It is Provider I’s terminal willingness to share up-to which I can always maintain agreed willingness to share irrespective of Provider II’s strategies. As we calculate $p^*$ with the fraction of $(b - f)$ to $(b - f)$, it is expected to reduce $p^*$ to that level where the fraction is located in Fig. 4.2b. We also observe that both providers maintain same strategy for certain period of $\omega_1$. It happens, because, between this period, Provider II cannot earn more from UCS.

4.4.2.2 Effect of Subsidy

We run the experiment with Provider I’s 100 different subsidies from 0% to 45% of $T_{mv}$, and observed the equilibrium behaviors. We have seen that Provider I is less interested in sharing with the increase of Provider II’s fees closer to fair market fees. However, if we continue increasing $\epsilon_1$, Provider I is finally able to overcome its loss due to UCS. Additional subsidy can encourage it to play the most sharing strategy, $p^* = 1$, which may initiate freeriding. Fig. 4.3a describes the case where we plot graphs against Provider I’s three different willingness to shares ($\omega_1 = 0.3, 0.8, 0.96$). For same $r$, a high value of $\omega_1$ encourages Provider II to undersell mostly, and this forces Provider I to play a less sharing strategy. In case of $\omega_1 = 0.8$, if we continue increasing $\epsilon_1$, Provider I is able to overcome revenue loss when $\epsilon_1 = 0.202T_{mv}$, which encourages Provider I to share more ($p^* = 1$). However, Provider II continues its mixed strategy onwards as it cannot make more profits.
from UCS. When $\omega_1 = 0.96$, we find the start of freeriding, $p^* = 1$, $q^* = 1$, at $\epsilon_1 = 0.175T_{mv}$.

Fig. 4.3b tells the same story from a different perspective where NEs are observed against Provider II’s three different fees ratios, $r = 0.3, 0.8$ and $0.96$. We observe, when $r = 0.3$, Provider I and Provider II play $p^* = 1$ and $q^* = 0$ respectively. When $r = 0.8$ and $r = 0.96$, Provider I and Provider II play mixed strategies up to $\epsilon_1 = 0.238T_{mv}$ and $\epsilon_1 = 0.139T_{mv}$ respectively. After these $\epsilon_1$’s, freeriding takes place.

**4.4.2.3 Effect of Base Stations**

We evaluate game NEs with Provider I’s fixed BS count to 100 and Provider II’s varying BS count between 1-100% of Provider I’s BS count. For all cases of Fig. 4.4, no freeriding takes place when the size of Provider II is too small. It happens because of Provider II’s customers overall perceived signal strength. When Provider II’s BS count is small, its customers will mostly find Provider I’s BSes as the nearest BS, and Provider I will serve these customers based on its strategic decision of sharing. As a result, Provider II’s customers overall perceived signal strength cannot
(a) Both providers’ strategies for different $\omega_1$, $r$ and $\epsilon_1$

(b) Both providers’ signal strength for different $\omega_1$, $r$ and $\epsilon_1$

Figure 4.4: Equilibrium strategies and perceived signal strength for Provider II’s different number of base stations

exceed that Provider I’s customers enjoy. If Provider II’s BS count is around half of Provider I’s BS count, the perceived signal strengths by both providers customers changes and UCS occurs. It forces Provider I to reduce sharing and start playing mixed strategy. If Provider II’s BS count is similar to the Provider I’s BS count, no freeriding takes place. Though Provider II’s customers receive better signal strength compared to Provider I’s customers, the difference between both providers’ charging fees remains low for which Provider II cannot initiate enough UCS to earn more by charging lower-than-fair fees. This low fees difference and low earning force Provider II to charge fair market fees. The freeriding and non-freeriding regions depend on parameters $\epsilon_1$, $r$, $\omega_1$. 

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and $\omega_1$. From Fig. 4.4a(ii) and 4.4b(ii), when $\omega_1 = 0.8$, $\epsilon_1 = 4.49\%$ of $T_{mv}$ and $r = 0.96$, we observe a freeriding case ($p^* = 1, q^* = 1$) if Provider II’s BS count is between 85-98% of Provider I’s BS count. This happens because of the high value of $r$ (i.e., $f_2$ is closer to $f_2^*$), Provider I loses few customers to Provider II and earns enough subsidy to overcome the loss. When both providers are almost equal in size (i.e., $X_2 = 99$ or 100% of $X_1$), no freeriding takes place. From Fig. 4.4a(iii), we observe freeriding takes place if Provider II’s BS count is between 74-78% and 43-78% of Provider I’s BS count when $\epsilon_1 = 15\%$ of $T_{mv}$ and $\epsilon_1 = 35\%$ of $T_{mv}$ respectively.

In the SBSS market, a user receives better signal strength which enables better wireless experience. From Fig. 4.4b(i), a customer of Provider II enjoys higher signal strength if Provider I increases $\omega_1$ when all other conditions remained unchanged. If both would share, then the perceived signal strength for both customers’ would have improved. This delineates how spectrum sharing in the SBSS market can improve a user’s perceived quality of service.

### 4.4.2.4 Effect of Sharing on Call Types

In an SBSS market, customers of Provider II can make calls similar to roaming. However, in roaming, the number of calls served by foreign providers are not high because of cellular providers geo-operational strategies. In the SBSS market, it can be significantly high because of pervasive sharing. If we vary Provider II’s size from 1 to 100% of Provider I’s size, customers of Provider II make fewer foreign calls using I’s network with the increase of size, Fig. 4.5a. At the same time, the percentage of rejections by Provider I are also reduced and overall home calls made through II’s network has been increased. For fixed-sized providers set, the percentage of foreign calls increases with the increase of $\omega_1$, Fig. 4.5b. If we change Provider II’s fees, the percentage of home calls, foreign calls or declined foreign calls remained unchanged. Because, this number depends on the sharing strategy taken by Provider I. If Provider I does not change $\omega_1$, the effective percentage of
Figure 4.5: Calls generated by the customers of Provider II

these 3 categories of calls do not change noticeably which is shown in Fig. 4.5c. If the market consists of more than two providers, declined customers may get served by other better providers instead of complete rejection or re-routed to home network.
4.4.2.5 Effect of Marginal Signal Improvement

Equilibrium strategies w.r.t. different π values are shown in Fig. 4.6a and 4.6b. If we increase π by same amount for both providers, Provider I’s higher sharing region increases. This happens due to two reasons, (1) the higher the π is, the closer each other’s fees are, and (2) if the customers get equal improvement on signal strength from both providers, Provider I still remains ahead of Provider II. As a result, UCS probability remains low, which encourages Provider I for higher sharing. If π is high, and Provider II’s charging fee stays near to fair market fee, Provider I can switch to play higher sharing pure strategy from a low sharing mixed strategy, Fig. 4.6b. It happens, because, higher sharing brings more revenue from the subsidy than the subscription revenue lost due to UCS. In this case, a small amount of subsidy is enough to drive a provider for higher sharing, e.g., if $\pi = 0.95$, and $r = 0.93$, $\epsilon_1 = 0.0449T_{nv}$ is enough to motivate Provider I to switch from a mixed strategy to the higher sharing pure strategy.

4.4.2.6 Effect of Price Averseness and UCS

Customers are very averse with the price they pay for a service. In an SBSS market, a provider’s willingness to share and low fees can cause UCS because of price averseness. If we increase $C$, the probability of UCS increases and the resource sharing provider looses customers. A resource sharing provider can maintain high sharing irrespective of customers’ price averseness if a competitor provider always charges same fee. From Fig. 4.7a, if Provider II always charges 80% of it’s fair market fee, Provider I can maintain pure strategy ($p^* = 1$) up-to $\omega_1 = 0.69$ irrespective of $C$. However, if Provider II charges different fees, we can see in Fig. 4.7b that the price averseness affects Provider I’s sharing and it chooses mixed strategy soon with the increase of $C$.

We observe the scenarios of how long Provider I can play pure strategy ($p^* = 1$) or always maintain agreed sharing (i.e., $\omega_1 = 0.8$ in Fig. 4.7c) if we gradually increase $C$ and take different π. It tells
(a) w.r.t. $\omega_1$

(b) w.r.t. fees ratio ($r$)

(c) w.r.t. price averseness

Figure 4.7: Equilibrium strategies and always on full sharing with a set of $C$

Figure 4.8: Threshold of Provider I’s willingness to share w.r.t fees ratio ($r = f_2/f_2^*$)

us the fees ratio ($f_2/f_1^*$) up-to which Provider I will play higher sharing pure strategy whatever Provider II does. Above this fees ratio, Provider I starts playing mixed strategy. We observe that, with the increase of $C$ and $\pi$, Provider I is more willing to share its spectrum resources. Because, it can tolerate a high price averseness at high marginal signal improvement. Also, if we increase $\epsilon_1$, the region of always on full sharing up-to agreed $\omega_1$ increases. In this observation, the assumption
However, for any $r$ and $\epsilon_1$, we observe a freeriding-free PSNE up-to $\omega_1 = 0.69$. 

### 4.4.2.7 Large Provider’s Willingness to Share and Weak Provider’s Effort to Trigger UCS

Higher sharing is expected in the SBSS market. However, higher sharing increases the chance of revenue loss for the provider who shares spectrum resources. Lowering fee is beneficial for a freeriding provider. However, if the fees are too low compared to fair market fee, lowering fees can be a bad move for it. Thus, there is always a willingness to share, and a fees ratio, below which any sharing can be ensured with PSNE.

We observe equilibrium strategies against given subsidy to Provider I and for a given set of Provider II’s fees ratio as described in Fig. 4.8. When the fees ratio is 30%, we see both providers are interested to play freeriding-free pure strategies, i.e., $p^* = 1$ and $q^* = 0$, for any $\omega_1$, Fig. 4.8a. With the increase of fees ratio, we observe both pure and mixed strategy NEs, Fig. 4.8b and Fig. 4.8c. However, for any $r$ and $\epsilon_1$, we observe a freeriding-free PSNE up-to $\omega_1 = 0.69$. 

Figure 4.9: Threshold of Provider II’s fees ratio w.r.t willingness to share ($\omega_1$) 

of a high $\omega_1$, e.g., 0.8, comes from the experiment (described in Section 4.4.2.7) where we found that for any $\epsilon_1$, Provider I always play higher sharing pure strategy up-to $\omega_1 = 0.69$. 

Figure 4.9: Threshold of Provider II’s fees ratio w.r.t willingness to share ($\omega_1$)
We also observe NE strategies against given subsidy to Provider I and its a set of willingness to share in Fig. 4.9. When sharing is low, e.g., $\omega_1 = 0.4$ in Fig. 4.9a, both providers play the freeriding free PSNE. With the increase of sharing, we observe both pure and mixed strategy NEs, Fig. 4.9b and Fig. 4.9c. If the fees ratio $r$ is high, the game exhibits a freeriding equilibrium with the increase of subsidy. The high $\omega_1$, the more we get the freeriding equilibrium when all game conditions remain unchanged. However, for all cases, if $r \leq 0.41$, we get freeriding-free PSNEs. Above of this ratio, we observe both players adjust their pure strategy to mixed strategy to ensure profits. In this case, $r = 0.41$ is the threshold fees ratio, bellow which Provider II is not interested to play freeriding strategy, $q^* = 1$, as it can not make profit from UCS.
CHAPTER 5: SYMMETRIC SPECTRUM SHARING IN A DYNAMIC SBSS MARKET

In previous chapter, we formed a single stage non-cooperative game to suggest strategies to participating providers in the SBSS market while mitigating freeriding. We considered asymmetric behavior of the market where only one provider shares the network and the other tries to maximize its revenue by freeriding. In this chapter, we will consider symmetric sharing where all providers participate in spectrum sharing in a dynamic market environment where market condition changes frequently. Here, we suggest regulated minimum fees to the government, and suitable fees and willingness to shares for participating providers.

5.1 Government’s Regulation on Fees

The government can introduce a regulation on fees in the SBSS market to minimize freeriding while encouraging spectrum sharing via subsidy. All participating providers will need to follow the fee regulation to maintain the overall market healthiness. The government knows the advertised fair market fees and the initial agreement of willingness to share of all providers. By using this information, the government can calculate and predict a probable customer switching from one provider to another. To minimize this switching due to freeriding small providers, the government can impose a cap on the minimum fee for each provider. This minimum fee could depend on the providers’ willingness to share and fees. As a result, this fee could differ from one provider to another. We determine the government regulated minimum fee in an SBSS market for a provider

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Most of the content of this Chapter have appeared in the Proceedings of [74]
using the subsidy amount. First, we will show how to determine the minimum fee for a provider in a two-provider market. Later, we will find the minimum fee in a \( J \)-provider SBSS market.

### 5.1.1 Regulated Fee in a Two-Provider SBSS Market

Consider, two providers \( j \) and \( k \) from provider set \( J \) where \( j \) shares spectrum resources and \( k \) tries to freeride. As provider \( j \) is sharing, it is also offering freeriding opportunity to \( k \) which initiates UCS from \( j \) to \( k \). Because of provider \( j \)’s sharing in the SBSS market, a customer of provider \( k \) can obtain greater than or equal utility compared to a customer of \( j \) [29]. If it happens and \( f_j > f_k \), we expect an UCS from \( j \) to \( k \). If \( f_j \leq f_k \), there will be no UCS. Thus, UCS becomes a function of both providers’ fees and willingness to share, and we define it as:

\[
\Upsilon_{kj} = \left[ 1 - \exp \left( -\frac{\omega_j(f_j - f_k)}{f_j + f_k} \right) \right] n_j. \tag{5.1}
\]

If \( \omega_j = 0 \), we get \( \Upsilon_{kj} = 0 \). When \( f_j \leq f_k \), no UCS takes place. For such cases, we can say, \( \Upsilon_{kj} = 0 \).

