

Managing Cross-Border Cellular Networks Interference via Game Theory-based Spectrum Sharing

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Declaration

I, the undersigned, declare that the thesis comprises my own work in compliance with internationally accepted practices; I have fully acknowledged and referred all materials used in this thesis work.

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This is to certify that the thesis prepared by **Seid Ahmed Endris**, entitled *Managing Cross-Border Cellular Networks Interference via Game Theory-based Spectrum Sharing* and submitted in partial fulfillment of the requirements for the degree of Master of Science In Telecommunication Engineering complies with the regulations of the University and meets the accepted standards with respect to originality and quality.

Signed by the Examining Committee:

Internal Examiner _____ Signature _____ Date _____

External Examiner _____ Signature _____ Date _____

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Dean, School of Electrical and Computer
Engineering

DEDICATION

Dedicated to my Father!
Advocated and Overwhelmed to see the fruit of my schooling but he was not
Lucky.

ABSTRACT

The need for wireless services and high data rate is growing rapidly as a result of development of communication technologies. The challenges for operators to meet this rising demand of high data rates is radio spectrum which is a scarce and expensive resources. This scarcity arises from the exclusive allocation of the available spectrum relatively from the physical scarcity and has inefficiency in bandwidth usage. To improve capacity and Quality of Service (QoS), it is essential to pay closer attention in increasing operational bandwidth.

The viable option to increase this operational bandwidth is spectrum sharing between operators. It refers to the common uses of a specific range of spectrum simultaneously by operators operating in the same geographical area. However, the main problem in operating with same frequency bands without coordination causes inter-operator or Cross-Border Interference (CBI). The mitigation techniques currently working for managing this type of interference is the physical and logical parameter optimization which is not effective.

In this thesis, an efficient approach of dynamic spectrum sharing among operators is proposed to alleviate this problem. The basic idea is to partition the available spectrum into private and shared frequency bands by exchanging spectrum usage favors from the common pool to minimize interference. We address this issue for two operators' spectrum sharing operating in the same geographical area.

Most of the mathematical models considered all over this thesis are based on the Game theory to model and analyze their competitive interactions. A strategic non-cooperative game is modeled to maximize throughput, where the operators simultaneously share the available spectrum dynamically as per their relative requirement. Finally, based on the simulations, the expected results of the proposed schemes outperforms the existing Fixed Spectrum Access (FSA) schemes under varying load factors.

KEYWORDS

Game Theory, Dynamic Spectrum Sharing, Non-cooperative Game, Cross-border Interference.

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ACRONYMS

3GPP	Third Generation Partnership Program
ACI	Adjacent Channel Interference
BS	Base Station
CBI	Cross-Border Interference
CDMA	Code Division Multiple Access
CSI	Channel State Information
DSA	Dynamic Spectrum Allocation
FDD	Frequency Division Duplex
FDMA	Frequency Division Multiple Access
FSA	Fixed Spectrum Access
GSM	Global System for Mobile
HetNet	Heterogeneous Networks
ITU	International Telecommunication Union
LTE	Long Term Evolution
LSP	Limited Spectrum Pool
MNO	Mobile Network Operators
NE	Nash Equilibrium
NGN	Next Generation Network
OFDM	Orthogonal Frequency Division Multiplexing
OFDMA	Orthogonal Frequency Division Multiple Access

PCC	Primary Component Carriers
PF	proportional Fair
QoS	Quality of Service
RAT	Radio Access Technology
RNC	Radio Network Controller
SCC	Secondary Component Carriers
SDMA	Spatial Division Multiple Access
SDMA	Spatial Division Multiple Access
SINR	Signal-to-Interference Plus Noise Ratio
SNR	Signal-to-Noise Ration
TDD	Time Division Duplex
TDMA	Time Division Access
TDMA	Time Division Multiple Access
TDMA	Time Division Multiple Access
TDMA	Time Division Multiple Access
UE	User Equipment
UE	User Equipment
UMTS	Universal Mobile Telecommunication System
UMTS	Universal Mobile Telecommunications System
WCDMA	Code Division Multiple Access

INTRODUCTION

The industry of Telecommunication is expand intensively as a result of the development of enormous communication technologies. Affordable wireless devices, smart phones, tablets, and applications facilitates huge number of users to join the wireless mobile network communication. This wireless devices and applications that has the ability to increase mobile data traffic globally also growing exponentially and expected to grow in the future as well [1]. In accordance with the forecasts of Cisco Mobile Visual Networking Index in 2016 [2], mobile data traffic will grow seven-fold or 700% from 2016 to 2021. The forecasts also estimated that by the end 2021, mobile data is projected to account 20% of total Internet traffic, up from just 8% in 2016.

The challenge of new generation wireless networks designers is the bandwidth required to handle this big data traffic growth that enable the operators to satisfy the increasing demand for high-quality services. This is to be considered as a key factor for the evolution of cellular networks and the usage of the available spectrum. Historically, in cellular networks, spectrum has been allocated in a static manner in order to avoid interference: each operator has its own portion and is allowed to use only it, without any overlapping. This type of allocation is commonly referred to as FSA. The only way to share the radio spectrum for multiple users was to divide it into orthogonal portions. Each portions was assigned to an operator through licensing, the so called command and control approach with national and international regulatory bodies [3].

Radio spectrum is defined as an electromagnetic spectrum, with frequencies ranging from 3Hz to 300GHz [1] and it is a scarce and an expensive natural resource. But the currently used static allocation scheme is a more significant problem than the actual physical scarcity. And it is clearly inefficient and inadequate in terms of

innovations and rapid deployment of new technologies [4].

To overcome this efficiency, the use of a unique shared spectrum would be a possible solution [5]. This is a growing awareness that radio spectrum must be shared as much as possible among operators without degrading their performance. In realization of the growing importance of spectrum sharing, many regulatory bodies worldwide have indicated policy shift towards to use the available spectrum flexibly. Spectrum sharing refers to the common use of a specific range of spectrum or operating in the same frequency bands simultaneously by Mobile Network Operators (MNO) operating in the same geographical area. However, the main problem in operating with same frequency bands without coordination causes inter-operator or CBI with in MNO's.

1.1 RESEARCH MOTIVATION

In mobile cellular communications, the key operational objectives is maximizing capacity and QoS that mostly depend on frequency reuse pattern and the interference resulting from it. However, both capacity and QoS are affected by any external interference [6]. External interference can be a major limiting factor in the performance of wireless communication systems. Frequency spectrum allocation in a region is managed by the telecom regulator of each country. However, this division of spectrum bands does not apply across national borders. Regulators try to coordinate across international borders under the recommendations of International Telecommunication Union (ITU) and regional regulatory organizations. The operators try to have mutual agreements to resolve these conflicts, but these agreements are difficult to achieve in certain cases [7]. Mostly, cross border coordination is not effective, leaving individual operators to resolve resulting conflicts on their own. So it is better to understand CBI as increasing in cellular networks is causing increased problem of interference in border regions.

An example of CBI which motivates for this research work is in the eastern border of Ethiopia, where networks of ethio telecom in border town of Togochale get impacted by emissions across the border from telecoms operators of So-Telesom, SOM60 and SOMTEL in Somali-Land [8].

In this border areas Ethiopian and Somalian regulators have failed to coordinate frequency planning. The result for this interference is that the same band of frequencies is allocated to Global System for Mobile (GSM) in Somali-Land and Universal Mobile Telecommunications System (UMTS) in Ethiopia to avoid their spectrum scarcity. Both capacity and QoS are adversely affected by this external interference and customers (business) in this area are dissatisfied and complaining. It has also a significant economic impacts in ethio telecom since most people living in and around Togochale town are using Somalian operator's sim card for the reasons their signal quality and coverage is better than ethio telecom in this area.

To mitigate this type interference, optimization action (physical and logical optimization) and changing the operating band was done [8], but all are not effective since they are not technical. So we explore the idea of an efficient dynamic spectrum sharing among cellular network operators by small cell deployment scenario. The basic idea is to partition the available spectrum into private and shared frequency bands by exchanging spectrum usage favors by creating a common pool of frequencies with the aim to mitigating interference and increase efficiency. We model and analyze their competitive interaction among operators mathematically with game theory. Besides mathematical modeling, the proposed algorithm in this work for MNO's dynamic spectrum sharing is validated with simulation. The remainder of this work is discussed in the next chapters.

1.2 STATEMENT OF THE PROBLEM

Telecom operators in these days largely follow exclusive allocation of the spectrum or orthogonal spectrum sharing called FSA. This is a command and control approach. Such a static frequency assignments are inconvenient because they are

time and space invariant and prevent devices from efficiently utilizing the allocated spectrum, resulting in spectrum holes (no devices in the area) and poor utilization [9]. However, with this traditional assignments [10], Next Generation Network (NGN) which have higher bandwidth requirements do not meet demands of end user capacities and QoS.

These limitations motivated a paradigm shift from this exclusive uses of the available spectrum to spectrum sharing. It uses a common specific range of spectrum or operating with the same frequency bands simultaneously between operators located at the same geographical area for different Radio Access Technology (RAT) in order to achieve the efficiency, which is defined as the per-user achieved capacity (data-rate in bits/seconds). But the coexistence of multiple operators in mobile environments using the same spectrum to different RATs in a non-orthogonal way, that is at the same time and in the same geographical area leads to inter operator interference. Therefore, spectrum sharing among operators ends up in a conflict in physical layer due to no coordination between operators participating in frequency planning.

To mitigate this problem, we need to explore another techniques that the operators can share the available spectrum dynamically. Dynamic spectrum allocation [11] is a technique with the best capability which each operator can share the available spectrum according to their needs from the limited spectrum pool. In this scenario, a low load operator could transfer some of its spectrum resources to a high load operator. The interaction among operators can be modeled and analyze using game theory.

1.3 OBJECTIVE

1.3.1 *General Objective*

The main objective of this thesis is to model the problem of spectrum sharing schemes with non-cooperative game theoretic approach to mitigate interference.

1.3.2 *Specific Objectives*

The specific objectives of this thesis are:

- Study the problem of spectrum sharing between operators located at the same geographical area and operating with the same frequency bands.
- Investigate the power of strategic non-cooperative games to model interactions between the operators operating with in the same frequency bands.
- Investigate spectrum sharing in different geographical settings.
- Perform numerical simulation and compare the performance of the currently used exclusive allocation schemes and the proposed DSA techniques for cellular networks.
- Identify actual interference mitigation techniques based on the research findings.
- Finally to recommend future works based on observation of the research findings.

1.4 SCOPE OF THE STUDY

The impact of two operators operating with the same frequency bands in the same geographical area is inter-operator interference. It is the main problem and performance limiting parameter in a shared frequency band and there are two broad types [12]: co-channel and adjacent channel interference. The general problem addressed by this thesis is how to mitigate co-channel interference. From a diversity of methods that may be employed to give solution to the identified problem, this thesis work scopes restricted and addresses the importance of pool based Dynamic Spectrum Allocation (DSA) with equal rights. We model and analyze interaction among competitive operators by using game theory.

1.5 CONTRIBUTIONS OF THE RESEARCH

The main contributions of this thesis are summarized as follows:

- The research enables to have insights on DSA, which the technical interference management techniques to mitigate Inter-operator interference for NGN networks ¹.
- It increase awareness about spectrum sharing between operator and its impact CBI in cellular networks and the limitation of the currently working mitigation techniques.
- Game theory gives insights the most and important theoretic bases for modeling spectrum sharing and also game theory used to inspire practical designs for the operator as it mainly uses as engineering approach in wireless communication.
- The problem raised in this work is happening in the border area with the neighboring county. If the government changes its policy in the near future and other operators invited to operate in the country, this thesis will be used as a basic tool to further study and share the spectrum efficiently and mitigate inter-operator interference.
- This research also could be the starting point to conducted researches in managing Inter-operator Interference in the shared spectrum based on game theory in ethio telecom. So it provides insights about the company's technical interference mitigation techniques and motivate for further works and used as a reference material for the researchers.

1.6 LITERATURE REVIEW

A number of researches have been conducted in spectrum sharing among operators and the problem of its coexistence in the same geographical area. In this

¹ If Interference is mitigating technically for NGN which have higher bandwidth requirements,so it can meet demands of end user capacities and QoS. This also have economic impact on the revenue of the company

section we review some works related to spectrum sharing between operators operating with the same frequency bands in the same geographical area.

Multi-operator spectrum sharing scenario has been considered in more studies on the past years in the literature [11], [13]. Mostly these papers which have been investigated are based on the concepts of DSA and spectrum refarming, which support different generations of cellular networks operating in the same radio spectrum together. The problem of spectrum sharing in a cellular radio network is recognized both from the perspectives of economics and network performance together. Round Robin scheduling were proposed to redistribute call loads between base stations and facilitate sharing of the spectrum increase their utility.

The assignment of exclusive spectrum bands in [14], to operators gives each operator the right to control their spectrum bands. However, exclusive allocation has inefficiency, spectrum sharing between the operators is required for better utilization. In a non-orthogonal sharing scheme, multiple operators can transmit on the same spectrum band at the same time and location. Here the operators are required to coordinate their operation and choose transmission strategies to mitigate the inter-operator interference. They can share their licensed spectrum band with each other by forming a common limited spectrum pool and can mitigate interference.

Spectrum sharing can be shared either on a pool or non-pooled basis. In study [3] the researcher presents the problem of spectrum sharing where competitive operators coexist in the same frequency band. They model this problem as a strategic non-cooperative game where operators simultaneously share the spectrum with non-pool based scenario. They also share the Radio Network Controller (RNC) to address the issue of code management between the two operators and to share the DSA related information needed to co-ordinate the DSA process. The effect of ACI is considered minimum when the base stations are co-located and maximum when the base stations are displaced. The performance of the proposed algorithm shows that under peak-hour loading, up to 32% increase in capacity can be ob-

tained when compared to currently used allocation schemes.

In [15], Co-Primary spectrum sharing protocol is proposed in an indoor deployment scenario with frequent network load variations that are expected for small cell deployments. The proposed protocol is distributed and does not require operator-specific information exchange, and incurs a minimal communication overhead between the MNOs. The protocol is based on a book keeping of spectrum usage favors asked and received by the MNOs. Thus, long term fairness can be guaranteed and MNO can enhance their QoS in comparison to a scheme where no spectrum sharing is allowed. Moreover, this work is extended in [16], in which two small cell operators are deployed in the same geographical area. Operators can enhance their QoS in comparison with a scheme where no spectrum sharing is allowed while also maintaining reciprocity that is no operator benefits over the other in the long run.

These related works have been done by considering different scenarios as proposed by the researchers and have their own strength to obtain the utility as the problem is formulated and designed. But most papers have limitation based on the level of our understanding, some of them based on non-pool based, which means they can't consider equal access rights, some considers centralized architecture which is not valuable in competitive environment, some share RNC in addition to spectrum and consider ACI which is out of our thesis scope and some consider spectrum sharing with power control which in and others are considered spectrum sharing among multiple operators operating in the same country.

So in this work, we consider two operators operating in the same geographical area with the same frequency bands competitively. We deployed one small cell BS for each operator for simplicity and tested by modeling their interaction in non-cooperative tit-for-tat strategy game from the pool with equal access rights in different geographical setting scenario.

1.7 METHODOLOGY

The main purpose of this work is to model spectrum sharing with game theory which is the most important theoretic bases for this thesis to manage interference in cellular networks. So in order to achieve the objective of this research works the following methods was considered.

Literature review: Literatures such as books, journals, magazines, internet sources and others are referred regarding the concept and the researches made on Spectrum Sharing, Inter-Operator Interference cellular networks, Game theory and DSA. Not only formal researches but also other papers that have direct or indirect relation to this work are reviewed.

Data collection: This involve collecting the real network data from ethio telecom network management system. This may contain global data like duplex types, operating bands and the necessary parameters. The parameters for this work is also literature aided from ITU and 3GPP releases documents. And collecting the necessary reports from ethio telecom's optimization engineering section.

System-level simulations: The work in this thesis relies largely on system-level performance evaluation. In the context of cellular networks, system-level simulations refer to the performance of an entire cell (single-cell simulations) or an entire cellular network (multi-cell system-level simulations). For this research works we have considered operators as a single cell operator and simulate with a MATLAB tool.

Analysis and interpretation of the results: It involves a small cell deployment scenario with a DSA techniques for inter-operator spectrum sharing and then the overall performance improvements analyzed and investigated against the static allocation schemes currently used.

1.8 THESIS ORGANIZATION

This thesis is organized into six chapters and the remainder of it is organized as follows. Chapter 2 Briefly reviews the theoretical background of this thesis, introduce the fundamental concepts of cellular networks, interference and its mitigation technics in cellular networks. Chapter 3, Presents a brief introduction to the basic principles of a game theory and methods to model and analyze spectrum sharing. Chapter 4 stated the proposed DSA scheme based on non-cooperative repeated game is explained. The system model and the utility functions are described together. Finally, an algorithm for distributed game model of dynamic spectrum sharing among the operators is explained. Chapter 5 focuses on the simulation scenario, simulation parameters, user distributions, and channel models are discussed. Simulation results are presented and analyzed. The benefits of the proposed DSA schemes are then assessed, comparing to static allocation schemes called FSA. Chapter 6 is the last chapter that we conclude the thesis work and recommend future works based on the study.

CELLULAR NETWORK INTERFERENCE

2.1 INTRODUCTION

In this chapter, a basic background for the thesis is provided. Operating with the common ranges frequency band or spectrum sharing of two cellular network operators is considered with the aid of the literature discussions. As stated in the problem statement, the most important problem in operating with the same frequency bands is the co-channel interference or inter-operator interference which is a result of coexistence of operators in the common spectrum band applying full frequency reuse in all cells of both of the operators.

2.2 OVERVIEW OF CELLULAR NETWORKS

A cellular network is a radio network distributed over a large geographic area divided into small structures called cells. The wireless channel in cellular networks which is made from radio-spectrum (bandwidth) enables the communication. The main aim of designing a cellular network is to serve as many users as possible within a given bandwidth. The wireless channel is an electromagnetic signal with the property that the power of the signal deteriorates as a function of distance which motivates frequency reuse. Spectrum reuses enables the cellular network to serve more users and also increased network capacity. Due to the propagation properties the spectrum, if the distance between cell is not perfect and hence the transmissions from different cells can interfere with each other when uncoordinated. The interference generating mechanisms and their management techniques are also different for downlink and uplink transmissions [5].

To achieve meaningful and spectral efficient communication between Base Station (BS) and mobile terminal, the transmissions are coordinated by an access method to the spectrum. In traditional cellular networks, the available spectrum resource can be divided into Time Division Multiple Access (TDMA), Frequency Division Multiple Access (FDMA), Code Division Multiple Access (CDMA) and Spatial Division Multiple Access (SDMA). This multiple access schemes determines for the users how to share the radio-spectrum since its main goal is sharing the bandwidth efficiently among users. Therefore, multiple access schemes are designed to maintain orthogonality and reduce interference [5].

Whatever all multiple access schemes can provide orthogonality and reduce interference, they are not spectral-efficient equally. Spectral efficiency of a mobile communications system gives how efficiently the spectrum is used by the system. All these techniques nowadays are employed and working well, but they wouldn't without spectrum management which partitions spectrum into bands, distributes them to owners who can then apply suitable modulation and multiplexing techniques for their purposes [17].

2.3 SPECTRUM SHARING

Radio spectrum is a part of the electromagnetic spectrum with frequencies ranging from 3 Hz to 300 GHz [18]. Cellular network operators coexist the wireless medium and it is common in modern cellular networks. The spectrum is a natural scarce resource that needs to be shared and reused among cells. Historically [19], in cellular networks, spectrum has been allocated in a static manner in order to avoid interference. AS shown in Figure 2.1 (c), both operators keep some part of the spectrum exclusively. This type of allocation is commonly referred to as orthogonal allocation or FSA. Multiple users can share the radio spectrum by divided it into orthogonal bands. Each band was assigned to an operator through licensing, the so called command and control approach with auction mechanisms and it is working still [20]. It also means, one radio access technology is assigned to the specific spectrum bands, e.g. for GSM, or UMTS or LTE as shown in Figure 2.1

(a). It is the simplest way for multiple users to share the spectrum without any

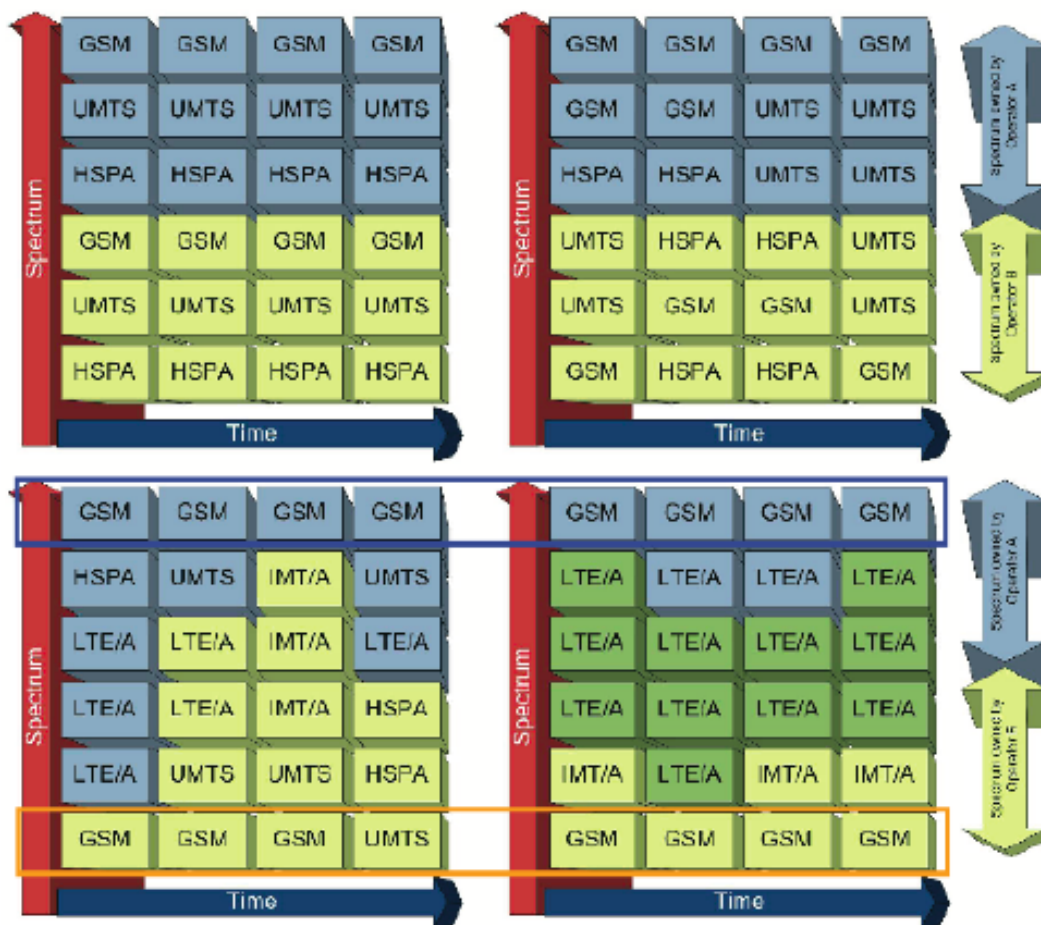


Figure 2.1: Classification of spectrum sharing methods: a) upper left: no spectrum sharing, b) upper right: intra-operator spectrum sharing, c) lower left: inter-operator orthogonal spectrum sharing, d) lower right: inter-operator non-orthogonal spectrum sharing. [20]

interference and from a communications engineering perspective, the orthogonality can be realized in different domains, i.e., frequency, time, physical space and space of coding. The scarcity problem of the spectrum is raised from this static allocation schemes than the physical scarcity. And it is totally inefficient in spectrum utilization.