We have seen the emergence of freeriders in the SBSS market because of small providers advertising lower-than-fair market fees. The lead providers’ defensive strategy alone (e.g., reducing its willingness to share) may not be sufficient, and a regulatory approach is needed to entirely eliminate freeriders. One solution can be a minimum subscription fee for each participating provider. However, the customers’ aversion to additional fees limits the practicality of this solution. For instance, if customers find a high price difference for a similar service they will choose providers with lower fees which can cause UCS. If provider \( j \) loses \( \Upsilon_{kj} \) customers due to UCS, then it needs to get a subsidy at least equal to the revenue loss. To make sure provider \( j \)’s participation in the
SBSS market, the following condition needs to be satisfied:

$$\chi_{kJ} f_j \leq (1 - P_j^k) \epsilon_j. \tag{5.2}$$

where $P_j^k$ is the penalty applied on subsidy amount based on “proof of sharing” [30]. In the initial phase of the SBSS market, $P_j^k$ is unknown to the government as no sharing information is available. By considering this situation, we assume the penalty for provider $j$ is equal to the residual of $\omega_j$, i.e., $(1 - \omega_j)$. After each subsidy period, the government gets actual sharing information, which it uses to determine minimum fees for the next subsidy period.

Substituting (5.1) in (5.2), we obtain:

$$f_k \geq \frac{\omega_j f_j}{\log \left( \frac{1}{1 - Y} \right)}, \tag{5.3}$$

where $Y = \frac{(1 - P_j^k) \epsilon_j}{n_j f_j}$. Note that $Y$ is the ratio of provider $j$’s subsidy revenue to subscription revenue. Further, to attain a positive fee range, it is necessary to have $\frac{1}{1 - Y} > 1$ which implies that $Y > 0$. This verifies that provider $j$’s subsidy earnings must be positive, i.e., it must be participating in the SBSS market with $\omega_j > 0$.

From (5.3), we can write the lower limit of subscription fee for provider $k$ as

$$f_{k, \text{min}} = \frac{\omega_j f_j}{\log \left( \frac{1}{1 - Y} \right)}. \tag{5.4}$$

This is the necessary condition to maintain provider $j$’s participation in the SBSS market considering UCS to provider $k$. A government can introduce this lower limit of fees for provider $k$ to participate in the SBSS market.
### 5.1.2 Regulated Fee in a J-Provider SBSS Market

Now assume, in a $J$-provider SBSS market, the subsidy given to any provider is evenly distributed for serving customers of all other $J - 1$ providers. It means a provider can earn at most $\frac{1}{J-1}$ of subsidy money by serving the customers of a particular provider where the applied penalty is 0.

If we consider the one-to-one relation between provider $k$ to every other provider $j \in J \setminus \{k\}$ in SBSS market, we get $J - 1$ different minimum fees for $k$. The largest fee of $J - 1$ fees will be the actual minimum fee for provider $k$. If $f_{k,\text{min}} > f^*_k$, where $f^*_k$ is provider $k$’s fair market fee which we obtain from the marginal utility (detailed in Section 4.4.1.1), then the government allows provider $k$ to charge $f^*_k$.

A participating provider is obliged to follow the minimum fee regulation in SBSS market. By following this regulation, it aims to capitalize revenue as much as possible. With the goal of revenue maximization, it adjusts its willingness to share and subscription fee. We will introduce an approach to adjust these two components in the following section.

### 5.2 A Provider’s Strategy

The sustainability of an SBSS market depends on the long-term participation of providers. The providers will participate only if the market is beneficial for their business. As they are going to share spectrum resources with each other, the SBSS market needs to be free of freeriders. Otherwise, providers will lose revenues and refrain to participate. Our game framework on SBSS market provides strategies only for a provider’s willingness to share in the equilibrium. We considered the case when a provider shares spectrum resources and others try to freeride. It did not consider bidirectional sharing between all providers and suggest any strategy on how to adapt a provider’s subscription fee. Subscription fee is a key parameter to regulate freeriders. Here, we consider a
Algorithm 1 Provider $j$’s strategy to adjust $f_j$ and $\omega_j$

1. **procedure** `FEANDWILLINGNESSTOSHARE($n_j$, $f_j$, $k_j$, $f_k$, $\omega_j$, $\omega_k$, $\epsilon_j$, $\epsilon_k$, $X_j$, $\pi$)`
2. Initialize provider $j$’s total revenue, $R_j^{t-1}$, subscription revenue, $S_j^{t-1}$, subsidy earnings, $E_j^{t-1}$, fee, $f_j^{t-1}$, willingness to share, $\omega_j^{t-1}$, and a tolerance, $\mathcal{M}$ as:
   3. $R_j^{t-1} \leftarrow n_j f_j$, $S_j^{t-1} \leftarrow n_j f_j$, $E_j^{t-1} \leftarrow 0$, $f_j^{t-1} \leftarrow f_j$, $\omega_j^{t-1} \leftarrow \omega_j$, $\mathcal{M} \leftarrow$ a value
4. loop:
   5. Compute the probabilities of customer switching, $\Upsilon_{jk}$ and $\Upsilon_{kj}$, using $f_j^{t-1}$, $f_k$, $\omega_j^{t-1}$ and $\omega_k$. Using this probabilities, compute provider $j$’s new number of customers, $n_j^t$, total revenue, $R_j^t$, subscription revenue, $S_j^t$, and subsidy earnings, $E_j^t$ in SBSS market.
   6. if $R_j^t < (R_j^{t-1} - \mathcal{M})$ then
      7. if $S_j^t < S_j^{t-1}$ then
         8. $f_j \leftarrow (n_j^t) / \left( X_j^\pi \right)$ \hspace{1cm} \triangleright \text{Update based on demand}
         9. $\omega_j^t \leftarrow \text{Linear decrease from } \omega_j^{t-1}$
       10. if $\omega_j^t < 0$ then
           11. $\omega_j^t \leftarrow 0$
       end if
      else
      14. $f_j^t \leftarrow f_j^{t-1}$, $\omega_j^t \leftarrow \omega_j^{t-1}$
      end if
    else if $R_j^t > (R_j^{t-1} + \mathcal{M})$ then
      16. if $S_j^t > S_j^{t-1}$ then
         18. $f_j^t \leftarrow f_j^{t-1}$, $\omega_j^t \leftarrow \omega_j^{t-1}$
      else
      21. $f_j^t \leftarrow (n_j^t) / \left( X_j^\pi \right)$\hspace{1cm} \triangleright \text{Update based on demand}
         22. $\omega_j^t \leftarrow \omega_j^{t-1}$
      end if
    else if $E_j^t < E_j^{t-1}$ then
      28. if $\omega_j^t > \omega_j^{t-1}$ then
         30. $\omega_j^t \leftarrow \text{Linear increase from } \omega_j^{t-1}$
      else
      33. $\omega_j^t \leftarrow \omega_j^{t-1}$
      end if
    else
      34. $\omega_j^t \leftarrow \omega_j^{t-1}$
      end if
  37. else
  38. $f_j^t \leftarrow (n_j^t) / \left( X_j^\pi \right)$ \hspace{1cm} \triangleright \text{Update based on demand}
  39. $\omega_j^t \leftarrow \omega_j^{t-1}$
end if
  41. if $(R_j^t == R_j^{t-1})$ & $(\omega_j^t == \omega_j^{t-1})$ & $(f_j^t == f_j^{t-1})$ then
     42. $f_j \leftarrow f_j^t$, $\omega_j \leftarrow \omega_j^t$
     43. return $f_j$ and $\omega_j$
     44. else
     45. $R_j^{t-1} \leftarrow R_j^t$, $S_j^{t-1} \leftarrow S_j^t$, $E_j^{t-1} \leftarrow E_j^t$, $f_j^{t-1} \leftarrow f_j^t$, $\omega_j^{t-1} \leftarrow \omega_j^t$
goto loop:
end if end-loop
end procedure
bi-directional sharing and propose a novel heuristic algorithm to attain a suitable subscription fee and willingness to share for providers in Algorithm 1. It takes current market parameters of two providers as input (e.g., number of customers, subscription fees, initial willingness to share, subsidies), and runs as long as it meets the necessary condition that the provider stably earns at least as much as the revenue without entering the SBSS market.

Assume that we are looking for the strategy set of a provider \( j \). We take the market parameters of \( j \) and a provider \( k \in J \setminus \{j\} \) as input in Algorithm 1. In each iteration, the procedure compares the earnings of the previous iteration to current iteration by parts, i.e., total revenue, \( R_j \), subscription revenue, \( S_j \), subsidy earnings, \( E_j \), after applying penalty, and generates a new \( f_j \) and \( \omega_j \) for \( j \).

We consider, the subsidy interval is longer than the subscription revenue interval. Hence, we apply new penalty on subsidy after each five consecutive iterations. We denote a parameter’s previous and current values by using \( t−1 \) and \( t \) superscripts respectively. The procedure repeats until it finds no change in \( R_j \), \( f_j \) and \( \omega_j \) for two consecutive iterations. If it finds such consecutive iterations, it returns \( f_j \) and \( \omega_j \) which are the best suited strategies for \( j \).

The procedure demonstrated in Algorithm 1 is well suited for a \( J \)-provider market as well. A provider \( j \) get’s \( J−1 \) fees and \( J−1 \) willingness to share from the market. The minimum fee from these fees is the best suited fee, \( f_j \), which can ensure minimum number of customer loss for \( j \) and it takes \( J−1 \) willingness to share each for individual competitor.

5.3 Simulation Results and Analysis

A government subsidized spectrum sharing market possesses a unique set of challenges. It involves individual customer’s choice of provider during making a call, the provider’s call acceptance, unfair customer switching from a spectrum sharing provider to an opportunistic freeriding provider, and finally making effective government regulation to minimize freeriding. To evaluate this market,
Table 5.1: Parameters & values in heuristic approach

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\eta$</td>
<td>1000</td>
<td>$n_1, n_2$</td>
<td>$\frac{\eta \lambda_1}{X_1 + X_2}, \frac{\eta \lambda_2}{X_1 + X_2}$</td>
</tr>
<tr>
<td>$\omega_1, \omega_2$</td>
<td>(1, 0.75, 0.45), 0.5</td>
<td>$f_1^<em>, f_2^</em>$</td>
<td>$\frac{\eta_1}{X_1^<em>}, \frac{\eta_2}{X_2^</em>}$</td>
</tr>
<tr>
<td>$\mu$</td>
<td>100</td>
<td>$V_1, V_2$</td>
<td>$n_1 f_1^<em>, n_2 f_2^</em>$</td>
</tr>
<tr>
<td>$\pi$</td>
<td>0.8</td>
<td>$T_{mv}$</td>
<td>$V_1 + V_2$</td>
</tr>
<tr>
<td>$X_1$</td>
<td>90, 70, 55</td>
<td>$X_2$</td>
<td>10, 30, 45</td>
</tr>
<tr>
<td>$\epsilon_1$</td>
<td>(40, 20, 10)% of $T_{mv}$</td>
<td>$\epsilon_2$</td>
<td>(15, 10, 5)% of $T_{mv}$</td>
</tr>
</tbody>
</table>

we assume all base stations operate at the same power, and a customer considers the distance from the base station when making a call. If the nearest base station belongs to the home provider, the call proceeds through home provider. However, if the nearest station belongs to a foreign provider, the serving decision depends on the willingness to share of the foreign provider. If the foreign provider does not accept the call, then the closest home base station carries the call. To determine a provider’s suitable fee and willingness to share with the presence of freeriders, we apply the procedure of Algorithm 1.

5.3.1 Experimental Environment

To evaluate our proposed algorithm to determine a provider’s strategy and understand the potential minimum fees to regulate freeriding, we simulate a two-provider market 5 times and take the average. Providers I and II are deployed in a $35 \times 35$ square grid region. We assume that Provider II always enters in the simulation with an initial $\omega_2 = 0.5$ unless otherwise stated. However, Provider I’s initial $\omega_1, \epsilon_1$, and Provider II’s subsidy, $\epsilon_2$, vary for different cases of the experiment. We define the subsidy to any provider as a percentage of total market value, $T_{mv}$. For simplicity, the market value of the providers, $V_1$ and $V_2$, are determined by their revenue earnings. We also consider the market consists of $\eta$ customers. The initial number of customers subscribed to Provider I, $n_1$ and

64
Figure 5.1: Market status for Provider I’s different initial $\omega_1$ with reference to $\epsilon_1$ and $\epsilon_2$

II, $n_2$ are proportionate to Provider I’s base station count, $X_1$, and Provider II’s base station count, $X_2$, respectively. We locate all base stations and customers position randomly on the grid. We allow each customer to make $\mu = 100$ calls in total. We determine marginal signal improvement, foreign and home calls, penalty, and fair market fees according to Section 4.4.1.1 and 4.4.1.2. We list all these parameters in Table 5.1.