2.4 INTERFERENCE

The most flexible way of spectrum sharing is non-orthogonal spectrum sharing. It is a new communication paradigm to exploit the existing wireless spectrum op-

portunistically and efficiently. In this approach both operators uses the common specific ranges of spectrum simultaneously operating in the same geographical area. This types of sharing creates interference. As shown in Figure 2.1 (d), both operator's two legacy GSM bands are protected for exclusive use and three bands are shared between two operators using LTE as RAT. However, the main problem in cellular network sharing the available spectrum with out coordination is interference.

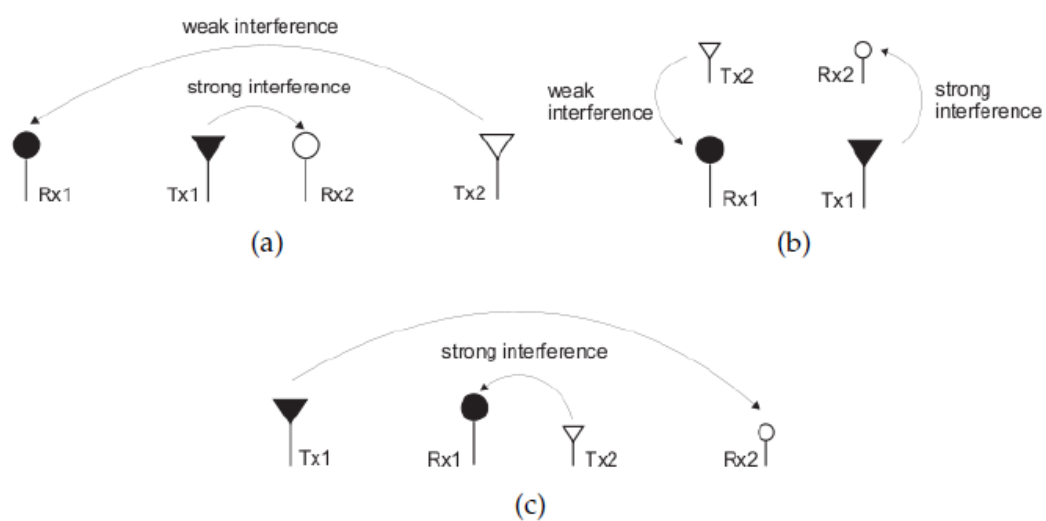


Figure 2.2: Examples of interference in bandwidth sharing [21]

And also the three common examples of interference due to spectrum sharing [21] is as shown in Figure 2.2. This effect mainly depends on the power of transmission used by the sender and on the distance between it: when the power is the greater, the area covered by is the larger; if the distance is lower from another transmitter, the lower the power needed to disturb communications. In scenario (a) both systems have similar power capabilities but, due to the locations of transmitters and receivers, one system receives large interference while the other does not. On the other hand, scenarios (b) and (c) describe situations where a high power system shares spectrum with a low power one. The main effects of interference is, it is a major limiting factor in the performance of cellular network systems.

2.5 CLASSIFICATION OF INTERFERENCE

Interference in wireless network may surely be classified from many points of view. Naturally interference can be classified as co-channel and adjacent channel interference [22]. Co-channel interference happen when the two different interfering signals are using the same frequency in the same geographical area. Otherwise, if they are using different but insufficiently separated frequencies, adjacent-channel interference occurs . Interference can also be classified by its sources, intra-operator or inter-Operator interference.

2.6 INTER-OPERATOR OR CROSS-BORDER INTERFERENCE

The coexistence of two or more cellular wireless network operators in mobile environments using the same spectrum in a non-orthogonal way (i.e., at the same time and in the same geographical area) leads to interference. Interference is any signal received from transmitter different than the intended one as shown in Figure 2.3. In [23], it is the major limiting factor when evaluating the performance of cellular radio systems. The problem is significant, because there exist many examples of cities residing close to a national border.

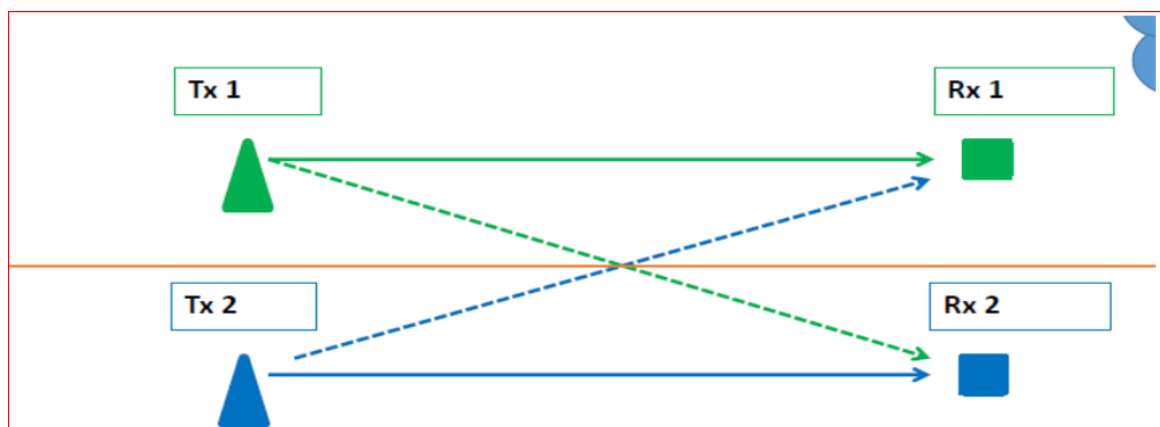


Figure 2.3: Cross-Border Interference [24]

Therefore, Spectrum Sharing of the operators ends up in a conflict in physical layer due to non-cooperative and selfish behavior of the network participants in design.

For Instance: In [5] when two operators share spectrum or operating with in the

same frequency bands in the same geographical area, the per-user data-rate (capacity) of i^{th} operator can be stated as:

$$R_i = \log_2\left(1 + \frac{P_i}{N_i + I_i}\right) = \log_2(1 + \text{SINR}_i) \quad (2.1)$$

where, R_i is the achieved data-rate in bits/sec, SINR_i is the Signal To Interference Plus Noise Ratio including the Interference power I_i . The achieved data-rate is a monotonic increasing function of SINR_i which is a decreasing function of the interference power I_i .

2.7 INTERNATIONAL CONCEPT OF INTERFERENCE (CROSS-BORDER)

There are some internationally accepted concept classification of interference based on [24]:

- **Permissible interference:** Observed or predicted interference which complies with quantitative interference and sharing criteria contained in these regulations or in ITU-Radio recommendations or in special agreements as provided for in these regulations.
- **Accepted interference:** Interference at a higher level than that defined as permissible interference and which has been agreed upon between two or more administrations without prejudice to other administrations.
- **Harmful interference:** Interference which endangers the functioning of a radio navigation service or of other safety services or seriously degrades, obstructs, or repeatedly interrupts a radio communication service operating in accordance with radio regulations.

2.8 INTERFERENCE MANAGEMENT TECHNIQUES

The main problem raised in thesis work is the the problem of CBI operating in the same geographical area especially in the border area. It is a Co-channel interference in which two different operators operate using the same frequency for

different RATs. The currently working methods for managing this interference type is the traditional way, which is a case by case basis, that means try to resolve after the issue or the problem happens. This takes long time and not efficient. Similarly, ethio telecom is one of the telecom operator affected by such a type of external interference and follow this traditional way to mitigate this type of interference. After the problem is happen, the optimization action which is doing in ethio telecom is traditional and divided also in to two:

The physical parameter optimizations are:

- Antenna Tilt Adjustment
- Antenna Azimuth Adjustment
- Antenna Height Adjustment

The logical parameter optimization are:

- Increase the Access Min Rx Level threshold of GSM
- Increase the Time Advance of GSM
- Power Control in Code Division Multiple Access (WCDMA):

2.9 DYNAMIC SPECTRUM ACCESS

There are two types of efficiency which regulators and the operators operating in the same geographical area have to take into account when considering spectrum management. The first is the technical efficiency, which refers to the requirement that different users and different uses of radio frequencies should not interfere with each other. The second type of efficiency is economic efficiency, regarding with the allocation of scarce spectrum among operators to provide different, in some cases competing, types of services. To fulfill this type of efficiency spectrum being managed and interference should be mitigated.

Technology has an increasingly important role to play in this spectrum management. For example, DSA systems [25] have been suggested as a fundamental, technology-enabled method to make more effective and efficient use of scarce

available spectrum. DSA technology enables radios to safely share multiple frequency bands without interfering with legacy and other protected wireless systems operating in the same location [26]. It improves spectrum utilization in three dimensions: frequency, location and time that enables a network to opportunistically use a wide range of frequencies when and where they are available.

When a non-cooperative user is detected on the same bands, a DSA-enabled device immediately moves to an unoccupied channel. Because many frequencies are utilized only a small portion of the time and in a fraction of locations, it enables two or more network operators to share a given spectrum band. Due to the technological advancement, there is only artificial boundaries between systems operating in the same geographical area. All of these techniques for opportunistic spectrum usage are encompassed in DSA category and also known as dynamic spectrum sharing with equal rights or access with primary/secondary usage.

The technology which support this DSA is an NGN or a cognitive radio [27], which have the ability to sense the environment. Cognitive radio is currently one of the key candidates for the Orthogonal Frequency Division Multiple Access (OFDMA) based wireless systems. Cognitive radio supports multiple accessing and spectral allocation for multiuser access inherited in the system design by assigning groups of sub carriers to different users (i.e., OFDMA) [28].

To overcome the problem of spectrum allocation in OFDMA based cellular networks, for both the uplink and the downlink, many recherches are conducted by assuming Channel State Information (CSI) at BS to exploit multiuser diversity and increase efficiency [19]. Several formulations of the problem exist and different mathematical tools have been used. One of the powerful tool is the OFDMA constrained optimization, with the objective function related to the sum rate. A promising multiple-access technique for high data rate transmission is the OFDMA, which is used to achieve for multiuser by spectrum. allocation.

2.10 GAME THEORETIC FORMULATION OF OFDMA

The mathematical way to approach the problem of spectrum allocation is through game theory. Operators access to the shared spectrum can be seen as players of a game who compete in order to maximize their own utility, e.g., their data rate or throughput. In this way, the efficiency and the evolution of the game are analyzed together with schemes that force players to move towards an efficient operating point.

Orthogonal Frequency Division Multiplexing (OFDM) is a multi carrier technology, where we divide available bandwidth into a multitude of mutual orthogonal sub-carriers. In OFDMA these sub-carriers can be shared between multiple users. Basically Long Term Evolution (LTE) downlink is based on this concept. With OFDM in downlink we can achieve higher data rates as compared to CDMA systems in 3G. So LTE networks is based on this schemes, it is the reference technology chosen for this work where spectrum sharing takes place among equals with small cell scenario.

It It as higher spectral efficiency and performance than the previous generations cellular technologies, and is packet-switched only [29]. Its air interface can employ either Frequency Division Duplex (FDD) or Time Division Duplex (TDD) duplexing schemes. Since LTE has rather flexible channel bandwidths: 1.4, 3, 5, 10, 15 and 20 MHz, than the previous technology, it is convenient for spectrum allocation purposes.

2.11 SMALL CELLS

In order to cope with the dramatic growth of customer demand and overcome the limits of existing cellular networks, it is necessary for operators to increase the data capacity and their network coverage significantly. This is possible with deploying small cells. This creates a hybrid system where the existing macro base stations overlaid with a low power and less coverage small cells called Heterogeneous Networks (HetNet). The idea of HetNet has emerge due to mobile operators necessity to get the ability to operate in networks which contain various radio access

models take into account all complex propagation loss mechanisms by making extensive path loss measurements and fitting an appropriate function to them with a set of parameters for a particular environment.