5.3.2 Strategies for Providers

Our proposed algorithm can generate a suitable fee and a willingness to share for a participating provider. Consider a case in which Providers I and II are similar in size, $X_1 = 55$ and $X_2 = 45$, as in Fig. 5.1. Now, if we vary Provider I’s $\omega_1$, we observe that whatever the subsidy amount is given to Provider I, its revenue starts dropping or saturating from a steady increasing phase after initial $\omega_1$ crosses initial $\omega_2$. However, at the same time Provider II’s revenue earning starts increasing. This happens because the higher sharing done by Provider I creates a higher UCS opportunity to Provider II. As a result Provider II becomes more greedy and increases its fees as demand increases. However, observing this UCS, Provider I starts lowering fees and tries to maintain its
Figure 5.2: Market status for Provider I’s different initial $\omega_1$ with reference to $X_1$ and $X_2$ revenue in a profitable region. By lowering fees it can retain a significant number of customers who were thinking to get Provider II’s subscription. This happens because of similarity in size and indicates a high-competition market where none has exclusive market dominance. As a result, if Provider I increases $\omega_1$, then Provider II gets more opportunities to freeride. For minimizing such freeriding, Provider I needs to lower $f_1$. Thus, by increasing $\omega_1$ and lowering $f_1$, Provider I maintains a profitable revenue and overcomes freeriding effects of Provider II.

However, if we maintain unchanged subsidy to both providers while varying $\omega_1$ and observe the strategies for different sized providers, we can see a continuous increase in revenue earnings for Provider I unless $\omega_1$ reaches closer to 100%, as shown in Fig. 5.2. When the size difference between providers is significantly large, then the large provider can maintain a high *willingness to share* as it knows the subsidy earning can be increased by higher sharing only. For higher sharing, it needs to lower fees. If the size difference between both providers’ is reduced, the rate of lowering fee increases. This happens because of similarity in size and indicates a high-competition market where none has exclusive market dominance. As a result, if Provider I increases $\omega_1$, then Provider II gets more opportunities to freeride. For minimizing such freeriding, Provider I needs to lower $f_1$. Though Provider I is lowering $f_1$ but it can still manage to earn higher revenue compared to non-SBSS market.
In Fig. 5.3, we continuously increase $\epsilon_1$, and make the market competitive where both providers’ are similar in size, i.e., $X_1 = 55$ and $X_2 = 45$. We consider Provider I’s three initial $\omega_1 = 1, 0.75, 0.45$, as reference. We observe Provider I is still able to maintain high revenue. However, for market competition, he chooses to lower $f_1$ and continue sharing closer to initial $\omega_1$ due to high customer loss from high sharing. Thus, subsidy motivates it to continue promised sharing and lower fees which eventually increases users wireless experience.
5.3.3 Perceived Signal Strength in SBSS and non-SBSS Markets

We measure a provider’s signal strength using the free-space radio propagation concept where the strength is proportional to the inverse of the square of the distance. In this simulation, we denote a customer’s distance from providers I and II’s base stations as $d_1$ and $d_2$ and calculate the received signal strength as: $\psi_1 = 1/d_1^2$ and $\psi_2 = 1/d_2^2$. In the SBSS market, a customer gets service from a foreign provider according to Section 5.3.1. In this way, both providers customers enjoy different levels of signal strength in the SBSS market which is higher than the signal strength in a non-SBSS market as shown in Fig. 5.4. We define the perceived signal strengths of Provider I and II’s customers in the SBBS market as $\hat{\psi}_1$ and $\hat{\psi}_2$ respectively. If we increase $\omega_1$ and $\omega_2$, we observe higher $\hat{\psi}_1$ and $\hat{\psi}_2$. We also find that, Provider II exploits the market if it does not increase initial $\omega_2$ and Provider I increases initial $\omega_1$ beyond the point where $\hat{\psi}_1 = \hat{\psi}_2$. If Provider II decides to freeride on Provider I’s network, we show, how further the value of $\omega_1$ can go in Fig. 5.4. When initial $\omega_2 = 0$, we find that $\omega_1 = \hat{\omega}_2$ at initial $\omega_1 = 0.44$. Provider I can ensure it’s customer gets better service than Provider II’s customer by following initial $\omega_1 < 0.44$ when Provider II does not serve I’s customer. In this way, Provider I can make the decision on serving Provider II’s customer based on the value of $\omega_2$.

5.3.4 Comparison of non-SBSS and SBSS Markets

The successful deployment of a minimum fee regulated SBSS market depends on higher revenue earnings by all participating providers. In Fig. 5.5, we analyze a provider’s government regulated minimum fee by making comparisons with the charging fee in SBSS market and the fair market fee of non-SBSS market. We can see for all cases, the ratios of regulated minimum fee, (5.4), to charging fee, Algorithm 1, are lower than the ratios of minimum fee to fair market fee for Provider II. Also, an interesting outcome we get from both ratios, none of the values cross 1 which indicates
Provider II tries to capitalize its chances of freeriding, however, too much lowering of its fees is not a beneficial strategy. Because if it lowers fees to freeride, Provider I adjusts its strategy by applying the procedure of Algorithm 1. If Provider II charges according to the regulated minimum fees, it can still earn significantly higher than the revenue of no sharing. This occurs because of subsidy as well as earnings from switching customers of Provider I. By comparing the ratios of both fees, we find that Provider II is either interested to charge equal to minimum fees or higher than that.
When Provider I opts for higher sharing, Provider II finds the fees between the fair market and the minimum fees.

Even though the government imposes a fee regulation, it can still offer all providers the ability to charge any fee above the regulated fee, so that, no provider can freeride on another’s network. As long as all providers follow this regulation, an SBSS market maintains high wireless experience for users and high revenue earnings for providers. If they do not follow the minimum fee regulation, they are no longer able to participate and take benefits of the SBSS market. In Fig. 5.5b, we show a competitive market in which Provider I is offering three different initial $\omega_1$. The resulting fees ratios of all conditions are closely following each other. A government does not need to introduce too much subsidy to motivate Provider I to increase sharing from a low sharing. A little increase of subsidy from 36% of $T_{mv}$ to 48% of $T_{mv}$ can ensure that Provider I will conduct maximum sharing, and Provider II will enjoy the open market rules of charging fees where the minimum fees go down to 0. However, a subsidy of 48% of $T_{mv}$ is too high for a government. If the government wants to provide a reasonable subsidy to Provider I, i.e., $\epsilon_1 = 4\%$ of $T_{mv}$, the minimum fee of Provider II roughly becomes 90% of the fair market fees for all values of $\omega_1$. If the government wants to impose fewer regulations on Provider II’s fees, it needs to provide more subsidy to Provider I. Consider the government introduces an SBSS market in a single provider dominant market where $X_1 = 90$ and $X_2 = 10$ from Fig. 5.5a. The government needs to allocate $\epsilon_1 = 38\%$ of $T_{mv}$ to allow Provider II to lower its fees to 50% of the fair market fees. If the dominance reduces, e.g., $X_1 = 55$ and $X_2 = 45$, a subsidy of 16% of $T_{mv}$ to Provider I can give Provider II the freedom of lowering fees around 50% of the fair market fees. Thus knowing the market dominance, a government can determine the amount of subsidy that should be introduced to limit a provider’s freedom of lowering fees. Fig. 5.5c and Fig. 5.5d also suggest that if Provider I increases its $\omega_1$ from 0% to 100%, Provider II still does not lower $f_2$ significantly, which encourages Provider I for higher sharing. Though based on different subsidies and market sizes the freedom of lowering
fees varies, the changes of willingness to share from minimum to higher requires a little increase of subsidy for all cases.

The freeriders in an SBSS market can adversely affect successful existence of the market. A government regulation on minimum fee can mitigate freeriders. Moreover, in the SBSS market, the customers enjoy a better wireless experience and get higher utility. Thus, by introducing fees regulation, a government can achieve all of these goals.

5.3.5 Optimality Gap from Observed Strategies

We looked for an SBSS market with providers strategy set on regulating freeriders to compare our results obtained from Algorithm 1 to an optimal result, and used the game-theoretic framework in [29] to calculate the optimum equilibria. In [29], the authors form a single stage non-cooperative game to suggest strategies to participating providers on sharing their spectrum resources while mitigating freeriding.

In our game-framework of Chapter 4, we considered asymmetric behavior of the market where only one provider shares the network and the other tries to maximize its revenue by freeriding. To compare the results obtained from Algorithm 1 to an optimal result, we update this game under a symmetric setting in which both providers have the freedom to choose fees and willingness to share.

Assume that the same set of providers, $J$, described in Section 3.2 are participating in this game, and optimize their fees and willingness to share using a best response strategy. We also assume all customers can have one subscription at a time. They can switch providers and none of them can go completely outside of the system. We use same parameter values of Table 5.1 and calculate each provider’s payoff using (3.4). We consider a set of willingness to share for a provider $j$ where the
Table 5.2: Game results

<table>
<thead>
<tr>
<th>Subsidy</th>
<th>Number of base stations</th>
<th>Pure Strategy Nash Equilibrium (PSNE)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\epsilon_1 = 0.1T_{mv}$, $\epsilon_2 = 0.05T_{mv}$</td>
<td>$X_1 = 55$, $X_2 = 45$</td>
<td>PSNE exists at ${(f_1, 1), (f_2, 1)}$</td>
</tr>
<tr>
<td></td>
<td>$X_1 = 70$, $X_2 = 30$</td>
<td>No PSNE</td>
</tr>
<tr>
<td></td>
<td>$X_1 = 90$, $X_2 = 10$</td>
<td>No PSNE</td>
</tr>
<tr>
<td>$\epsilon_1 = 0.1T_{mv}$, $\epsilon_2 = 0.05T_{mv}$</td>
<td>$X_1 = 100$, $X_2 = (1 - 100)%$ of $X_1$</td>
<td>PSNE exists at ${(f_1, 1), (f_2, 1)}$ for $X_2 = (52 - 100)%$ of $X_1$</td>
</tr>
<tr>
<td>$\epsilon_1 = 0.2T_{mv}$, $\epsilon_2 = 0.1T_{mv}$</td>
<td>$X_1 = 70$, $X_2 = 30$</td>
<td>PSNE exists at ${(f_1, 1), (f_2, 1)}$ for $X_2 = (28 - 100)%$ of $X_1$</td>
</tr>
<tr>
<td>$\epsilon_1 = 0.4T_{mv}$, $\epsilon_2 = 0.15T_{mv}$</td>
<td>$X_1 = 90$, $X_2 = 10$</td>
<td>PSNE exists at ${(f_1, 1), (f_2, 1)}$ for $X_2 = (14 - 100)%$ of $X_1$</td>
</tr>
</tbody>
</table>

range is $0 < \omega_j <= 1$ and fees range in $f_{j,\text{min}} \leq f_j < f_{j,\text{choke}}$. $f_{j,\text{min}}$ and $f_{j,\text{choke}}$ are the government regulated minimum fee and the choke-fee respectively. The choke-fee, $f_{j,\text{choke}}$, is a fee above which provider $j$’s service does not have any demand in the market. We adopt this choke-fee from [75] and calculate using

$$f_{j,\text{choke}} = A_{r,j}(1 + 1/(-\xi)).$$

(5.5)

where $A_{r,j}$ is provider $j$’s average revenue per customer and $\xi$ is the elasticity of demand. In our case, $A_{r,j} = f_j$. We accept $\xi = -1$ as per the study of [76]. Now the choke fee becomes: $f_{j,\text{choke}} = 2f_j$. We consider a fee $\hat{f}_j$ where $\hat{f}_j < f_{j,\text{choke}}$ and $\hat{f}_j \approx 2f_j$, for which our considered fees range becomes $f_{j,\text{min}} \leq f_j \leq \hat{f}_j$.

We use 100 different fees and 100 different willingness to share for each provider within the range described in previous paragraph. In this way, we get a total of $10^4$ different actions for each provider, if we consider an action consists of a fee and a willingness to share. We sort these actions in an increasing order to draw the strategic form of the game. As we are considering a two-provider case, we have a total of $10^8$ possible outcomes from the game. We list the pure strategy NE (PSNE) in Table 5.2. From the results, we find only one PSNE if Providers I and II choose
to play \( \{\hat{f}_1, 1\} \) and \( \{\hat{f}_2, 1\} \) respectively. We also observe, if the size difference between both providers isn’t significantly large, we always get a PSNE regardless of subsidy amount. However, if the difference increases, we find fewer PSNEs which indicates the game may end up with mixed strategy NEs. Due to the large search space, we do not compute mixed strategies as described in [29]. We get the only PSNE at maximum \textit{willingness to share} and fee. Hence, the components of the action sets in mixed strategies are lower than or equal to the components of PSNE action set. From our heuristic approach, we also find each provider’s \textit{willingness to share} is lower than 1 and the fee significantly lower than the amount given by game PSNE. If we consider the fees ratios of Fig. 5.5c, we find the observed fee of Provider II, \( f_2 = f^*_2 \), if \( X_1 = 55, X_2 = 45, \epsilon_1 = 0.1T_{mv}, \epsilon_2 = 0.05T_{mv}, \) initial \( \omega_1 = 0.5 \) and initial \( \omega_2 = 0.5 \). We also observe the same scenario in Fig. 5.1b, from where we get observed \( \omega_2 = 0.5 \). However, Provider II’s optimal strategies given in Table 5.2 for the same condition is \( \{\hat{f}_2, 1\} \). If we compare these strategies to our observed strategies, we can say the observed strategies are \textit{halfway} to the optimal strategies. Now, if we gradually increase the initial \( \omega_1 \), the observed \( f_2 \) and \( \omega_2 \) starts changing, where both forward towards optimal strategies. Thus, if we compare optimal strategies of all cases from Table 5.2 to our observed strategies, we can find the optimality gap between both providers strategies.