- **Okumura-Hata model:** is arguably the most widely used empirical model which was created by making a series of path loss measurements used to develop a prediction model. This model has been enhanced by creating approximations of measured data to capture the effects of terrain irregularities and different antenna heights. And it covers frequency range of 150–1500MHz and distances of 1–20 km.
- **COST-Hata model:** which is also known as the COST-231 models is a radio propagation model that extends the Hata-Okumura model to cover a more extended range of frequencies. It supports a range of frequency of 1500 MHz to 2000 MHz, a base station antenna height from 30m to 200m, a mobile station antenna height from 1 to 10m and a link distance of 1 to 30km.
- **Stanford University Interim (SUI) model:-** is developed jointly by IEEE 802.16 group and Stanford University. It is used for WiMAX application and for frequencies above 1900MHz. Path loss depends, among other things, upon frequency, distance, antenna height and environmental characteristics. Frequency and distance are taken into account in all models. Other characteristics are not always considered explicitly and frequently.

So in our thesis works by considering a power budget of wireless communication system and other path loss behavior we proposed a simple power-law distance based propagation path loss model at a carrier frequency of 2.6 GHz.

GAME THEORY FOR SPECTRUM SHARING

The imbalance between the increasing demands of wireless spectra and limited radio resources poses an imminent challenge in efficient spectrum sharing. In this context, an efficient dynamic spectrum sharing faces several difficulties: a) users' mobility and network topology is of a dynamic nature, b) various network infrastructures are likely to be interacting in the future, c) users may have different behaviors upon accessing the spectrum (cooperative, selfish, and even malicious) and finally d) the optimization of spectrum usage in a centralized approach is in general a multi-objective optimization problem, which is very difficult to analyze and solve. Therefore, game theory [33] is seen as a natural paradigm to study a network where UEs of different operators compete with each other for a common resource, namely the spectrum.

Game theory is an effective tool to predict the results of cooperative and non-cooperative actions in resource sharing and to find a compromise between them. It is concerned with predicting the outcome of games of strategies. In expressing briefly, game theory [33] is the formal study of decision-making where it analyzes or models the interactions between interdependent decision-making entities that have mutual and possibly conflicting objectives. It is formal analytical framework with a set of mathematical tools to study the complex interactions among independent rational players.

The importance of studying dynamic spectrum sharing from a game theoretical perspective is:

- It gives a wide range of optimality criteria (e.g., in simultaneous, multistage games),
- It is used to optimizes problems where no centralized control is present (non-cooperative games),

- Each players plan strategies independently and intelligently, and give a power to make decisions locally (non-cooperative one-shot games, non-cooperative repeated games). By using a good strategic mechanism players can enforce others to cooperate in non-cooperative environment (non-cooperative repeated games).

3.1 DEFINITION OF THE GAME

A game is naturally formalized as a triple of a set of players, a set strategies and a utility function. Utility function represents a player's valuation of gains/loss in a game. Players play strategies for the purposes of maximizing their utilities. Usually the strategies are conflicting, i.e., increasing own utility occurs at the expense of other's decreasing utility. So, the players have to be rational while playing strategies as too much greedy approach can harm themselves because of consequences and too much of honesty can let their misuses by greedy opponents.

We can represent the game mathematically as, *Game G is :-*

$$G = (P, S, U) \quad (3.1)$$

where,

- P is a finite set of players, s.t., $P = (1, 2, 3, \dots, m)$,
- S is a pure strategy sets, one for each player, that means, $S = (s_1, s_2, s_3, \dots, s_m)$, where, s_i is the strategy profile of i^{th} player, that is $s_i \in S_i$ and S_i is finite number of strategy sets of i^{th} player which is $S_i = (1, \dots, q_i)$ and
- $U =$ is the utility function, whose proposed explanation is the reward given to a single player at the outcome of the game, that is, $U = S_1 \times S_2 \times S_3 \times \dots \times S_m \rightarrow \mathbb{R}$.

3.2 GAME STRATEGIES

There are different type of game strategies [34], that the players can obtain various game resolutions Nash Equilibrium, Max-Min Strategy, Mixed Strategy, Dominant

Strategy, Pure Strategy, Best Response and Optimal/suboptimal solution. The followings are the possible strategies relating our thesis works of the *game G*.

Best Response Strategy: A strategy $s_i^* \in S_i$ is best response for player i to $s_{-i} \in S_{-i}$ if $\forall s_i \in S_i$,

$$U_i(s_i^*, s_{-i}) \geq U_i(s_i, s_{-i}) \quad (3.2)$$

Nash Equilibrium: In a game theory, Nash Equilibrium (NE) is a concept used to describe the steady state of a game. NE is also called strategic equilibrium, and can be defined as a strategy profile which no player maximizes its utility by unilaterally deviating from this strategy profile [35]. Thus, as long as the other player's strategy remains the same no player will change its strategy and get a better payoff.

A strategic *game G*, of NE can be defined as a strategy profile (s_i^*, s_{-i}^*) , where s_i^* is player i 's strategy and the strategy of all other remaining players denoted as s_{-i}^* such that:

$$U_i(s_i^*, s_{-i}^*) \geq U_i(s_i, s_{-i}^*) \quad (3.3)$$

This holds true for all strategy $s_i \in S_i$ and every player $i \in P$. In other words, for a strategy s_i^* to be considered as a NE for any player i there must be no strategy s_i^* that yields a better utility, given that all other players strategy is other than s_{-i}^* .

3.3 BASIC MODELS OF GAME

There are two major branches in game theory, cooperative game and non-cooperative game. In this game formulation, players act rationally according to their strategies with the objective to maximize their outcome. However, the strategic profile of players is highly influenced by the regulation imposed by the nature of the environment of the game. Cooperative game provides analytical tools to study the behavior of rational players when they cooperate. In a cooperative-game scenario, the players are allowed to form agreements among themselves that can impact the strategic choices of these players as well as their utilities. Cooperative game

in wireless networks is practically unattractive because of excessive overhead signaling and trust issues, but it provides a unique Pareto optimal solution for the problem modeling.

Whereas the non-cooperative game involves a number of players having totally or partially conflicting interests in the outcome of a decision process. The signaling overhead is low, and knowledge of a competitor's CSI is not assumed. It reflects a competitive situation where each player needs to take its decision independently of the other players, given the possible choices of the other players and their effect on the player's objectives or utilities. Non-cooperative does not always imply that the players do not cooperate, without centralized control, but it means that any cooperation that might arise must be self-enforcing with no communication or coordination of strategic choices among the players. Repeated game appears when the players have to interact with each other more than one time, and every interaction between the players is called a stage which has utility, and the total utility of the game will be the summation of the utility for each stage in the period of the game for each player individually. The methodology of game theory for spectrum sharing have two expected advantages of game theory in cellular networks based on [35]. These are:-

- Direct Application: the investigated problem is modeled as a game, and game theory is used to analyze it.
- Engineering approach: Game theory is used to motivate practical designs.

Most of this thesis is dedicated to the second approach, where game theory is seen as a valuable tool for inspiring the design of practical solutions to the raised problem and particularly the solution for this problem is mostly rooted on game theory.

The used methodology for game theory application in this thesis can be described in:-

- The analysis of game theory offers awareness into the problem.
- This awareness were used to expertise practical distributed algorithms and if feasible this algorithm analyzed .

- When feasible, the resulting algorithms are analyzed with game theory.

Game theory is easily applicable to two-player problems than for an arbitrary number of players. It is important to notice that in the case of this thesis problem, two-player analysis only tells part of the story based on repeated games. So for this research works:

- Effort to exactly model spectrum sharing among equals.
- Focus on only two number of Operators (players).
- Effort to set theoretical background for good designs.

3.4 PRISONER'S DILEMMA

The very common example used to explain a game theory is the prisoner's dilemma. The story tells about two suspects for committing a crime and put into a jail before a trial. The prosecutor believes that they are guilty, but he couldn't get enough evidence to send them to jail for what they did. The prosecutor offers the prisoners a bargain with two choices to either confess or refuse. If one confesses and the other does not, the one who refuse will sent to jail for 6 years, and the one who confess will be free for his cooperation with the prosecutor. On the other hand, if they both confess they will go to jail for 2 years each.

However, if they both refuse to confess the prosecutor has enough evidence to send them to prison for one year. Therefore, the prisoners have same two strategies: confess and refuse C,R. The prisoners are in different cells, they do not have a means to communicate. Each of them has to make their decision individually. However, the decision made by one prisoner affects the other prisoner stay in prison. Their stay in prison is the result of both prisoners' strategy choice. Now in this game, the players are the two prisoners and their payoff is the number of years in prison. Players would like to maximize their payoff, which is to have a minimum stay in prison. However, one player does not have a control on the other one's decision, which in turn affects its payoff. The matrix shows the players

strategies and their payoffs.

Table 3.1: The Prisoner's Dilemma Game

		Prisoner 2	
		Defect/Non-Cooperate	Lie/Cooperate =Refuse
Prisoner 1	Defect/Non-Cooperate /Confess	(-2, -2)	(0, -6)
	Lie/Cooperate /Refuse	(-6, 0)	(-1, -1)

To predict what a player chooses to minimize its payoff at a prison lets observe prisoner 1 choices and the outcomes. Before making a decision player1 analyzes each outcome assuming with the other players choice. Supposes that player 2 betrays player1 and selects strategy confess to maximize its payoff. Then, the optimal strategy for player 1 will be to select strategy confess since (C, C) has a better outcome than (C,R). In case players 2 stays faithful to his friend and selects strategy refuse, player 2 will have two choices either to cooperate or betray. Being faithful to his friend select strategy refuse and stay one year in prison or betray his friend confess and get free from jail. To be faithful to each other and to select strategy refuse, they do not trust each other. Thus, each will try to minimize their stay in prison. Generally, the optimal choice for both prisoners is to select strategy confess. Thus, it will be a reasonable prediction is to assume that both prisoners will confess.

BORDER GAMES FOR SPECTRUM SHARING BETWEEN MOBILE NETWORK OPERATORS

The proposed solution for the problem raised in this thesis work is a dynamic spectrum sharing method in which two operators actively attempt to share their spectrum with each other in the downlink based on some policy. Since operators are competitive by nature, it is not wise to design a cooperative game model. Instead it is better to model the interaction between operators as a non-cooperative games. So in this chapter we only focus on modeling dynamic spectrum sharing with non-cooperative game.

4.1 REPEATED GAME FOR DYNAMIC SPECTRUM SHARING

In a non-cooperative game, operators do not exchange any operator specific information. Operators are competitors in nature and, therefore, the rationale to make them cooperate would be either a legal framework or self-interest. So in order to model spectrum sharing with game framework simply, we assume that the players or operators are rational, which means that they try to maximize their utilities with self-interest. Since the operators are assumed to interact for long periods of time, and have a well-defined and publicly known identity, the appropriate framework is the repeated games.

No monetary transactions are involved; instead, spectrum sharing is based on a RAN-internal virtual currency based utility for inter-operator spectrum sharing. For this case, operators estimate their utility gain distributively for a new carrier allocation strategy. For example, in downlink transmission, the operator can ask its UEs to measure the carrier utilization and Signal-to-Interference Plus Noise Ratio (SINR) levels, and report them to the home BS.

The operator uses this information to analyze its carrier allocation strategy in which it uses its own unused carrier, or may ask the opponent to stop using it. The operators interact and approve each other carrier allocation strategies if they see utility enhancement for themselves. The operators are self-interested; therefore, they examine their mutual interaction in terms of spectrum usage favors given to each other. This asking and granting of favor is done when an operator experiences a high inter-operator interference on the shared part of the spectrum pool. The main objective of this study is to investigate the power of non-cooperative repeated game. It can model and show how one operator enforce others to cooperate with a good strategy in a non-cooperative environment with non-cooperative repeated game.