The game exhibits optimal result for the market in an ideal condition. However, in the real world, providers do not get ideal conditions most of the times and operate in a dynamic environment where market condition changes frequently. To adjust with the market trend, each provider lowers or increases its subscription fee according to the costs and revenues [75]. A provider advertises lower than optimal fee to give a significant customer surplus for making a good impression of its product in the market. When one provider lowers its fees, others are expected to follow similar steps which is a common trend of the market. Eventually, both providers will end-up charging fee near to fair market fees. If the maximum charging fee by a provider gets closer to the fair market fee, the PSNE resulted fee also gets closer to the fee given by our heuristic approach. The PSNE
gives willingness to share equal to 1 where our heuristic approach provides a fraction closer to 1. This fractional output gets justified when the size difference between two participating providers increases. For other cases, mixed strategy may exist which we do not test for this experiment.
CHAPTER 6: PROOF OF SHARING ARCHITECTURES

We assume a set of providers are participating in a SBSS market, where the government provides subsidy to the providers to share spectrum resources and penalizes based on PoS. To attain a verifiable PoS accounting system, we propose two different architectures. In the first model, the participating providers will provide the sharing information to a local designated module, called spectrum manager (SM), which will reside in an operational region and it can be a joint-venture or individual investment by the providers. In the case of individual investment, other participating providers will pay to obtain its service. The SMs from different regions will send the sharing information to a Central Spectrum Manager (CSM) which can be a trusted third party server or the joint venture of the providers or the investment from the government. Finally, the CSM reports the aggregate sharing information to the government to account PoS. In the second model, we get the verified sharing information from the cellular users where an application resides in each UE and the UE will communicate with a cloud-based module, which we call Cloud Spectrum Manager (Cloud-SM), to exchange spectrum usage information.

6.1 Central PoS Architecture

We envision a market with two providers $A$ and $B$ to demonstrate our centralized PoS architecture as shown in Fig. 6.1. Each provider participates in the market with the promise of sharing a portion of their licensed spectrum resources to serve the customers of other providers. The Spectrum Manager (SM) is a node (server) which monitors this promised spectrum resources for accounting.

Most of the content of this Chapter have appeared in the Proceedings of [30] and [31]
Figure 6.1: A central PoS architecture

purposes. Considering a large cellular market, there will be a distribution of SMs within different operational regions. Besides spectrum usage monitoring role, it helps both providers to reduce congestion. The SM records all spectrum sharing information locally from the base stations (eNodeBs) of the participating providers and makes these records transparent to all providers and shares the information with the Central Spectrum Manager (CSM) which aggregates sharing information from different operational regions and, finally, shares with the government periodically.

The spectrum sharing can take place in different ways [77, 78]. In Fig 6.2, we describe different scenarios on spectrum sharing and how the SM exchanges information. Let’s consider, $UE_A$ and $UE_B$ are two customers of providers $A$ and $B$, respectively. The coverage area of $A$ and $B$ are
considered as home network for $UE_A$ and $UE_B$, respectively. Outside of this home network, all coverages provided by the other provider is considered as foreign/visiting network. Let’s consider a case where $UE_B$ travels out of its home coverage and ends up in $A$’s coverage. As both providers are participating in the SBSS market, $A$ will attach this customer to its network as a foreign customer and notify the location information of $UE_B$ to SM and provider $B$. Now, if $UE_B$ wants to make a call, provider $A$ will have two different ways to serve $UE_B$:

**Case I: Foreign Infrastructure Foreign Spectrum.** The provider $A$ accepts the incoming call from $UE_B$ and establish the call using his promised spectrum resources and infrastructures. From the beginning of the call establishment to the end of the service, provider $A$ sends all sharing information to the SM, 6.2(I). The SM keeps track of such infrastructure and spectrum sharing by provider $A$ and sends detailed records to the government via CSM for assessing the validity of PoS.

**Case II: Foreign Infrastructure Home Spectrum.** This is the case when all spectrum resources of provider $A$ are busy to serve his own customers. If the $UE_B$ wants to make a call during that moment, provider $A$ can follow an approach where it shares it’s infrastructure and uses spectrum of provider $B$, Fig. 6.2(II). To make such this scheme successful, provider $A$ exchanges signal
messages with the SM to check the availability of provider $B$’s shared spectrum resources. As the SM has a role to monitor shared spectrum resource, it continuously keeps track of resource usage. When it receives a signal message from the provider $A$ to accommodate spectrum resource from provider $B$’s shared spectrum, if it is available the SM signals provider $A$ to use it and notifies the spectrum occupancy to provider $B$. Here, the SM plays a role of coordinator between providers. Thus provider $A$ can serve $UE_B$’s call using provider $B$’s shared spectrum. The SM keeps track such mode of sharing to help the accounting needed for proof-of-sharing.

There may arise a different case when provider $A$ will need to use the spectrum resources of provider $B$ to serve its own customer $UE_A$. Before using $B$’s resource, $A$ always communicates with the SM for signaling purpose.

**Case III: Home Infrastructure Foreign Spectrum.** This case happens when all spectrum resources of provider $A$ are busy with high loads for serving either its own customers or provider $B$’s customers. Now, if a customer $UE_A$ wants to make a call, the provider $A$ makes a query to the SM to check the availability of $B$’s shared spectrum resource. If available, $A$ requests to use that spectrum. The SM grants the use and informs $B$ not to use that spectrum. In this case, the SM records the spectrum sharing to $B$’s favor and reports to the CSM for further processing. Fig. 6.2(III) describes this scenario where $UE_A$ gets service through $A$’s infrastructure and $B$’s spectrum.

Now, if a customer of $A$ ends up in provider $B$’s coverage area then $B$ will act in the same way as $A$ does. In short, the role of the SM is to monitor shared spectrum resources, communicate with different providers for the availability of shared resources, record the types of services, account the rejected calls of visiting customers, and finally, send reports to the government through CSM with detailed verified information of sharing, PoS, to apply penalty on given subsidy as per policy on spectrum sharing.
6.2 Cloud-based PoS Architecture

We present our cloud-based architecture while assuming the similar set of spectrum sharing cases and system model as considered for our aforementioned architecture with SM. We consider an open spectrum market, where providers can announce their potentially available spectrum at a time epoch to let UEs select or negotiate and select the best available spectrum during the epoch (refer to Fig. 6.3). In this architecture, we propose each UE to be aided with a system level application that monitors spectrum sharing information. Contrary to the previous centralized architecture, where most of the decisions were made at the SM, which regulates and accounts the sharing, we consider an open market where multiple providers compete to share more and UEs dynamically evaluate the options and negotiate with possible providers before deciding which infrastructure and spectrum resources to use.
Whenever $UE_A$ moves to any location with a low signal or RSSI from the primary provider’s eNodeB, the spectrum handover process starts for using any available spectrum by other providers at that particular location. Here, it is worth mentioning that available spectrum will be able to improve the UE’s experience of service as well. Based on such criteria, once the spectrum from a foreign provider (for example, provider $B$) is selected, a system level application at $UE_A$ takes a note of following information:

- **Location**: It records the location where $UE_A$ uses a foreign spectrum band.

- **SignalStrength**: It records the signal strength when $UE_A$ uses a foreign spectrum band.

- **Timeepoch**: This is the record of the time epoch that $UE_A$ uses a foreign spectrum band. It consists of the start time and duration. In case of multiple foreign spectrum, the $UE_A$ keeps a record in the local memory.

- **ProviderID**: This field is used to store the information about the foreign provider(s), of which resources are being utilized.

- **SpectrumID**: Here, we let $UE_A$ to store the value of spectrum band that is being used. It helps in distinguishing multiple providers and also after few processing steps at cloud, it can categorically guide the government to calculate the level of sharing for providers.

- **ServiceID**: This field stores and provides the information regarding the services being offered or used during the connection with foreign provider by $UE_A$. For instance, $UE_A$ can use spectrum for services such as an audio call, SMS/MMS, LTE data, and so on.

- **TotalUsage**: Here, we sum up all the usage information including total number of timeepochs that gives us the total duration of foreign spectrum being used. This will help the Base station in 5G cellular network is known as eNodeB
government, other decision makers, and stakeholders to analyze various statistics; and also
decide whether to provide incentives or penalize any provider for sharing or not providing
available spectrum.

When $UE_A$ meets an unlicensed band, for instance WiFi, the system level app on $UE_A$ uploads
all the information in the form of a usage report, tentatively named as “Shared Spectrum Report
(SSR)” to the secure Cloud-SM server. The SSR will contain all five attributes above. However,
the access control strategies to the cloud will be determined between participating providers and
the government. For simplicity, we assume that only the government can fetch the information
from the Cloud-SM as it is the party to invest in the form of incentives for providers with maxi-
mum spectrum sharing records. Moving further, when we qualitatively study the cloud-based PoS
architecture for the three cases in Section 6.1, we find that the proposed architecture can minimize
multiple operations involved in a centralized architecture. For example, the cloud-based PoS ar-
chitecture does not require eNodeBs to keep track of shared spectrum or provide suggestions to
the UE(s). Moreover, it also brings simplicity to the system as every info is in the cloud which
is being used as a verification tool by the government. It is hard to say who will be owning the
Cloud-SM in the cloud-based PoS architecture, and it can be an private or semi-private entity that
can establish enough trust among participating providers.

6.3 Qualitative Comparison of Centralized & Cloud-Based PoS

We make a qualitative comparison of the Centralized and Cloud-based PoS architectures and dis-
cuss the advantages and disadvantages of both. Table 6.1 shows a high level comparison in terms
of metrics such as market size, decision makers, signaling overhead and reliability.

With regards to functions placement, Centralized PoS puts more of the burden on SMs located
at each tower or edge point while Cloud-based PoS relies more on the UEs to keep a record of
sharing. In Centralized PoS, SMs, while recording PoS, can regulate the sharing taking place at the edge and, hence, make more efficient decisions in utilizing the spectrum at a crowded edge. But, a key challenge will be scaling the SMs and CSMs in this architecture since they will have to exchange messages with every UEs within the coverage of the tower or edge point. On the other hand, in Cloud-based PoS, the UEs will have to bare the complexity of negotiating for available network and spectrum resources. Although this will incur signaling complexity among UEs and provider eNodeBs, the market at the edge will be open and self-regulating which is attractive for the healthiness of the spectrum sharing market. Further the Cloud-SM server, where UEs will be sending their reports, will likely be easy to scale due to abundance of compute and memory at the cloud.

In terms of handling mobility, both approaches have challenges. Centralized PoS will require CSMs to actively participate in hand-offs, while Cloud-based PoS will require UE-eNodeB negotiations every time a hand-off is taking place. The former is likely to be more scalable as existing hand-off technologies in MSC can be integrated with CSMs. While the latter one will face challenges as hands-offs often bring delays and may trigger interruption if there is an ongoing service at the UE side. Another challenge with Cloud-based PoS is that the entire system is depending on the UE’s feedback (i.e. SSR) to be uploaded using unlicensed band. Here one key issue is that what if the UE gets crash or after using a lot of spectrum from the other foreign provider, if UE fails to upload the SSR, it will be difficult for the Government to get verified data. Having said that, in this chapter, we describe the important concept of Proof of Sharing (PoS) and our proposed architectures are providing preliminary qualitative evaluations in case of pervasive spectrum sharing and PoS concepts.
Table 6.1: Comparison of two PoS architectures: Centralized vs. Cloud-based

<table>
<thead>
<tr>
<th>Attributes</th>
<th>Centralized PoS</th>
<th>Cloud-based PoS</th>
</tr>
</thead>
<tbody>
<tr>
<td>Network Edge</td>
<td>eNodeB</td>
<td>UE</td>
</tr>
<tr>
<td>Data Flow</td>
<td>eNodeB to SM</td>
<td>UE to Cloud-SM</td>
</tr>
<tr>
<td>Decision of Spectrum Sharing</td>
<td>Decisions made at eNodeB</td>
<td>UE chooses from available signal</td>
</tr>
<tr>
<td>Investment</td>
<td>Requires investments to establish SMs at each tower or edge</td>
<td>Requires a Cloud-SM server and integration of a system level app to UEs</td>
</tr>
<tr>
<td>Reliability Issue</td>
<td>eNodeB may deceive the SM on the availability of spectrum</td>
<td>Sharing information can be lost due to UE crash down</td>
</tr>
<tr>
<td>Signaling Overhead</td>
<td>Message exchange is limited between eNodeB and SM</td>
<td>Requires more signal exchanges between UE and eNodeB for negotiations</td>
</tr>
<tr>
<td>Data Loss</td>
<td>High loss due to SM failure</td>
<td>Relatively low loss due to UE failure</td>
</tr>
<tr>
<td>Market Granularity</td>
<td>Each tower or edge represents the smallest unit of the spectrum market</td>
<td>Each UE acts as the smallest unit of the spectrum market.</td>
</tr>
<tr>
<td>Freedom of Provider Selection</td>
<td>Limited to eNodeB’s decision</td>
<td>UE can choose best provider</td>
</tr>
<tr>
<td>Customer Satisfaction</td>
<td>eNodeB’s decision is responsible</td>
<td>UE is responsible</td>
</tr>
</tbody>
</table>

6.4 PoS Report with UE Movement

We have seen the necessity of a PoS module in a government subsidy-based spectrum sharing market [30]. However, an effective integration of this module in the cellular network is required to deliver successful operations and serve the purpose of a PoS module.

In an incentive-based spectrum sharing market, customers are expected to move frequently among eNodeBs of different providers and each such movement triggers the handover procedure [32]. Recent trend of using small cells instead of macro cells has added more handover procedures during a session, e.g., a call or a data service [79]. A PoS node needs to update this event to
keep track of which provider is going to serve after the handover takes place. No prior works of PoS have considered costs of UE movement on a cellular network while integrating a PoS module [30]. An effective integration of PoS report initiator (a node which sends sharing information to a PoS module) can reduce the number of update messages sent to the PoS module. We propose three different architectures of PoS module considering the placement of the report initiator in a cellular system. The PoS report initiator node can be an MME, an eNodeB or a UE. An MME or an eNodeB generated PoS reporting approach works with the CSM-based architecture and a UE generated PoS report works with Cloud-SM-based architecture. We also consider the shared-MME concept [80] to design these architectures.
6.4.1 An eNodeB-generated PoS Information (EPoS)

An eNodeB of a provider can be the PoS report initiator node. The eNodeB can record details of serving a foreign UE and report to a CSM module when the UE leaves. This model of PoS architecture is shown in Fig. 6.4 where a UE of provider 2 roams between different providers and gets seamless service from different eNodeBs. According to this model, all eNodeBs are responsible to upload an provider’s spectrum sharing information to the CSM module. In this architecture, an MME can belong to an individual provider or a shared-MME of different providers. Inclusion of shared MME in the cellular system can reduce MME to MME handover messages [33]. However, it will not help to reduce PoS update messages to a CSM. Because, each time a UE leaves an eNodeB, the eNodeB sends a PoS update message irrespective of the upper layer configuration in the core of a LTE network. Among all PoS architectures, eNodeB generates maximum number of update messages towards a CSM. In urban regions, small cells are being deployed instead of traditional macro cells. As a result, UE movement among eNodeBs will be increased. Thus, the number of updates will be higher in a small cell network compared to a macro cell network.

6.4.2 An MME-generated PoS Information (MPoS)

An MME can initiate PoS reporting to a CSM module as shown in Fig. 6.5. We get two types of MME in a cellular system. Hence, PoS updates from an MME can be two types also. Each time a UE moves between eNodeBs, an MME gets handover message from the eNodeBs. The MME keeps track of the usage information of the UE in each eNodeB. If it is a shared MME, it can keep different logs for different providers, otherwise it maintains a single log for a UE’s single session (a continuous call or a data service). When the session is over, the MME reports to a CSM module. An MME handles multiple eNodeBs. Thus, the number of PoS update messages generated by the MME is fewer than the eNodeB generated messages.
This reporting model works with Cloud-SM architecture. A UE records service information from different providers and saves it locally. If it gets service from different foreign providers for a single session, it keeps different logs for each foreign provider. When the UE enters in the home network or an unlicensed network service, it sends PoS report to the Cloud-SM node as shown in Fig. 6.6. If a UE does not change its position during a single session then the number of update messages generated by a UE can be equal to a eNodeB-generated messages. However, it is expected for a UE to move between eNodeBs. Thus, the message generated by a UE is actually fewer than an eNodeB-generated messages. Unless a UE travels a long distance, it remains under a single MME.
Figure 6.6: A UE reports PoS information in a LTE network

most of the time. Hence, PoS reports generated by a UE is higher than an MME-generated PoS reports. In short, we can say the number of PoS update messages sent from a UE to the Cloud-SM lies between messages sent by an MME and an eNodeB.

6.4.4 Comparison of EPOs, MPoS and UPOs architectures

We make a qualitative comparison between EPOs, MPoS and UPOs with the focus of PoS messaging overhead, report initiator, types of basic PoS architecture, effects of small cell deployment, risk of data loss as shown in Table 8.1. EPOs and MPoS work with a CSM module and UPOs works with a Cloud-SM module. Due to the nature of distributed data storing, the risk of data loss in case
Table 6.2: Comparison of EPoS, MPoS & UPoS

<table>
<thead>
<tr>
<th>Attributes</th>
<th>EPoS architecture</th>
<th>MPoS architecture</th>
<th>UPoS Architecture</th>
</tr>
</thead>
<tbody>
<tr>
<td>Basic PoS module</td>
<td>A CSM</td>
<td>A CSM</td>
<td>A Cloud-SM</td>
</tr>
<tr>
<td>PoS report initiator</td>
<td>An eNodeB</td>
<td>An MME</td>
<td>A UE</td>
</tr>
<tr>
<td>Number of PoS messages</td>
<td>Highest among all architectures</td>
<td>Minimum among all architectures</td>
<td>Lies between the other two architectures</td>
</tr>
<tr>
<td>Advantage of a shared-MME</td>
<td>No change in the amount of PoS messages</td>
<td>Reduction of PoS messages</td>
<td>No change in the amount of PoS messages</td>
</tr>
<tr>
<td>Small cell deployment</td>
<td>PoS messages increase compared to a macro cell deployment</td>
<td>PoS messages increase compared to a macro cell deployment</td>
<td>No change in the amount of PoS messages</td>
</tr>
<tr>
<td>Effect of infrastructure (eNodeB) sharing</td>
<td>Reduction of PoS messages</td>
<td>Reduction of PoS messages</td>
<td>Reduction of PoS messages</td>
</tr>
<tr>
<td>Risk of data loss</td>
<td>Lies between the other two architectures</td>
<td>Maximum loss in case of a failure</td>
<td>Minimum loss in case of a failure</td>
</tr>
<tr>
<td>UE movement among eNodeBs</td>
<td>PoS messages increase</td>
<td>Amount of PoS messages depends on types of MME</td>
<td>No change in PoS messages</td>
</tr>
</tbody>
</table>

of failure is minimum in UPoS among all architectures. An MPoS posses maximum risk of data loss. The risk of data loss in EPoS lies between MPoS and UPoS.

We know in a cellular system, the number of UEs is higher than the number of eNodeBs and MMEs; and the number of MMEs is lowest among all three of them. As a result, the amount of PoS message generation in case of UPoS is higher than all other PoS architectures and MPoS initiates minimum amount of message.

Along with spectrum sharing, if all providers share their infrastructure, e.g., eNodeB, the amount of messaging overheard reduces compared to a non-infrastructure shared environment. In case
of infrastructure sharing, the possibility of finding the home network is high. Until a UE uses a foreign network, no PoS message gets generated.

The amount of messaging overhead also depends on types of cell deployment and the UE movement among the cells. In case of a small cell deployment, the amount of PoS messaging in MPoS and EPoS increases compared to a macro cell deployment. If a UE moves between different eNodeBs for a single session, it will produce higher number of messages in MPoS and EPoS architectures. However, the cell types and UE movement have no effect on the UPoS architecture. Irrespective of provider network use, a UE reports at most only once for a session. If it uses different networks, it keeps different logs, each for a provider.
CHAPTER 7: CELL TOWER LOCATION PREDICTION FROM POS-LIKE CROWDSOURCED DATA

Prompt response during a disaster is very crucial. People are trying and will try to make emergency services and respond more efficiently and instantaneously. It is always troublesome to respond to all the victims rapidly. One of the greatest ways to minimize the loss of the victims is to keep communication among the victims and the first responders. However, it is obvious that the cellular infrastructure, i.e., cell towers and antennas, can be destroyed during a disaster. So, an alternative way of communication, that can be promising, is to continue communication among the victims and the first responders. In particular, device-to-device (D2D) communication, which is capable of maintaining communication without cellular infrastructure, can be a good option for such emergency and disaster communications.

D2D communication, however, involves several challenges. It is very difficult to coordinate all the devices in the D2D communication if we initialize communication among all the devices in an area. Besides, prioritizing a victim could also be very important during a disaster-affected scenario because there might be many requests from victims at a single time. Therefore, it will take time to decide to prioritize. It would be very efficient if we can initiate the D2D communication in a small scale in case of an emergency. Prediction of cell tower locations can be one way to predict the areas where D2D communication is needed and to help manage the overall communication in a disaster-affected scenario. Further, identification of vulnerable cell tower locations can give guidance in terms of the number of D2D hops needed to reach the closest active tower in the case of a disaster. By identifying the tower locations which can be damaged during a disaster, we can trigger and enhance the D2D communication that can save many invaluable lives.
7.1 Crowdsourced Data to Predict Cell Towers

User responses via PoS can contribute to generating actual perceived coverage map by predicting truthful cell towers and antenna locations. It will also help to differentiate the edges of different providers. Thus, we will get an overlapped coverage map along with the individual coverage area of each provider. The providers are reluctant to provide actual coverage maps to the government which obstructs some good intentions of the government [81]. The government in the US is highly interested to expand high-speed connectivity in rural America and wants to subsidize providers to establish network infrastructure in underprivileged areas [82]. With lack of providers’ intention to supply a truthful coverage map and other sources of coverage, it is becoming a necessity to get an alternate solution of collecting data and generating coverage maps. The government in the US is also interested to collect more data for generating such maps and identifying those areas most in need of high-speed connectivity [83]. PoS can be a good crowdsourced data for generating truthful maps as the data are coming directly from the users’ perceived wireless experience. Also, in the subsidized/reward-based spectrum shared markets, users’ will be motivated to share their experience via PoS as they will not require to pay charges beyond the subscription fees to receive roaming like services.

In the Cloud-based PoS model, a user-reported PoS will contain the user’s location, cell id, etc. We focus on utilizing the attributes from crowdsourced data to predict cell tower locations and making a comparison with available sources of cell tower locations. We find that OpenCellId [5], a crowdsourced database contains some necessary attributes similar to our PoS data. As the PoS is still in the architectural design phase and OpenCellId provides some similar essential attributes, we consider OpenCellId data to predict cell tower locations. A truthful prediction has many-folded benefits for the users apart from generating truthful coverage maps.
7.2 Data Collection and Tower Prediction Methodology

Several Internet sites including FCC [84] show the locations and number of cellular towers all over the world. FCC only contains registered tower locations those are at least 200 feet height which include already dismantled towers information. As a result, the number of cell towers provided by FCC may be different from the number of cell towers exist within an area. There are no such references that provide accurate locations of all antennas including towers, and the cellular providers do not share information about the location of towers. There are only few countries where the correct locations of towers are known [85]. The sites may provide the information based on war-driving data or from crowdsourced data. So, there is no entirely valid source of information to know and validate the exact locations of cell towers, which makes it even more important to design a system for predicting them given publicly available data.

To optimize the time and cost of finding the location of cell towers, crowdsourcing can be one of the most effective ways. We have collected the crowdsourced data from OpenCelliD database and processed the data for using in prediction. We have used a weighted $k$-means clustering algorithm [86] to predict the locations of cell towers from processed OpenCelliD data. We have also collected tower locations data which we call physical towers from AntennaSearch.com [87] and FCC [84] to compare our predicted locations of cell towers. For the comparison, we have developed a mapping algorithm to show the difference of distances among the physical towers and predicted towers. We have also analyzed the cumulative distributive function (CDF) for the results found from the comparison. We have performed the clustering analysis, mapping and CDF analysis for an urban (Orange) and two rural counties (Union and Calhoun) of Florida.

OpenCelliD data set has different fields that include information regarding a cell [85]. The data are given under different fields such as radio, mcc, net, range, and area. The data fields and respective description of the data fields are given in Table 7.1. We have only use the information of
Table 7.1: Description of data fields of OpenCelliD database [5]

<table>
<thead>
<tr>
<th>Data Field</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>radio</td>
<td>Network type. Either GSM, UMTS, LTE or CDMA.</td>
</tr>
<tr>
<td>mcc</td>
<td>Mobile Country Code.</td>
</tr>
<tr>
<td>net</td>
<td>Mobile Network Code (MNC) for GSM, UMTS and LTE. System Identification number (SID) for CDMA.</td>
</tr>
<tr>
<td>area</td>
<td>Location Area Code (LAC) for GSM and UMTS. Tracking Area Code (TAC) for LTE. Network Identification number (NID) for CDMA.</td>
</tr>
<tr>
<td>unit</td>
<td>Primary Scrambling Code (PSC) for UMTS. Physical Cell ID (PCI) for LTE. Empty for GSM and CDMA.</td>
</tr>
<tr>
<td>lon</td>
<td>Longitude in degrees between -180.0 and 180.0.</td>
</tr>
<tr>
<td>lat</td>
<td>Latitude in degrees between -90.0 and 90.0.</td>
</tr>
<tr>
<td>range</td>
<td>Estimated cell range, in meters.</td>
</tr>
<tr>
<td>samples</td>
<td>Total number of the cell’s measurements.</td>
</tr>
<tr>
<td>changeable</td>
<td>If 1: The lon,lat values have been calculated from available measurements. If 0: The lon,lat values are correct - no measurements have been used to calculate it.</td>
</tr>
<tr>
<td>created</td>
<td>The first time the cell was seen and added to the database.</td>
</tr>
<tr>
<td>updated</td>
<td>The last time the cell was seen, and thus updated.</td>
</tr>
<tr>
<td>averageSignal</td>
<td>Average signal strength for all the cell’s measurements.</td>
</tr>
</tbody>
</table>

in the fields of ‘lon’, ‘lat’ and ‘samples’ which represent longitude, latitude and number of sample counts for a particular cell, respectively to predict tower locations. The data set use the longitude and latitude coordinates for a particular cell by measuring the mean of measurements of longitudes and latitudes done for that cell. Thus, the larger the ‘samples’ field, the more reliable the other data fields of that cell.