As discussed in Chapter 3, the key concept in non-cooperative game theory is the NE [36], which provides a benchmark for investigating how purely rational decision makers would perform. Nash Equilibrium is a profile of strategies (S_i, S_i) such that each intelligent operator has knowledge of its environment and thereby rationally acts to maximize its own utility function U_i , depending on not only its own actions, but also other's actions. However, the game formulation covered by this work is based on a Tit-for-Tat strategies where acceptance of a strategy requires cooperation from the opponent operator. This can minimize cross-border interference and benefit from the usage of a spectrum between MNOs operating in the same geographical area.

4.2 SYSTEM MODEL AND ASSUMPTION

It is based on a distributed game model. We consider a deployment scenario with two (MNOs), Operator A (ethio telecom) and Operator B (Somaliand telecoms), and a geographical area is served by this operators as simple as illustrated in Figure 4.2 better from the currently sharing schemes as shown in Figure 4.1 . The operators are self-interested and not willing to share operator-specific information such as load, channel usage, nor CSI. We consider both operators actively attempt to share their spectrum with the other operators in the downlink based on some

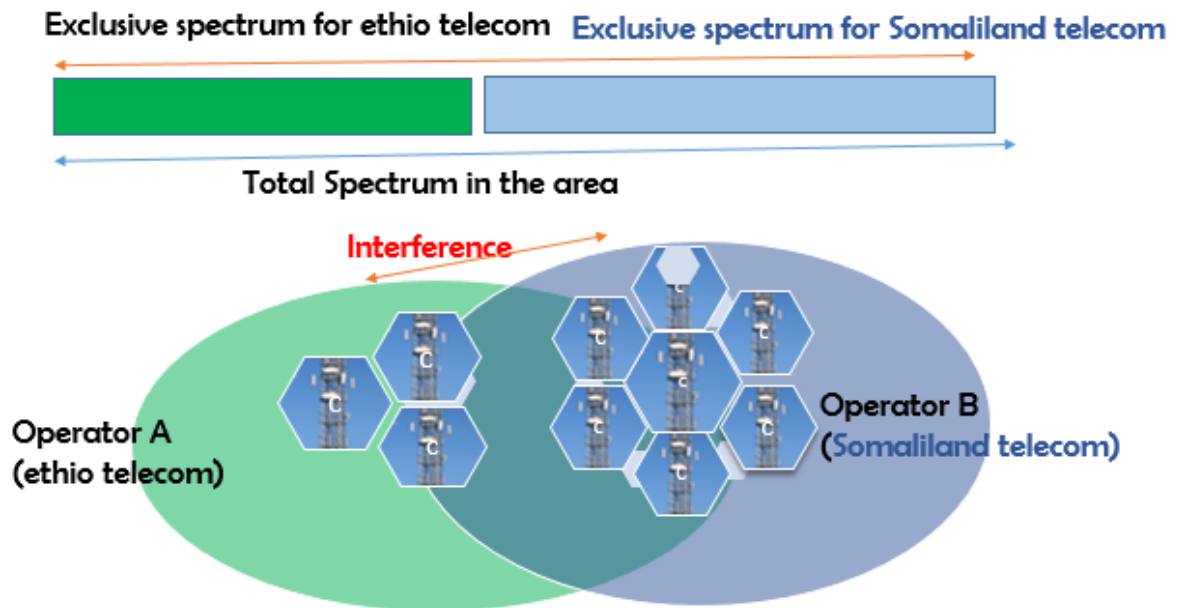


Figure 4.1: Currentl spectrum sharing scenario among MNO's (modeled by the researcher)

policy and they are a single cell operators. The total available spectrum of carriers K is divided in to two allocation namely FSA and DSA in the given geographical area. In the former scenario each operator has its own independent and exclusive spectrum usage rights or PCCs. So in this case, there is no frequency overlapping occurs, nor it generates any inter-operator interference.

However, instead of exclusive allocation of the particular licensed frequency bands to single operator, allocates them to a number of MNOS (limited number). This access mode provides an opportunity for the all operators to access additional licensed bands on a shared basis, where/when it is needed, to improves spectrum utilization efficiency. From this spectrum pool, each operators contend for the spectrum usage rights based on some established policies, and is termed as DSA. As this two operators have the right to access the spectrum in in this schemes and there is no direct mechanism to control interference between the operators, inter-operator interference is generated as shown in Figure 4.2.

The proposed coordination protocol can be used to negotiate the usage of Secondary Component Carriers (SCC) in the downlink. It is assumed that the base stations (BS)

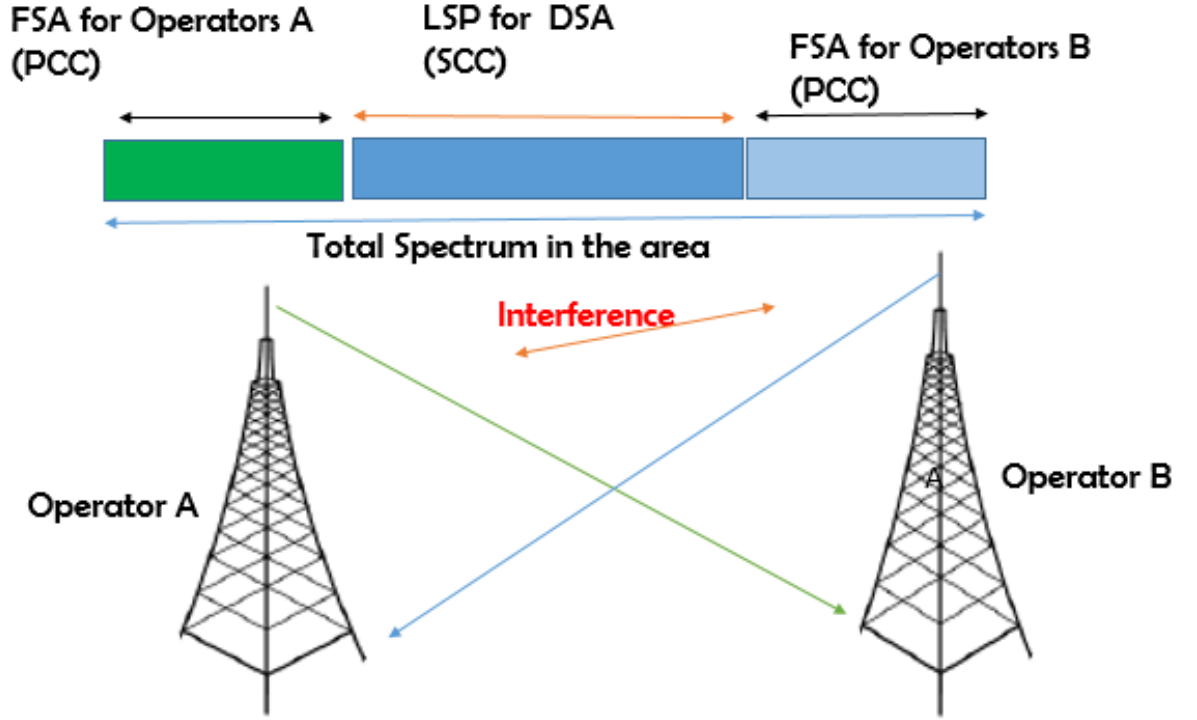


Figure 4.2: Proposed DSA among MNO's from LSP (modeled by the researcher).

always transmit at maximum power level P_t per each component carrier no matter where their users are located. We denote the rate of each j^{th} user in the k^{th} carrier in the i^{th} operator by $r_{i,j}(k_i, k_{-i})$. Where k_i, k_{-i} are the carrier allocation of operators O_A and O_B respectively, where the O_B signal may interfere with the O_A signal. We estimate throughput $T_i(k_i, k_{-i})$ for a single cell operator O_A serving J_i by the Shannon capacity as:

$$T_i = \sum_{j=1}^{j_i} r_{i,j}(k_i, k_{-i}) \quad (4.1)$$

$$T_i = \sum_{j=1}^{j_i} \sum_{k=1}^k w_{i,j,k}(k_i, k_{-i}) \log_2(1 + \text{SINR}_{i,j,k}(k_i, k_{-i})) \quad (4.2)$$

Where, $\text{SINR}_{i,j,k}(k_i, k_{-i})$ and $w_{i,j,k}$ are the downlink user SINR and time scheduling weight of the k^{th} carrier of the j^{th} user in the i^{th} operator, respectively.

The $\text{SINR}_{i,j,k}(k_i, k_{-i})$ is also defined as:

$$\text{SINR}_{i,j,k} = \frac{P_i(k_i)C_{i,j}}{(\sum_{q=1 \neq i}^I P_q(k_q)C_{q,j}) + N_o} \quad (4.3)$$

Where, $P_i(k_i)$ is the signal power of the k^{th} carrier, that is the total power budget P is uniformly distributed over K_i active component carriers out of total K carriers of the i^{th} operator, accordingly, P/K_i , $C_{i,j}$ is the gain of the j^{th} user within the i^{th} operator, N_o is the power density.

And $\sum_{q=1 \neq i}^I P_q(k_q)C_{q,j}$ represents the total interference power perceived by the i^{th} user in the k^{th} carrier, which is engendered by the other operators while sharing the same carrier frequency in dynamic spectrum allocation.

4.2.1 Spectrum Usage Favors

According to the proposed schemes, operators with low load fulfill spectrum usage favors to heavily-loaded operators. Operators are needed to maintain the reciprocity, and the operators with granted favors in the past will return these favors in future. In this way, all operators offer better QoS in comparison with static spectrum allocation without revealing their specific performance indicators nor making any agreement beforehand [37].

The favors are referred to carrier component utilization. Each operator exchanged the same amounts of favors and preserves a bookkeeping system listing the number of times each operator has been cooperative. They can exchange also if they showed each other a cooperative spirit. This strategy is called a tit-for-tat strategy in a sense that it is forgiving and avoids immediate punishment [33], [35].

Table 4.1 shows the most common behaviors for the repeated games of a Tit-for-Tat strategy. It is defined as cooperate at the first play; then, on subsequent plays,

Table 4.1: Tit-for-Tat Strategy of Repeated Game [36]

$S_1(o)$	$S_1(t)/S_2(t)$	$S_1(t)/S_2(t)$	Strategy function	Name of strategy
D	D	D	$S_1(t+1)= D$	Always defect (All-D)
D	C	D	$S_1(t+1)= S_2(t)$	Suspicious tit-for-tat
D	D	C	$S_1(t+1)= S_2(t)^c$	Suspicious anti-tit-for-tat
D	C	C	$S_1(t+1)= C$	Always cooperate (S-All-C)
C	D	D	$S_1(t+1)= D$	Always defect (Nice-All-D)
C	C	D	$S_1(t+1)= S_2(t)$	Tit-For Tat (TFT)
C	D	C	$S_1(t+1)= S_2(t)^c$	Anti-Tit-for-Tat
C	C	C	$S_1(t+1)= C$	Always Cooperate (All-C)

mimic the action of the other player chosen on the immediately preceding play. An important fact to notice about this “strategy” is that it specifies exactly what action to take at every play of the game, in every possible eventuality. Based on this strategy, operators agree on prior rules for the regulation of the spectrum pool usage. And operators can ask each other a spectrum usage favor for exclusive use of some component carriers of the common pool based on interference profile and traffic load.