7.3 Clustering Algorithm to Predict Tower Locations

We use the locations (longitude and latitude) data reported in OpenCelliD which are found within a county boundary. We apply a weighted $k$-means clustering algorithm where the number of samples
is used as a weight to predict the location of the cell towers in that county. Here, $k$ is the number of predicted locations for a particular county. We use the number of active towers from the list of registered towers of a county given by FCC [84] as the values of $k$ for clustering by separating already dismantled or under construction towers. In the future, we plan to integrate the population effect to estimate the value of $k$. We aim to utilize machine learning techniques to improve numbers of towers prediction by using trustworthy tower/antenna location sources as training data sets that contain both the registered and unregistered towers information, e.g., Antennasearch.com [87].

7.3.1 Algorithm for Mapping Predicted Towers to Physical Towers

According to FCC [84], the number of active cell towers in Orange, Calhoun, and Union counties is 326, 21, and 13 respectively. For the same counties, Antennasearch.com reports 1605, 52, and 22 cell towers. The numbers of cell towers given in the FCC site and Antennasearch.com are different. And, we do not have any ground-truth information about the location of the cell towers. Yet, we would like to apply one-to-one mapping of cell towers based on the distance to find out how close our predicted towers are to the ones made available from Antennasearch.com. We also apply similar mapping to FCC reported tower locations to generate CDF for our predicted towers. The towers reported either in FCC site or Antennasearch.com, we call them “physical towers” or “physical locations”.

We find the nearest cell tower among the physical locations for a particular predicted location in the mapping. When designing the mapping algorithm, we faced two issues:

- Case I: A single physical tower can be the nearest one for multiple predicted towers.
- Case II: Two predicted towers can have equal distance for a physical tower.

We develop a one-to-one mapping algorithm Algo. 2 that considers these two issues while mapping two sets of locations with different number of locations in each.
Algorithm 2 Mapping between predicted and physical towers

Input: Longitude and latitude values of of data set $P$ with $M$ numbers of predicted towers and $W$ with $N$ numbers of physical towers

Output: One-to-one mapped locations of a predicted tower, $m$ and a physical tower, $n$ for all the data of $P$ and $W$

1: procedure MAPPING($P, M, W, N$) 2: for $i = 1$ to $M$ do 3: for $j = 1$ to $N$ do 4: Find Haversine distance from $i$-th element to $j$-th element, and update distance matrix, $D_{MN}$ 5: end for 6: end for 7: for $i = 1$ to $M$ do 8: Sort the values of $i$-th row of $D_{MN}$ in ascending order and update $D_{MN}^{(sorted)}$ 9: end for 10: for $i = 1$ to $M$ do 11: Find the indexes of the elements of $i$-th row in $D_{MN}^{(sorted)}$ from $D_{MN}$ and update $D_{MN}^{(index)}$ 12: end for 13: Create a binary matrix, $B$ of size $M$-by-$N$ with all values are ‘0’ 14: for $i = 1$ to $M$ do 15: Randomly select row $r$ from $D_{MN}^{(index)}$ and find $k = D_{MN}^{(index)}(r, 1)$ 16: Check the first column of every other rows if there are same index values, $k$ i.e., $D_{MN}^{(index)}(j, 1) == k$ where $j \neq r$ 17: if There are multiple rows in which first columns have same index value, $k$ then 18: Form a set, $P_k$ of data points in $P$ such that $D_{MN}^{(index)}(l, 1) == k$ where $l \in P$ and $l$ includes $r$ 19: Find out the data point $u \in P_k$ such that $D(u, k) == \min_d(d_{u,k})$ where $u \in P$. 20: if There are multiple $u$ then 21: Pick a $u \in P_k$ randomly 22: Map $k \in W$ to $u \in P$ for $u \in P_k$ by putting $B(u, k) = 1$ 23: else 24: Map $k \in W$ to $u \in P$ for $u \in P_k$ by putting $B(u, k) = 1$ 25: end if 26: Remove $u$-th row of $D_{MN}^{(index)}$ and $k$ from every other row of the index matrix, $D_{MN}^{(index)}$ 27: else 28: Map $k \in W$ to $r \in P$ by putting $B(r, k) = 1$ 29: end if 30: Remove $r$-th row of $D_{MN}^{(index)}$ and $k$ from every other row of the index matrix, $D_{MN}^{(index)}$ 31: end for 32: end procedure

Assume that there are two sets of data $P$ and $W$ of longitude and latitude pairs for predicted and physical locations, respectively. We also consider that there are $M$ and $N$ data points (each corresponding to a location) in $P$ and $W$, respectively:

\[
P = \begin{bmatrix} 1 \\ 2 \\ \vdots \\ M \end{bmatrix}, \quad W = \begin{bmatrix} 1 \\ 2 \\ \vdots \\ N \end{bmatrix}
\]
Now, we can get the distance for every data point of $P$ to the all points of $W$ which means every location in $P$ will have $N$ distance values according to line 4 of Algo. 2. We represent these distances as an $M$-by-$N$ matrix, $D_{MN}$ where $d_{mn}$, $m = 1..M$, $n = 1..N$ is the distance between $m$th point in $P$ and $n$th point in $W$:

$$D_{MN} = \begin{bmatrix} d_{1,1} & d_{1,2} & \cdots & d_{1,N} \\ d_{2,1} & d_{2,2} & \cdots & d_{2,N} \\ \vdots & \vdots & \ddots & \vdots \\ d_{M,1} & d_{M,2} & \cdots & d_{M,N} \end{bmatrix}$$

Our goal is to find out the minimum distance from $N$ distance values for every location of $P$. We sort the $N$ distance values in each row of $D_{MN}$ to get the minimum distance for all location points of $P$. In this way, we get another matrix $D_{MN(sorted)}$ according to line 8 of Algo. 2 where the distance values are sorted in each row. An example $D_{MN(sorted)}$ may appear as:

$$D_{MN(sorted)} = \begin{bmatrix} d_{1,7} & d_{1,N} & \cdots & d_{1,8} \\ d_{2,3} & d_{2,5} & \cdots & d_{2,10} \\ \vdots & \vdots & \ddots & \vdots \\ d_{M,N} & d_{M,8} & \cdots & d_{M,1} \end{bmatrix}$$

Then, we create another matrix $D_{MN(index)}$ called index matrix to show only the index for the sorted distance matrix where the row of the matrix stands for the locations of $P$ and the column stands for the locations of $W$. It is obvious that the 1st value before comma in the subscript of every element in $D_{MN(sorted)}$ matrix represents the row number while the 2nd value after the comma represent the index value for the $D_{MN(index)}$ matrix. However, the first column of every row of the matrix $D_{MN(index)}$ represents the closest tower location. For instance, $D_{MN(index)}$ for
the above $D_{MN(sorted)}$ will look like this:

$$D_{MN(index)} = \begin{bmatrix}
7 & N & 8 \\
3 & 5 & 10 \\
\vdots & \vdots & \vdots \\
N & 8 & 1
\end{bmatrix}$$

As the last step of the initialization of the algorithm, we create a binary matrix $B$ of same size as the distance matrix to keep track of the mapping values. We initialize $B$ to all zeros, i.e., $B(i,j)_{i=1..M,j=1..N} = 0$ at line 13 of Algo. 2.

Then, we iteratively map a data point in $P$ to $W$ one by one starting from line 14 of Algo. 2. We randomly pick a data point $r \in P$ and try to map the closest point in $W$ to it. This means we need to mark the corresponding element of $B$ with it. Let $k = D_{MN(index)}(r, 1)$ be the data point in $W$ that is closest to $r$. The operation we would like to do is $B(r, k) = 1$. However, it is possible that $k \in W$ is the closest data point to data points in $P$ other than $r$, i.e., $D_{MN(index)}(j, 1) == k$ where $j \in P$ and $j \neq r$. This is Case I of our earlier discussion on tentative issues during mapping. To resolve this case, for those data points in $P$ closest to $k$ in $W$, we compare their distances to $k$ and pick the one with the shortest distance to $k$. At this iteration of the algorithm, let $P_k$ be the set of all data points in $P$ such that $D_{MN(index)}(j, 1) == k$ where $j \in P$. We choose the data point $u \in P_k$ such that $D(u, k) == \min(d_{u,k})$ where $u \in P$. Then, map $k \in W$ to $u \in P$, i.e., $B(u, k) = 1$.

It is also possible that there are multiple $u$ satisfying $D(u, k) == \min(d_{u,k}), u \in P$. This is Case II and, it means that the minimum of the closest distances to $k \in W$ happens for multiple data points in $P$. To resolve this tie, we randomly pick a $u \in P_k$ such that $D(u, k) == \min(d_{u,k}), u \in P$. Then, we map $k \in W$ to $u \in P$, i.e., $B(u, k) = 1$. 

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At the end of the above steps, let \( r \in P \) be mapped to \( k \in W \). We remove \( k \)th row of \( D_{MN(index)} \) and \( k \) from every other row of the index matrix \( D_{MN(index)} \) so that it does not get mapped to another data point in \( P \) in the subsequent iterations. This operation decreases the size of \( D_{MN(index)} \) by 1 in both dimensions.

The steps above complete the mapping of one data point in \( P \) to another one in \( W \). We continue to these mappings iteratively based on the updated \( D_{MN(index)} \) and \( B \). At the end, \( B \) holds the resulting one-to-one mapping of all data point in \( P \) to \( W \), i.e., \( \sum_{n=1..N} B(m, n) = 1, \forall m \in P \) and \( \sum_{m=1..M} B(m, n) \leq 1, \forall n \in W \). Note that the algorithm assumes \( M \leq N \), which requires that the data set with smaller size be given as \( P \) to the algorithm. This design of the algorithm is a minimalist approach as it may not necessarily inspect all possibilities and it just attempts to make a mapping to every data point in the smaller input set. We consider this strategy because of the number of active towers in FCC record [84] is lower than the total reported tower locations. It is also much lower compared to the number of towers reported in Antennasearch.com.

### 7.3.2 Example

Consider two data sets \( P \) and \( W \) with Cartesian coordinates as below.

\[
P = \begin{bmatrix}
    (0, 0) \\
    (1, 0) \\
    (2, 0)
\end{bmatrix} \quad W = \begin{bmatrix}
    (0, 1) \\
    (0, 2) \\
    (1, 1) \\
    (1, 2)
\end{bmatrix}
\]

Here, \( M = 3 \) and \( N = 4 \) are the number of coordinates in the data sets of \( P \) and \( W \), respectively.
We then initialize the distance matrix $D_{MN}$, a $3 \times 4$ matrix, as below:

$$D_{MN} = \begin{bmatrix} d_{1,1} & d_{1,2} & d_{1,3} & d_{1,4} \\ d_{2,1} & d_{2,2} & d_{2,3} & d_{2,4} \\ d_{3,1} & d_{3,2} & d_{3,3} & d_{3,4} \end{bmatrix} = \begin{bmatrix} 1 & 2 & \sqrt{2} & \sqrt{5} \\ \sqrt{2} & \sqrt{5} & 1 & 2 \\ \sqrt{5} & \sqrt{8} & \sqrt{2} & \sqrt{5} \end{bmatrix}$$

So, the $D_{MN(sort)}$ and $D_{MN(index)}$ matrices will be:

$$D_{MN(sort)} = \begin{bmatrix} 1 & \sqrt{2} & 2 & \sqrt{5} \\ 1 & \sqrt{2} & 2 & \sqrt{5} \\ \sqrt{2} & \sqrt{5} & \sqrt{5} & \sqrt{8} \end{bmatrix}$$

$$D_{MN(index)} = \begin{bmatrix} 1 & 3 & 2 & 4 \\ 3 & 1 & 4 & 2 \\ 3 & 1 & 4 & 2 \end{bmatrix}$$

We also initialize $B$ to all zeros.

**First Iteration:** We see that the first elements of both rows 2 and 3 of $D_{MN(index)}$ are the same and equal to 3. So, this is a Case I and we choose the minimum of $d_{2,3}$ and $d_{3,3}$ in the $D_{MN}$ matrix. We find that $d_{2,3} = 1$ and $d_{3,3} = \sqrt{2}$. So, $d_{2,3}$ is the one with minimum value. So, we mark 1 in the 3rd column of 2nd row in the binary matrix $B$ and remove the row 2 and all the elements of $D_{MN(index)}$ which are 3 from other rows. So, the updated $D_{MN(sort)}$ and $B$ will be as below:

$$D_{MN(sort)} = \begin{bmatrix} 1 & 2 & 4 \\ 1 & 4 & 2 \end{bmatrix}$$

$$B = \begin{bmatrix} 0 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 \end{bmatrix}$$
Second Iteration: Now, we see that the first elements of the row 1 and row 3 in $D_{MN}(sorted)$ are same and equal to 1. So, this is another Case I. We compare the distances $d_{1,1} = 1$ and $d_{3,1} = \sqrt{5}$. Here, $d_{1,1}$ is minimum and we remove row 1. We also remove ‘1’ from the remaining row. Hence, the updated $D_{MN}(sorted)$ and $B$ will be:

$$D_{MN}(sorted) = \begin{bmatrix} 4 & 2 \end{bmatrix} B = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 \end{bmatrix}$$

Third Iteration: There is only one row remaining in $D_{MN}(sorted)$ which also means there is only one data point in $P$ left to be mapped. We find that row 3 has 4 in the 1st column. So, we map the 3rd predicted location to the 4th web location. And, the final binary matrix is:

$$B = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

So, we can find the mapped towers and the respective distances from matrix, $D_{mapped}$.

$$D_{mapped} = \begin{bmatrix} d_{1,1} \\ d_{2,3} \\ d_{3,4} \end{bmatrix} = \begin{bmatrix} 1 \\ 1 \\ \sqrt{5} \end{bmatrix}$$

The matrix states that the 1st, 2nd, and 3rd locations (assume as predicted ones) are mapped the 1st, 3rd and 4th locations (physical towers).
7.3.3 Complexity of the Mapping Algorithm

If there is a huge amount of data points within a certain boundary, then the algorithm will take significant time to accomplish. The computational complexity of the algorithm involves the following three major steps:

- Computation of the distance matrix, i.e., $O(MN)$.
- Computation of the sorted and index matrices, i.e., $O(MN\log N + MN)$.
- Computation of the final binary matrix after completing $M$ iterations, i.e., $O(M^2N)$.

Thus, the total computational complexity is $O(MN + MN\log N + MN + M^2N)$ which can be simplified to $O(M^2N)$.

7.4 Results

We apply weighted $k$-means algorithm on OpenCelliD data for predicting tower locations in Orange, Calhoun, and Union counties of Florida. The maps of the predicted towers for the Orange, Calhoun, and Union counties are shown in Fig. 7.1a, 7.2a, and 7.2b, respectively. Additionally predicted towers for Orange county on Google Maps is shown as red dots in Fig. 7.1b. We choose predicted towers of Orange county to display on Google Maps because of the high number of cell towers within the county boundary. We can see from the map that predicted towers are mostly near the lines of the roads or the densely populated areas. We can also see that none of the predicted towers are in the deep forest or within the water body, seen in green and blue colors of the maps, respectively. The insights from the maps indicate the feasibility of our cell tower localization scheme and demonstrate a sign of predicting towers accurately.
Figure 7.1: Predicted towers for Orange County

Figure 7.2: Predicted towers for Calhoun and Union Counties
Once we have the predicted tower locations for the three counties, we run our mapping algorithm Algo. 2 to map the towers with the physical towers reported in AntennaSearch.com. The mapping of the towers for the Orange, Calhoun, and Union counties are shown in Fig. 7.3, 7.4a, and 7.4b, respectively. The more towers within a county boundary, the better prediction of location. A significant number of predicted towers in Orange county is located within close proximity of the physical towers. In Calhoun and Union counties, some of the predicted towers are close proximate of physical towers and some of them are far from the physical towers. It happens because of data collecting procedures associated with OpenCelliD. As OpenCellid gets these data from the users voluntarily, the users are not interested to send data very often as they don’t have any incentive for sharing their experience. In most cases, OpenCelliD contains a single-digit sample count which is
Figure 7.4: Mapping among predicted and physical towers for Calhoun and Union Counties

Figure 7.5: CDF comparison with Antennasearch.com reported towers
not sufficient to identify an access point/antenna location properly. Hence, the location reported in OpenCelliD can be already significant away from an antenna if very few samples are taken for that particular antenna/cell id. Here, our proposed PoS can contribute significantly to get enough data. In this model, users will be motivated to share their wireless experience to get better service without paying more. It will also provide actual perceived information of the network edges where inter-provider network switching usually happens.

![CDF Comparison](image)

**Figure 7.6**: CDF comparison with FCC reported towers

Cumulative distributive function (CDF) of the distances between our predicted tower locations and their mapped physical tower locations from Antennasearch.com shows a better representation of the mapping. The CDF comparison for the three counties is shown in Fig. 7.5. Our approach attained notably better performance in predicting the tower locations for the average case in the urban county of Orange. We can see, almost 98% of physical towers are within 2 miles of our predicted towers, and approximately 90% are within 0.6 miles. We also generate CDF for the mapping of predicted towers to the physical towers reported in the FCC site in Fig. 7.6. It shows
a similar trend of mapping in comparison to the CDF of Antennasearch.com towers. In Orange county, approximately 97% of predicted towers are within 2 miles, and 90% towers are within 0.6 miles of the physical towers. It interprets the accuracy of our prediction and mapping processes regardless of the sources of physical towers. With the increase of $k$ value in the weighted $k$-means, we can predict higher number of cell towers and expect better mapping.

A good prediction of a cell tower location can provide a good idea of surrounding cellular coverage. It can be helpful to deploy network nodes in case of tower failure during disaster situations. To obtain each cellular provider’s actual coverage map, crowdsourced data can be a truthful and alternative approach instead of provider reported coverage map which is mostly exaggerated. Crowdsourced database OpenCelliD contains a range value for each reported cell. Utilizing this range value with the predicted towers can give an excellent and reliable source of coverage map. It can also provide an overlapped coverage map if the providers share their spectrum resources under an SBSS or a reward-based spectrum-shared market. However, OpenCelliD data has some limitations, especially with the sample counts and its average perceived signal strength field contains ‘0’ for all entries. Thus PoS can be an appropriate source of crowdsourced data to generate a better-perceived coverage map.
A commercial provider always looks for maximum benefit to operate within an area. If it needs to share its spectrum resources without direct monetary transaction, it requires other means of compensation to overcome potential loss as well as generating new revenue opportunities. Here, we propose two different reward models for the providers to participate in pervasive co-primary inter-provider sharing. Both models need to be initiated by the government. In one approach, ‘Share for Spectrum’, a participating provider will serve other providers’ customers without any charge. By doing it, the provider will be eligible for using government/federal spectrum resources without any cost. On the other approach, ‘Share for Infrastructure’, the government will establish cellular eNodeB in the areas which are not commercially beneficial for a provider. However, a significant number of cellular customers may stay or travel within that area frequently. If a provider serves each others’ customer when needed, the provider will get access to these government eNodeBs to serve its own customers as a reward. Both reward models depend on the willingness-to-share of the providers. The government will allocate the reward based on “proof of sharing (PoS)” [30] where a PoS module keeps detailed sharing information.

8.1 Reward Models for Spectrum Sharing

Assume a set $\mathcal{J}$ of $J$ providers that are active in the cellular system. The customers subscribed to a provider are treated as home customers and all other customers will be considered as foreign customers. The calls (or use of the radio spectrum) by a customer are ‘home calls’ or ‘foreign calls’

Most of the content of this Chapter have appeared in the Proceedings of [88]

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if the customer is a home or foreign customer, respectively. Initially, each participating provider will provide its willingness-to-share which is the percentage of incoming foreign calls promised to be served by a provider. We denote this willingness-to-share for a provider $j$ as $\omega_j, j \in J$.

Consider a customer $i$ gets subscription from a provider $j$ with the fee $f_j$. provider $j$ has licensed bandwidth $b_j$, owns $X_j$ eNodeBs, invests $I_j$ to operate its cellular network, and earns $R_j = n_j f_j - I_j$ revenue from its $n_j$ subscribers. Customer $i$ makes $\alpha$, $\beta$ and $\lambda$ calls using his home, foreign and government eNodeBs respectively. Assuming that the marginal signal improvement of provider $j$ diminishes as $X_j$ and $b_j$ increase, we can express the utility of a customer making a call on this provider’s network as a concave function: $\log(X_j b_j)$. Then, the utility customer $i$ of provider $j$ would get from his home calls is

$$U(i,j) = \alpha \log(X_j b_j) - f_j. \quad (8.1)$$

### 8.1.1 Government Spectrum as Reward (GSR)

In this reward model, a provider gets a license to use a particular band for certain period of time and can obtain access to a government band as a reward for sharing its own spectrum resources (which also includes the infrastructure of that provider) to serve customers of other providers. Fig. 8.1 shows the structure of this model. In a real implementation of this model, the government would allocate bandwidth to all participating providers based on their market positions (e.g., number of customers, coverage area, and quality-of-service (QoS)) and the initial willingness-to-share. For simplicity, we only consider each provider’s willingness-to-share to allocate the reward bandwidth. The government has $R$ bandwidth to distribute among providers as reward. Initially, the provider $j$ will get reward bandwidth as:

$$\nabla_j = R \frac{\omega_j}{\sum_{i=1}^{J} \omega_i}. \quad (8.2)$$
Figure 8.1: A GSR market

If bandwidth $k$ is necessary to serve a customer, with the given reward bandwidth, provider $j$ will be able to serve $S_j = \frac{\nabla_j}{k}$ additional customers at an eNodeB. If the provider has $X_j$ eNodeBs, the total capacity improvement will be $X_jS_j$. After joining GSR market where $j$ gets reward bandwidth $\nabla_j$ for sharing resources with the customers of other providers’, customer $i$ of provider $j$ will get utility $\alpha \log(X_j(b_j + \nabla_j))$ from the signal intensity of $j$ for making home calls. This assumes that provider $j$’s signal quality to its own customers will not deteriorate because of sharing its resources with other providers’ customers. This is true as long as provider $j$ does not increase its willingness-to-share too much. But, if it allows too many of foreign customers to its network, it will start suffering from congestion and will not be able to offer signal quality as good as before. In a GSR market, customer $i$ will get service from other providers as well. If we consider
all $l \in J \setminus \{j\}$ foreign providers, the utility customer $i$ can have from foreign providers’ signal intensity during foreign call is $\sum_{l \in J \setminus \{j\}} \beta \log(\omega_l X_l (b_l + \nabla_l))$ where $\omega_l$ is the willingness-to-share of provider $l$. Now, the overall utility gain by the customer $i$ in a GSR market from the subscription to $j$ is

$$U_{gsr}(i, j) = \alpha \log(X_j (b_j + \nabla_j)) + \sum_{l \in J \setminus \{j\}} \beta \log(\omega_l X_l (b_l + \nabla_l)) - f_j. \quad (8.3)$$

If we consider all customers of $J$ providers, the utility maximization problem in GSR cellular system becomes:

$$\max_{\{b_j, f_j, X_j\}_{j=1}^J} \sum_{j=1}^J \sum_{i=1}^{n_j} U_{gsr}(i, j) \quad (8.4)$$

such that

$$\sum_{j=1}^J b_j \leq B, \quad (8.5)$$

$$\sum_{j=1}^J \nabla_j \leq R, \quad (8.6)$$

$$f_j, b_j, X_j, \omega_j > 0, \forall j. \quad (8.7)$$

### 8.1.2 Government Cell as Reward (GCR)

Assume the government establishes eNodeB in a region where no commercial eNodeB is available. In this case, if the customer arrival rate within the government eNodeB’s range is $\nu$ and the average time a customer spends in that region is $\zeta$, from the Little’s law, the average number of customers under the eNodeB at any time is $\mathcal{C} = \nu \zeta$. These customers are composed of active and inactive customers. Consider the number of inactive customers within the region is $\mathcal{C}_i$. Now, the number of active customers, $\mathcal{C}_a$ within the region becomes $\mathcal{C}_a = \mathcal{C} - \mathcal{C}_i$. If the government establishes $X_g$ eNodeBs within such regions and each eNodeB can serve $\Omega$ customers simultaneously, the shared
If we consider $X_g$ eNodeBs, provider $j$ will be awarded $X_g \Omega_j$ capacity. These many customers of provider $j$ can enjoy services from the government eNodeBs where $j$ has no coverage.

In a conventional non-shared market, a customer $i$ gets the utility of (8.1) by subscribing to provider $j$. There will be additional utility if the provider $j$ participates in the GCR spectrum sharing market where $i$ gets service from the government eNodeBs in regions which are not financially viable for provider $j$ to establish eNodeB. In the GCR market, customer $i$ also gets service through all
foreign providers. Thus, customer \(i\) obtains \\
\[
\sum_{l \in \mathcal{J} \setminus \{j\}} \beta \log(\omega_l X_l b_l) + \lambda \log(\Omega_j X_g b_g)
\]
utilities from foreign providers and government, respectively, where \(b_g\) is the allocated bandwidth to government eNodeBs. It can come from the participating providers’ bandwidth or the government can use a federal bandwidth. Finally, customer \(i\) obtains overall utility from a GCR market as:

\[
U_{\text{gcr}}(i, j) = \alpha \log(X_j b_j) + \sum_{l \in \mathcal{J} \setminus \{j\}} \beta \log(\omega_l X_l b_l) + \lambda \log(\Omega_j X_g b_g) - f_j.
\] (8.9)

If we consider all customers in the GCR market, the overall utility maximization problem will become:

\[
\max_{b_g, X_g, \{b_j, f_j, X_j\}_{j=1}^J} \sum_{j=1}^J \sum_{i=1}^{n_j} U_{\text{gcr}}(i, j)
\] (8.10)

such that

\[
\sum_{j=1}^J b_j \leq B, \quad \Omega_j \leq \Omega,
\] (8.11) (8.12)

\[
f_j, b_j, b_g, X_j, X_g, \omega_j > 0, \forall j.
\] (8.13)

A structure of a GCR market is shown in Fig. 8.2. The PoS node keeps track of the sharing information and periodically allocates new reward capacity to the providers according to their sharing information. The government can facilitate a provider in two different ways under this model. It can deploy small or femto-cells in a busy area where the number of users is significantly high and the government owns the facility (e.g. lands and buildings). On the other case, in places where the number of permanent customers is not high (e.g., national parks and sea shores), it can deploy macro cells to get larger coverage. In both ways, the government may act as a micro-provider which forms a new spectrum market to facilitate future generations of spectrum sharing.
Table 8.1: Comparison between GSR & GCR models

<table>
<thead>
<tr>
<th>Attributes</th>
<th>GSR market</th>
<th>GCR market</th>
</tr>
</thead>
<tbody>
<tr>
<td>Utility gain</td>
<td>High</td>
<td>Low</td>
</tr>
<tr>
<td>Provider’s cost for infrastructure</td>
<td>Moderate cost</td>
<td>Low cost</td>
</tr>
<tr>
<td>No. of customer served at a time</td>
<td>Significant increase</td>
<td>Low increase</td>
</tr>
<tr>
<td>Coverage expansion</td>
<td>Low</td>
<td>High</td>
</tr>
<tr>
<td>Scalability</td>
<td>High</td>
<td>Low</td>
</tr>
<tr>
<td>A government’s cost</td>
<td>Loss of license fee</td>
<td>Investment for infrastructure</td>
</tr>
<tr>
<td>Market competition</td>
<td>Increases to gain reward spectrum</td>
<td>No significant increase</td>
</tr>
<tr>
<td>New services</td>
<td>High possibility</td>
<td>Low possibility</td>
</tr>
</tbody>
</table>

Contrary to other micro providers, the government will operate on a large portion of the federal band which will improve the capacity to serve more customers without imposing any charge on the providers, which eventually removes burdens from the customers.