We are assuming that both operators selects the carrier k randomly to get the favors for different strategies:

- Both operators utilize carrier k . In this case Operator O_A asks Operator O_B to stop using the carrier in case if it sees the utility gain is based on the equation,

$$U_i(s_i^*, s_{-i}) > U_i(s_i, s_{-i}) \quad (4.4)$$

In this case Operator O_B does the favor only if its own utility gain is positive too also as the equation is like,

$$U_{-i}(s_i^*, s_{-i}) > U_{-i}(s_i, s_{-i}) \quad (4.5)$$

- Operator O_A does not use carrier k , but Operator O_B is using it. Operator O_A accepts the strategy of using carrier k . If both operators see the utility gain according to the game,

$$U_i(s_i^*, s_{-i}) > U_i(s_i, s_{-i}) \quad (4.6)$$

and

$$U_{-i}(s_i^*, s_{-i}) > U_{-i}(s_i, s_{-i}) \quad (4.7)$$

So the new strategy is approved and regarded as a favor as it causes interference to operator O_B .

- No operator utilizes the carrier and thus, operator O_A can start using it.
- When only operator O_A utilizes the carrier, there is no interaction between the operators.

4.2.2 Utility Function

The most and widely accepted approach to quantify the radio resource allocation problems in the recent wireless communication is the utility-based approaches. Utility function represents the system's performance level or QoS that represent the degree of satisfaction of the user function of the rate with allocated bandwidth by the cellular network. The configuration of a utility function is strictly non-decreasing as depicted in Figure 4.3 based on system parameters in [38].

The fairness is better than optimality, PF allocations have been proposed for this works. The logarithmic PF allocation maximizes the overall utility of user rates by providing a compromise between user fairness and maximum throughput.

It also described as:

$$U(x_i) = \log(x_i) \rightarrow \text{PF} \quad (4.8)$$

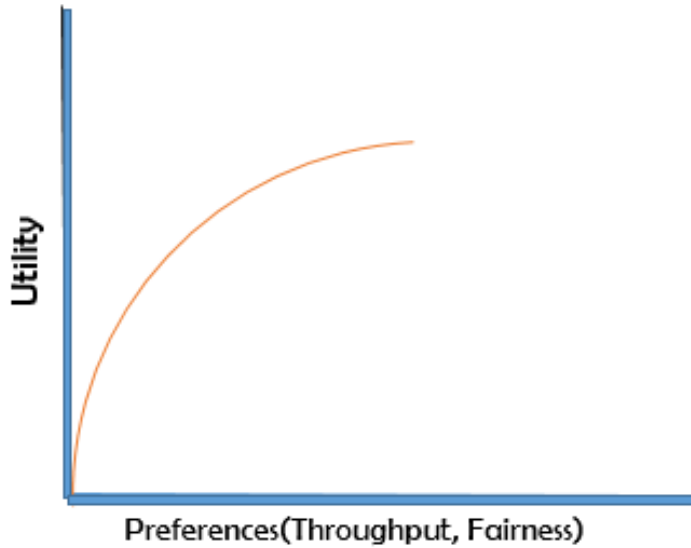


Figure 4.3: Utility Function Behavior

Operators playing non-cooperative games do not have to maintain same utility nor be aware of the utility of other operator. The utility function is occasionally defined as:

$$U_{O_{AB}} = f(T_{O_{AB}}(k_i, k_{-i})) \quad (4.9)$$

where k_i and k_{-i} are carrier allocation of operator O_A and operator O_B respectively and f represents the fairness criteria. So operators plays strategies involving carrier allocation (k_i, k_{-i}) and aim to maximize their utility function continually:

$$\max_{k_i, k_{-i}} U_{O_{AB}} \text{ s.t. } k_i, k_{-i} \in K \quad (4.10)$$

4.3 DYNAMIC SPECTRUM ALLOCATION ALGORITHM

The algorithm for two operators O_A and O_B in order to asking/granting a favor from the shared Component Carrier or Limited Spectrum Pool in the form of pseudo code is as below:

Algorithm 1 Dynamic Spectrum Allocation Algorithm for two MNOs based on Repeated Game

1: **Procedure:** Both Operators, O_A and O_B investigate their strategies by exchanging favors, that is asking to switch on the carrier k_i or removing the interfering carrier k_{-i} .

Calculate the new Utility Gain $U_{O_A}(k_i^{t+1}, k_{-i}^{t+1})$ and compares it with the currently working $U_{O_A}(k_i^t, k_{-i}^t)$.

if $\rightarrow U_{O_A}(k_i^{t+1}, k_{-i}^{t+1}) > U_{O_A}(k_i^t, k_{-i}^t)$

Do start using $(k_i^{t+1}, k_{-i}^{t+1})$

end if

2: Operator O_B its outstanding favors with surplus S :

if \rightarrow favor of O_B - favor $O_A \leq S$ then,

3: Operator O_B compares new utility $O_B(k_i^{t+1}, k_{-i}^{t+1})$ for strategy s with present utility U_B **if** $U_{O_B}(k_i^{t+1}, k_{-i}^{t+1}) > U_{O_B}(k_i^t, k_{-i}^t)$

4: Strategy s is accepted.

5: **end if**

6: **end if**

4.4 MATHEMATICAL DESCRIPTION OF THE GAME

Here with in this section, we present a mathematical model that can dealing with non-cooperative game between two operators with varying load factor.

4.4.1 For Orthogonal Spectrum Sharing

When both Operators O_A and O_B have loads N_a and N_b with respectively, then both were initially sharing the spectrum orthogonally, each were having equal and non-overlapping $K/2$ carriers allocation and thus no inter-operator interference was generated. So the utility function of Operator O_A with orthogonal carrier allocation can be written mathematically as follows in terms of PF Throughput.

$$T_{O_A} = \sum_{n=1}^{N_a} \log\left(\sum_{k=1}^{K_a} w_{n,k} \log_2(1 + \text{SNR}_{n,k})\right) \quad (4.11)$$

As per the earlier discussed assumption and initial condition, the utility function in terms of proportional Fair (PF)-throughput can be discussed in mathematically as follows:

$$T_{O_A} = N_a \log\left(\frac{K}{2} \frac{1}{N_a} \log_2(1 + \text{SNR}_a)\right) \quad (4.12)$$

where Signal-to-Noise Ration (SNR) is used for users in operator O_A . As each operator has a single BS, and according to the assumption, SNR is same for all component carriers for all users within an operator.

And similarly for Operator O_B we can define the utility function in terms of PF-throughput mathematically as follows:

$$T_{O_B} = N_b \log\left(\frac{K}{2} \frac{1}{N_b} \log_2(1 + \text{SNR}_b)\right) \quad (4.13)$$

Once we have gained the Utility function of every user served by every single

BS in the access area, then we can find the sum- PF Throughput for both two operators O_A and O_B as:

$$T_{O_{AB}} = T_{O_A} + T_{O_B} \quad (4.14)$$

So we briefly described:

$$T_{O_{AB}} = N_a \log\left(\frac{K}{2} \frac{1}{N_a} \log_2(1 + \text{SNR}_a)\right) + N_b \log\left(\frac{K}{2} \frac{1}{N_b} \log_2(1 + \text{SNR}_b)\right) \quad (4.15)$$

4.4.2 For Repeated Game based Spectrum Sharing

This also called non-orthogonal spectrum sharing with proposed schemes. And let us take the earlier assumption that both operators have asymmetric loads, that means $N_a > N_b$ and Operator O_A is the high load operator, so it is more suitable that operator O_A gets more carriers in order to avoid the congestion and blocking probability in **amin2013dynamic**. Assuming that, xK amount of carriers are transferred to high load operator O_A from low load operator O_B at the end of the sequence of a game from the initial orthogonal allocation where, $xK \in (0, K/2)$.

So the new particular PF-throughputs of the operators during the game T_{G_A} and T_{G_B} are:

$$T_{G_A} = \left(\left(\frac{K}{2} + xK\right) + \frac{1}{N_a} \log_2(1 + \text{SINR}_a)\right) \quad (4.16)$$

and

$$T_{G_B} = \left(\left(\frac{K}{2} - xK\right) + \frac{1}{N_b} \log_2(1 + \text{SINR}_b)\right) \quad (4.17)$$

So the sum-PF throughput of both operators is described as:

$$T_{\text{GameTotal}} \text{ is, } T_G = T_{G_A} + T_{G_B} \quad (4.18)$$

This can also defined well as mathematically as follows:

$$T_G = \left(\left(\frac{K}{2} + xK\right) + \frac{1}{N_a} \log_2(1 + \text{SINR}_a)\right) + \left(\left(\frac{K}{2} - xK\right) + \frac{1}{N_b} \log_2(1 + \text{SINR}_b)\right) \quad (4.19)$$

However, we can say the game is only beneficial if sum-PF throughput of game is more than the sum-PF throughput in case of orthogonal sharing, that is:

$$T_G > T_{O_{AB}} \quad (4.20)$$

Thus when described mathematically, the gain of the game for high load operator O_A that get much carrier in equation is,

$$\left(\frac{K}{2} + xK\right) + \frac{1}{N_a} \log_2(1 + \text{SINR}_a) + \left(\frac{K}{2} - xK\right) + \frac{1}{N_b} \log_2(1 + \text{SINR}_b) \quad (4.21)$$

must be greater than that of the low load operator O_B since it gives some of its carriers and punished as follows:

$$N_a \log\left(\frac{K}{2} \frac{1}{N_a} \log_2(1 + \text{SNR}_a)\right) + N_b \log\left(\frac{K}{2} \frac{1}{N_b} \log_2(1 + \text{SNR}_b)\right) \quad (4.22)$$

So in this chapter we addressed the issue using a carrier virtual currency based utility function that gain/loss during spectrum favor exchange.

SIMULATION RESULTS AND ANALYSIS

In this chapter, MATLAB-generated several system level simulation results of the proposed schemes in the previous are presented. The DSA techniques for spectrum sharing between two operators are analyzed and investigated against the static allocation schemes called FSA with varying Load factor. We have used Monte Carlo methods for the simulations, which is a simple algorithm to serve the users by assigning time and/or frequency resources one after each other to a different user. And Proportional Fair scheduling is performed by allocating more resources to a user with better channel quality.

5.1 SIMULATION SCENARIO AND PARAMETERS

The system under consideration as discussed in previous chapter consists of two small cell MNOs participating in the spectrum sharing simulation. The effectiveness of the proposed DSA scheme and the game-based interference management is shown through computer simulations.

5.1.1 *Simulation Scenario*

We consider a small cell OFDMA based cellular network [39], comprising of two operators operating in the same geographical area and each have one BSs and a Poisson distributed mean load of varying but reached up to 25 users each in their given access area. The reason we consider to deploy OFDMA based technology is, it is a spectrum efficient technology. Spectrum efficiency can also be described as how big the data rate (in bits/second) can be successfully sent per unit spectrum(Hz). Increasing spectrum efficiency means that more data can be sent for the

same amount of spectrum.

The simulation scenario in this thesis is described to show the efficiency of the proposed approach by using this efficient technology to achieve the required data rate [40] by avoiding interference. For the users which seems and located close to interference sources, served by orthogonal utilization of spectrum with PCC and this gives a better throughput in addition to give wide coverage for specific operators.

The small cell (Picocells) BSs are deployed in outdoor open spaces for suburban scenario inside macro cell coverage with separated area deployment strategy since it offers small area coverage and low-power consumption. Furthermore, these cells can offer better coverage and better data rate services in the zones in which they are deployed, which makes them an interesting technology for the improvement of QoS. We have to consider different approaches during deployment of Pico-BSs inside a macro cell area since the SINR is affected. In this thesis scenario, the chosen algorithm and the coordination protocol act effectively in case if there happens a harmful scenario called interference. And this MNO's benefit from inter-operator spectrum sharing by deployed small cells since the interference even not harmful due do this coordination protocol modeled on a game.

Whatever the area affected by interference problem which we motivated for this research work is high, we have to consider the spectrum sharing and model with game theory, by following different geographical settings. So we consider a small simulation area and small number of user for this work. This is the behavior of the algorithm and the game framework that we used to model and analyze the gain.

So the simulation environment considers BS locations and coverage areas of both operators as illustrated in Figure 5.1 with deployment parameters in 100 [m] x 100 [m] Square unit area.

We consider also PF scheduling algorithm. It is based upon maintaining a balance between two competing interests: Trying to maximize total throughput while at the same time allowing all users at least a minimal level of service, which can be

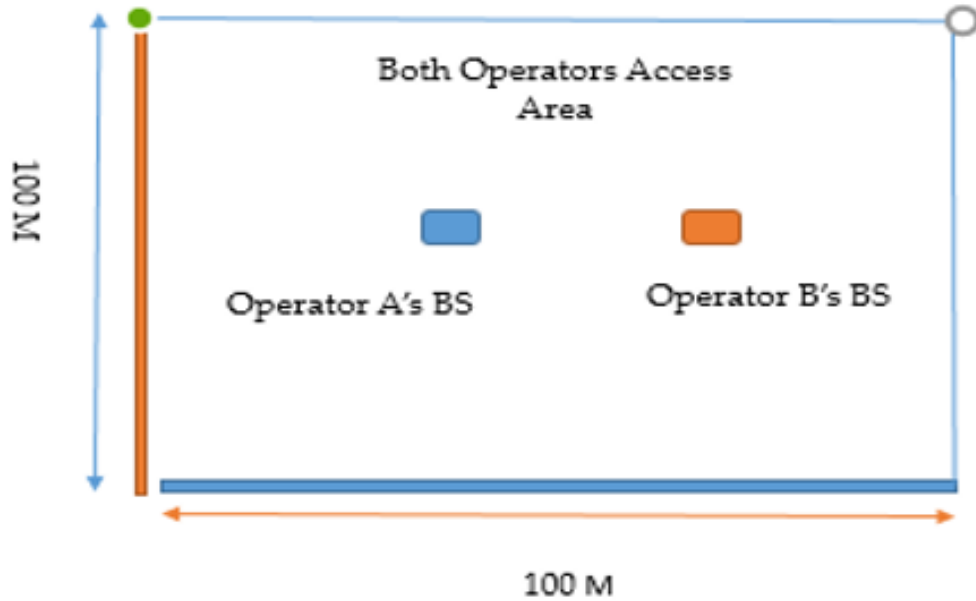


Figure 5.1: Outdoor inter-operator deployment scenario

achieved by means of weighted fair queuing.

During the simulation, the number of users follow Poisson distribution with mean N_a for operator O_A and N_b for operator O_B . We consider also two scenarios where both operators have equal and unequal mean number of users for the given access area. The traffic model used in the simulation is the Full-buffer, with 400 kbps as minimum required data rate [40]. It is not as realistic as the burst traffic model, but it offers a worst interference scenario as it considers that the UEs and BSs always have the buffer full of information that needs to be sent if there is no coordination.

The simulation has been focused in the downlink connection since it is the one that demands larger data rates, thus making it more sensitive to lower SINR. The total bandwidth of the system comprising operators O_A and O_B is equally divided into 10 component carriers. The additive white Gaussian noise (AWGN) for each component carrier is kept constant, N_0 . The available power budget is divided equally among the used carriers for down-link transmissions, we wouldn't control the down link power.

For outdoor signal propagation, we consider a simple power-law distance based propagation path loss model at a carrier frequency of 2.6 GHz. In this channel modelling, the signal power attenuates or diminish according to distance-based path loss in free space area. The distance d between the BS and the UE. The degree of spectrum sharing depends on the inter-operator interference and variation of loads.

5.1.2 *Simulation Parameter*

Details of the system parameters are given in the Table 5.1 below. The aforementioned and the parameters listed this section were chosen taking into account Third Generation Partnership Program (3GPP) recommendations on [41] [40].

Both operator's operator O_A and O_B 's licensed frequency total bandwidth of 100 MHz is divided into 5 equal component carriers of 10 MHz each with a carrier BW of 10 MHz.

The outdoor deployed small cell BS of each operator can transmit their signal over 5 component carriers of their own licensed spectrum with the available power budget of 37 dBm. During orthogonal sharing, small cell of each operator O_A and O_B can use only three component carriers each to serve with their BS of UEs. For the creation of the common spectral pool, both operators O_A and O_B contribute two component carriers each of small cell in order to provide a total size of a pool four component carriers.

5.2 DYNAMIC SPECTRUM SHARING PERFORMANCE EVALUATION

The results are presented for 400 arbitrary stage game instance, generated according to the above-mentioned parameters. Before examining the actual simulation results, let us first observe allocation of the common pool for suggested specific localized spectrum sharing case. Initially both operators uses their own component carriers orthogonally. That means for their legacy network both operators uses the dedicated primary component carriers exclusively and for the newly de-

Table 5.1: Simulation Parameter [41]

Parameter	Value
Carrier Frequency	2.6 [GHz]
Total Bandwidth/Operator	50 [MHz]
Spectrum Allocation	10 * 10 [MHz] Carrier
Carrier Bandwidth	10 [MHz]
Total component carriers	10
Primary Component Carrier(PCC)	6
Secodary Coponent Carrier (SCC)	4 (Limited Spectrum Pool)
BS transmit power	37 [dBm]
Antenna patterns	Omnidirectional (odBi)
Noise thermal power	-174 [dBm/Hz]
Scenario Model	
Number of Operators	2
Number of BSs	2
Simulation Area	100[m] * 100 [m]
Traffic Model	
Number of UEs/operator	Poisson Distribution Load with mean number of 5 or 25 users
UEs distribution	Uniformly distributed

ployed RAT, they can use their secondary component carrier from the LSP with equal access.

Assume Operator O_A asks a favor over the access area to get an exclusive use of two component carriers from the common pool. At the given stage operator O_B stops using this two component carrier from the pool, means granted favor to operator O_A and vice versa. This is called favor exchange and utilization of the common pool returns to default state after the expiration of favor exchange valid time.

For instance, in order to get the outcome of the game, each operator asking/granting favors from the pool to achieve their maximum utility. To get this expected utility, they can calculate and know their available carriers, their own and exchanged carriers as shown in simple 400 stage game as depicted in Figure 5.2 if both operators propose to share a Component Carrier with this coordination protocol (Spectrum Usage favors). The operators' favors and gains/losses are recorded at the end of the game sequences and fed to the next deployment. . During the sim-

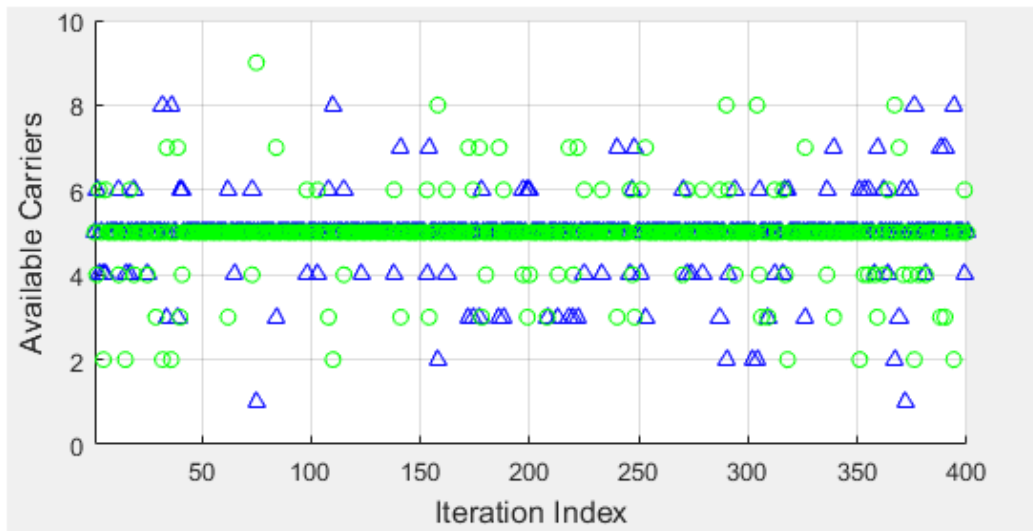


Figure 5.2: The available carriers for each operator after each operator exchange favors in one shot game.

ulation, the number of users follow Poisson distribution with mean load of N_a for Operator O_A and N_B for Operator O_B . We can observe two scenarios where both operators have equal and unequal mean number of users for the given ac-

cess area. For the first considered scenario when the operators have symmetric mean network load, we take a mean number of users for both operators, with $N_a = N_b = 5$.

In another scenario, the simulation carried out with the operators having asymmetric mean number of loads (users) in the shared area, which is $N_a = 5$ and $N_b = 25$ and also vice versa. In spectrum sharing game, as we have discussed in the earlier section of the thesis, each operator can get a spectrum usage favor from lightly loaded operator and improve its performance. On the other hand, less loaded operator declines its user throughput for granting a favor for the opponent operator. This load reversal cases also been considered to assess the performance with varying load conditions in addition to balance the exchanged number of favors between the operators. The effect of temporal load variations shown in the simulations describes also the practicability of the scenarios.

The data rates are experienced by the specific users followed after each deployment and summed over the total number of deployment. The user rates (average throughputs) are plotted for operators O_A and O_B with respective Poisson distributed mean load varying users and with respect to the percentage of the shared spectrum.

5.3 SIMULATION RESULT

Simulation results are presented based on different scenario like the deployment area size, Load variation and percent of shared amount of spectrum or pool and the throughputs obtained in all the spectrum-sharing scenarios, generated according to the above-mentioned parameters. This shared amount of spectrum in percent are plotted for operators O_A and O_B with respective of symmetric and asymmetric mean Poisson distributed loads.

5.3.1 *Symmetric load Cases*

First the results for the considered spectrum sharing schemes are obtained in a situation where the operators have equal mean number loads or users, $N_a = N_b = 15$

in the access geographical area. The exchanged favors during the simulation in 400 stage games or iteration index between this two operators are illustrated in Figure 5.3. In order to get the result depicted in Figure 5.5, the available carrier

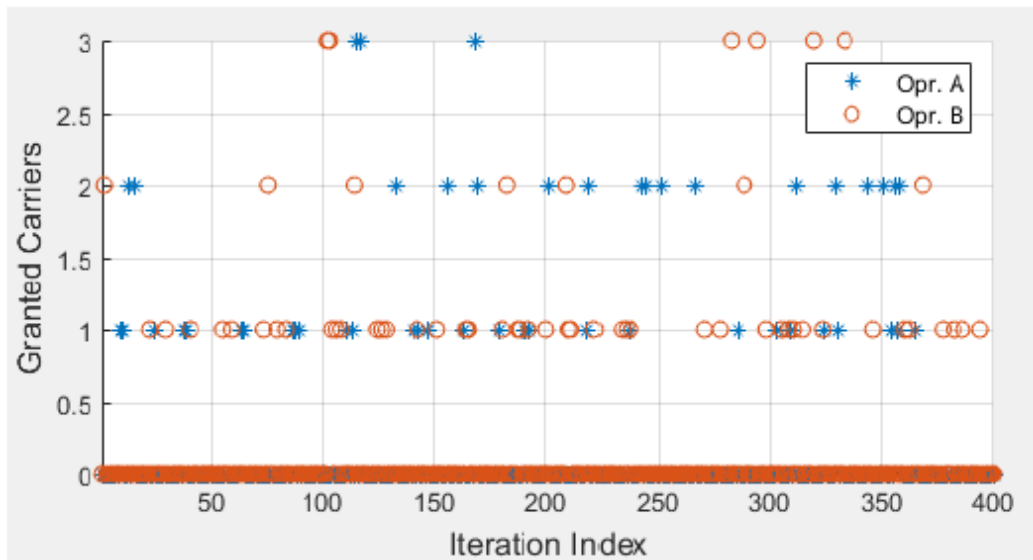


Figure 5.3: Exchanged favors during simulation for Operator O_A and Operator O_B with symmetric mean load case

which we used during 400 stage game simulation in the area for equal mean load is illustrated in Figure 5.4. It indicates that the total number of carrier in every single iteration of the game that each operator has and available with the addition of its own carrier plus the granted carrier from the pool during spectrum sharing. The numerical result of the average throughput gain for both operators O_A and O_B with symmetric loads for the proposed dynamic spectrum sharing game, compared to the orthogonal static allocation shown in Table 5.2 for 60% of shared spectrum.