8.2 Qualitative Comparison of GSR & GCR Models

We make a qualitative comparison between GSR and GCR models. In doing so, we focus on business models, opportunities, utility gains, and the market healthiness as shown in Table 8.1. Both reward models come with the promise of higher utility than conventional spectrum sharing models. However, relative utility gain in GSR is significantly higher than GCR model. Because, the GSR offers freedom to a provider to utilize spectrum in its eNodeBs. This creates an opportunity for a provider to serve more customers at a time.

The number of customers being served in both models also increases. However, GSR definitely gets an edge over the GCR in this regard. In GCR, the location and availability of an eNodeB depends on government which may obstruct serving more customers. Contrary, GSR allows admitting new customers to a provider’s eNodeB. The placement of a provider’s eNodeB depends on
its business policy. If the demand grows, it can establish new eNodeBs and use reward bandwidth to serve customers.

Future cellular systems are going to include high speed services. GSR offers opportunity to include new network services. GSR surpasses GCR to offer such new opportunities. Besides additional customer inclusion, a provider in GSR can allocate more bandwidth for a new service which is harder to do in the GCR model.

The GCR model offers higher coverage expansion than GSR. The goal of a GCR market is to cover an area where most of the commercial providers do not have interest or faces difficulty to operate. These areas are mostly crowded with travelling customer and lack a permanent customer base. Contrary, GSR increases an eNodeB’s capacity. Although, it still offers opportunity to increase coverage area, a provider can expand its coverage without reward bandwidth.

The operating cost may increase in the GSR model for a provider compared to the GCR model. In GSR, a provider is responsible to have the infrastructure to integrate the reward bandwidth in its network where the government takes care of establishing eNodeBs in GCR market. If we consider the current market where federal/government band is not being used for commercial purpose, the government does not earn any money from license fees. Although in future network services, this band is going to be used for commercial shared access. If the government leaves some part of this band to distribute as reward spectrum, it will not incur any direct cost to the government revenue’s or tax-payers. In contrast, the GCR market directly involves additional costs for the government. The government is responsible to establish eNodeBs to improve users’ wireless experience.

The government can choose any of these models based on the purpose. If the government focuses on expanding coverage towards a particular area, it can choose the GCR model. If it looks for low cost and high utility gain at regions with a permanent customer base and competitive inter-provider market, it can choose the GSR model to incite more spectrum sharing.
8.3 Preliminary Evaluations

We have made an initial numerical evaluation of our proposed reward-based spectrum sharing models by estimating the average utilities of each customer. We also find a spectrum sharing provider’s operating regions of safe willingness to share to avoid freeriding effects. For this experiment, we considered two US providers, AT&T as Provider I and T-Mobile as Provider II. We also used some real data from these providers.

8.3.1 Experimental Setup

We considered an unlimited single-line service from both providers with similar offers for which Provider I charges $80 and Provider II charges $65 [89]. We scaled down the number of customers and cells each provider can have within a 100x100 sq. miles area in the US. We also consider that each cell can have only one eNodeB. Thus, by scaling down the total numbers of customers and cells we get: Provider I has 420595 customers, \( n_1 \), and 305 eNodeBs, \( X_1 \), and Provider II has 218857 customers, \( n_2 \), and 198 eNodeBs, \( X_2 \), [90], [91].

In the US, approximately 70% of the landmass has high-speed coverage [92]. We randomly placed both providers eNodeBs within 70% of a 100x100 square grid area using Matlab for this experiment. In the rest of the areas of the grid, we only considered establishing government eNodeBs randomly. Determining the number of government eNodeBs, \( X_g \), within this area is a tricky decision to make. If both providers want to cover the rest of the uncovered areas (30% of the US landmass) maintaining the current number of eNodeBs to area ratio, we find that they will require 215 more eNodeBs together. As these uncovered areas are either barren lands or protected regions [93], none of the providers will have a significant incentive for establishing eNodeBs. Here we need the government to come forward. We consider the government is interested to establish
15% of these additional towers which is 32. This number can vary based on the government’s decision considering the feasibility of establishing eNodeBs within a region. We also consider same numerical value of spectrum bandwidth for all providers as well as government bases where $b_1 = b_2 = b_g = 8$.

We allow each customer to make 100 calls, $\eta$, in total. The customers can make a call from any random position within the test area. These calls will include home calls, $\alpha$, foreign calls, $\beta$ and calls through government eNodeBs, $\lambda$. During making a call, we consider the nearest eNodeB is expected to process a customer’s request. If a customer of Provider I finds home eNodeBs as the nearest base, the call will be processed through the home network. The probability of this customer’s all foreign calls will be served through Provider II’s network based on II’s willingness to share, $\omega_2$. Similarly, the customer’s calls through the government eNodeBs will be processed based on (8.8), the PoS of Provider I. The numbers of calls were the only unknown entities to compute the utilities. We use random user positions to make calls to allow randomness in the system. Thus, the utility computations will follow a similar trend irrespective of the machine where we run the simulation. We run the entire process 7 times and took the averages of the number of home calls, foreign calls, and calls through the government bases to get each provider’s customers average utilities in a non-shared, spectrum reward-based, GSR, and infrastructure reward-based, GCR, markets using the analytical utility forms of eq. (8.1), (8.3) and (8.9) respectively. Initially, we test with different numerical values of $\alpha$, $\beta$ and $\lambda$ where $\alpha > \beta > \lambda$ to identify the trends. Later, we run experiments considering a customer’s randomness of making a call. The findings follow similar trends. Considering randomness in the system and using the obtained utilities, we illustrate the observations on willingness to share in the following section.
Figure 8.3: Average utilities in a non-shared, spectrum reward-based, and infrastructure reward-based spectrum sharing markets

8.3.2 Results

We plotted average utilities from different markets in Fig. 8.3 to make a comparison. Here, Provider II always maintains 100% willingness to share, $\omega_2$. We vary Provider I’s willingness to share, $\omega_1$, from 0% to 100%, and observe the utility gains. We find that in a non-shared market, Provider I’s customer gets better utility gain compared to Provider II’s customers. However, in both cases of the reward-based spectrum sharing markets, these utilities are higher compared to the non-shared market. Initially, we find, Provider II’s customers have a relatively low utility than Provider I’s customer. If we continuously increase $\omega_1$, we find that Provider II’s customers can get higher utility than Provider I’s customer. It is the place where freeriding starts. We see that freeriding starts if $\omega_1$ is above 87%. Thus, Provider I can enjoy sharing up to 87% without incurring significant customer loss due to unfair customer switching. In such government reward-based
markets, the government usually expects to elevate welfare for the users. We assume the government is interested to ensure at least equal utility to the current non-shared average utility for all users in the spectrum shared market. If we apply this policy in our proposed market, we find that in the GCR market a small $\omega_1$ is enough to meet the criteria. However, in GSR market $\omega_1$ needs to be at least 8\% to meet such policy. Now, if we consider both, 1) the government’s requirement to meet certain utility gain and 2) avoiding Provider II’s freeriding effect, we can say the suitable operating region of $\omega_1$ is between 8\% to 87\% for Provider I.

Similarly, we can find an operating region of $\omega_2$ for Provider II by taking a fixed $\omega_1$. After following repetitive selections of a fixed willingness to share for one provider and getting a range for another we may reach an optimal solution for both providers where they can have fixed individual willingness to share. We kept this work as future work along with further theoretical explorations on the reward models.
CHAPTER 9: CONCLUSIONS AND FUTURE WORK

One way of promoting pervasive sharing is to incentivize the providers for sharing their licensed spectrum to the secondary users, when there is no signal or low quality signal from the primary provider. Government incentive can be a solution for such improvement of end-users’ wireless experience. In this dissertation, I have considered government incentivized SBSS market and proposed a non-cooperative game-theoretic framework, where the amount of customer switching triggered by a freeriding provider can be reduced and the earnings of the spectrum sharing provider remains at least as much as the earnings from the existing non-shared spectrum market. Our proposed game model can ensure the spectrum sharing provider to serve up to a certain sharing percentage of total incoming foreign calls at all times. Above this willingness to share, our model helps both providers to maintain a mixed strategy to control freeriding. Also, there exists a fees ratio (i.e., the disparity of the freeriding provider’s fee to a fair market fee), below which a spectrum sharing provider can always share. I have considered customers’ price averseness to determine customer switching probability arising from freeriding and shown the impact of subsidy in an SBSS cellular market. I also observed the NEs with different sizes of the providers. If the size difference between two providers is large or they are similar in size, we observed no freeriding takes place. I also discussed the application of the two-provider game in a multi-provider environment.

I have proposed a novel heuristic algorithm for providers to select strategies to gain higher revenue in an SBSS market. I also have explored regulation of minimum fees by the government for eliminating freeriders. Our heuristic algorithm is able to determine the suitable fee and willingness to share which ensures all providers to get the highest benefit from the market while governmental regulations against freeriding providers encourage spectrum sharing providers to share more resources. I have considered the symmetric behavior of customer switching to compute a provider’s revenue where a customer can choose any provider’s subscription. Again, I have observed that the
fees of a freeriding provider is either higher than regulated minimum fees or equal to fair market fees which indicates the high stability of an SBSS market. I have also observed that, if the government provides a significant amount of subsidy to the spectrum sharing providers, the minimum fees for freeriding providers can be zero. If the subsidy amount is reasonable, the freeriding provider can enjoy lowering fees significantly. Further, if the sizes of the participating providers don’t change, then a little increase of subsidy can motivate spectrum sharing providers for maximum sharing.

Proof of sharing is an important issue for an incentivized spectrum sharing market. It maintains trust among participating providers and provides necessary information to the incentivizing organization. An effective model of a PoS can reduce the amount of messaging overhead and associated delays in a cellular network. Again, the government may seek a validated data of how much spectrum being shared by whom in order to appropriately provide incentives and penalize the providers with no contribution. In this dissertation, I addressed this issue by proposing two novel architectures for keeping the Proof of Sharing (PoS) either in a centralized way or by using PoS mobile app installed in UE(s). I also provided a qualitative comparison of proposed PoS architectures. I demonstrated how PoS-like crowdsourced data could be used to predict cell tower locations that could be useful during disaster situations.

In this dissertation, I also have proposed two new government incentive models: reward cell and reward spectrum models for promoting pervasive sharing among competing wireless providers. I have made a qualitative comparison between the proposed models and showed the average utility gains.

I leave exploration of NEs from the repeated games as future work. This will allow better observation of dynamics involved in freeriding and sharing providers. Exploration of marginal signal improvement in a provider’s network with an addition of a base station is another worthy future
work. In the game, I have used same value for both providers. Different values may substantially increase/ decrease the size of the desired/undesired equilibrium regions. In a competitive market, along with different marginal signal improvement values, a small amount of subsidy can motivate a provider for higher sharing.

I plan to consider dynamic game formulations for further insights on the dynamics and compare the results of heuristic approach to game equilibria in future. Heuristic approach only focused on government regulations on fees. Future work can introduce regulations on a provider’s *willingness to share* for participating in an SBSS market. The total number of customers remain constant for all cases of this experiment. I am interested to run the experiment with a variable number of customers. Also, I have not considered Mobile Virtual Operators (MVNOs) in the game-theoretic model as well as heuristic approach. As such virtual operators without any infrastructure are being considered, looking at the effect of such operators on the SBSS markets will be an interesting direction to take.

In future, I would be interested in exploring the negotiation processes involved in the cloud-based PoS and providers via eNodeB(s) for selecting the best available spectrum. Also, it would be worth investigating the signaling overhead of messages to be exchanged among UEs and cloud-based PoS as compared to the formally proposed CSM architecture. I aim to develop a prototype along with a simulation framework for these PoS architectures. A real-time observation on messaging overhead and delays will be helpful to find appropriate placement of a shared-MME. The observation of PoS messages in different types of cells is also a worthy future work. Finally, a truthful coverage map generation from the PoS data to assist the government on rewarding or punishing providers on their published coverage map can be a new direction for future research.

As future work, exploring how to attain effective sharing and improvement of users’ wireless experience in the government reward models is of interest by simulations and prototyping. It will
be a worthy investigation of finding places for establishing government eNodeBs in the reward cell model. Finding new business opportunities and models with the reward-based spectrum sharing is also a valuable future work. Finally, I expect from the wireless networking community to come forward with further comparisons and evaluations.
APPENDIX : PUBLICATIONS


LIST OF REFERENCES


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[52] “Communication from the commission to the european parliament, the council, the european economic and social committee and the committee of the regions promoting the shared