The result gained with equal mean load scenario shown in the table are not only compared to the allocation schemes of DSA with FSA, but the throughput for the localized or small geographical area (100 [m] * 100 [m]) with (200 [m] * 200 [m]) deployment cases and the former have better throughput gain than higher access area. This means when the serving area increase, the average throughput gain decrease also. Whatever the results in both deployment access geographical area are different due to the size of the coverage, still the performance of the proposed game called DSA outperforms over the existing traditional allocation

Table 5.2: Throughput gain based on Symmetric mean Load for different simulation area size

Sharing Mechanism	Average Throughput [Mbps]	Simulation Area
Operator A		
Fixed Spectrum Allocation	111.2528	100[m]*100[m]
Dynamic Spectrum Allocation	118.5375	
Operator B		
Fixed Spectrum Allocation	113.2582	
Dynamic Spectrum Allocation	120.4095	
Operator A		200[m] *200[m]
Fixed Spectrum Allocation	70.7481	
Dynamic Spectrum Allocation	73.3635	
Operator B		
Fixed Spectrum Allocation	69.8283	
Dynamic Spectrum Allocation	71.3562	

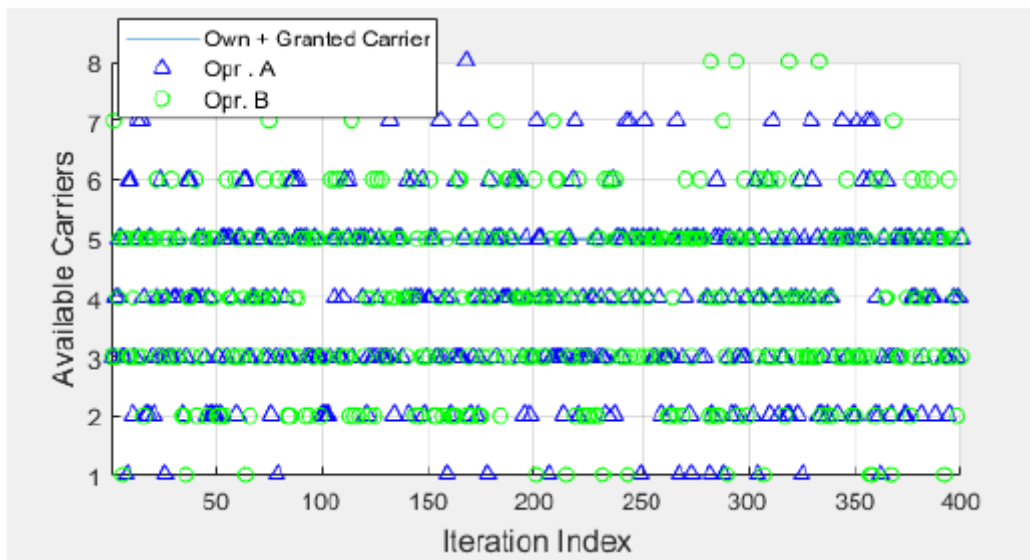


Figure 5.4: The available carriers for each operator after each operator exchange favors with symmetric load between O_A and O_B

schemes called FSA. And also the average throughput gains vary due to based on another factor like the percentage of sharing.

In Figure 5.5, the simulation results for Operator O_A with traditional allocation schemes and the proposed spectrum sharing mechanisms are depicted. Since we are calculated the over all average throughput gain in access area, this gain is more similar to Operator O_B since results for the considered spectrum sharing mechanisms are obtained in a situation where the operators have equal mean number of users. And the simulation results in Figure 5.5 are tabulated with the percentage of shared carriers and average throughput for various fraction of shared carriers for both the considered spectrum sharing scenarios in Table 5.2. The average throughput gain of of symmetric load for spectrum sharing as illustrated in Figure 5.6 is decrease when the size of the deployment area is increase and also the percentage of the shared spectrum increase. So deployed in small area has a better throughput gain. As discussed in the previous chapter the utility function which represents the system's performance level or QoS is strictly non-decreasing (monotonic) and concave function. But as we have seen in Figure 5.5, the gain of average throughput increasing but at some point game reached to its steady state and converges in its initial state.

So in the beginning of game, the values of the gain/loses thresholds are set arbitrarily some amounts for both operators. For instance, for our 400 stage games

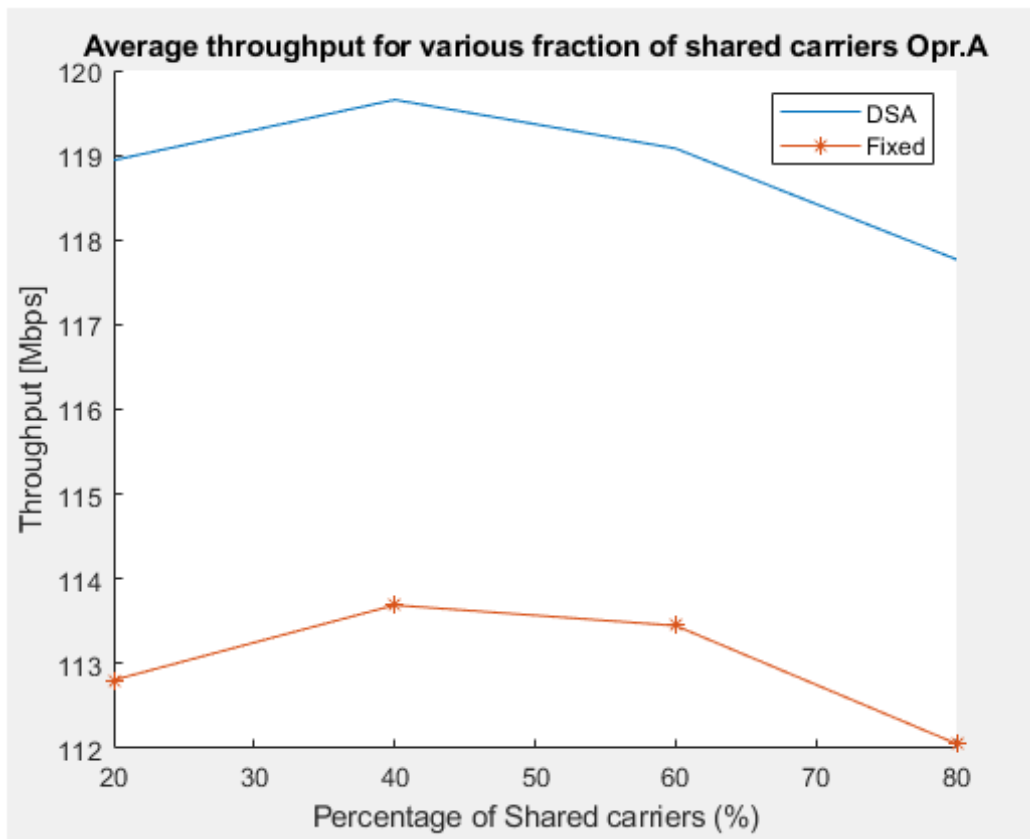


Figure 5.5: Average Throughput Gain of Operator O_A for symmetric mean loads.

or iterations, in every 50 stage games, the operators' probabilities for asking and granting favors are recomputed considering all stage games. Based on this idea, the decision thresholds are updated by solving the optimization problem maximizing the utility function. Unless the strategy profile in the end of the game reached to its steady state (converge), due to full probability as show in the result.

Based on the above all measure and deployment scenarios Figure 5.8 and ?? shows the comparison for the proposed algorithm with a game DSA and the exiting allocation scheme for FSA with average cell throughput for both operators, O_A and O_B with equal mean loads and 40% of the shared spectrum.

5.3.2 Asymmetric Load Cases

Next comes the second simulation scenario for the case when the operators have asymmetric mean number of users over the given shared geographical area. The results obtained for Operator O_A and Operator O_B with mean number of users $N_a = 5$ and $N_b = 25$ for the number of the game stage and vis versa.

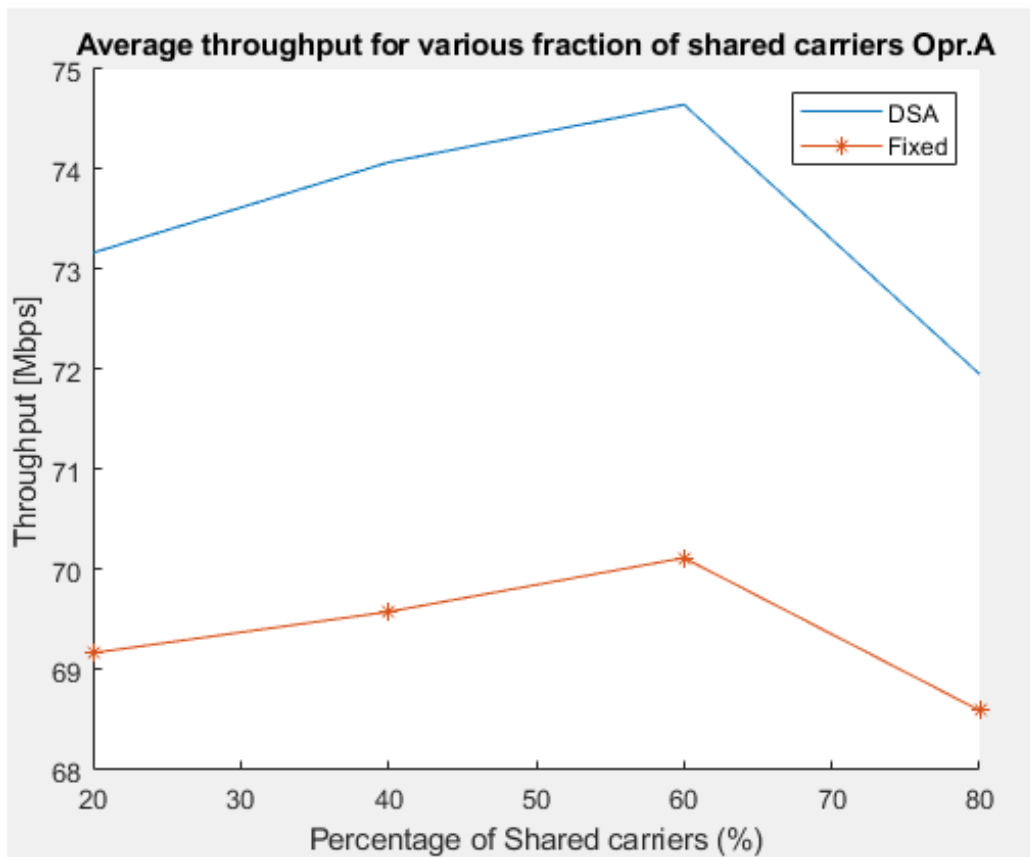


Figure 5.6: Average Throughput Gain of Operator O_A with symmetric mean loads for higher area.

For instance, Figure 5.9 shows the users distribution in the proposed deployed access area for proposed dynamic spectrum sharing schemes, for high load operator O_B and low load operator O_A for a single game stage or a single game iteration. The assumed spectrum sharing repeated game between the operators O_A and O_B are performed in a 400-stage game, where a single stage game represents an exchange of favor in the deployed access area. The DSA algorithm considers the currency in terms favor of the carrier usage based utility function for the repeated games framework. Each operator O_A and O_B should have to pay the price on their carrier's usage which forces them to share the bandwidth resources according to their relative requests.

The maximum number of remaining favors exchanged during each stage game is set according to the percentage of sharing to, starts from $S = 2$ up $S = 4$ as show in Figure 5.10 for simple 400 stage games or iteration Index during simulation with load variations between operators O_A and O_B . The maximum asked/granted carrier with asymmetric loads of operators $N_a = 5$ and $N_b = 25$ in Figure 5.10 is 4,

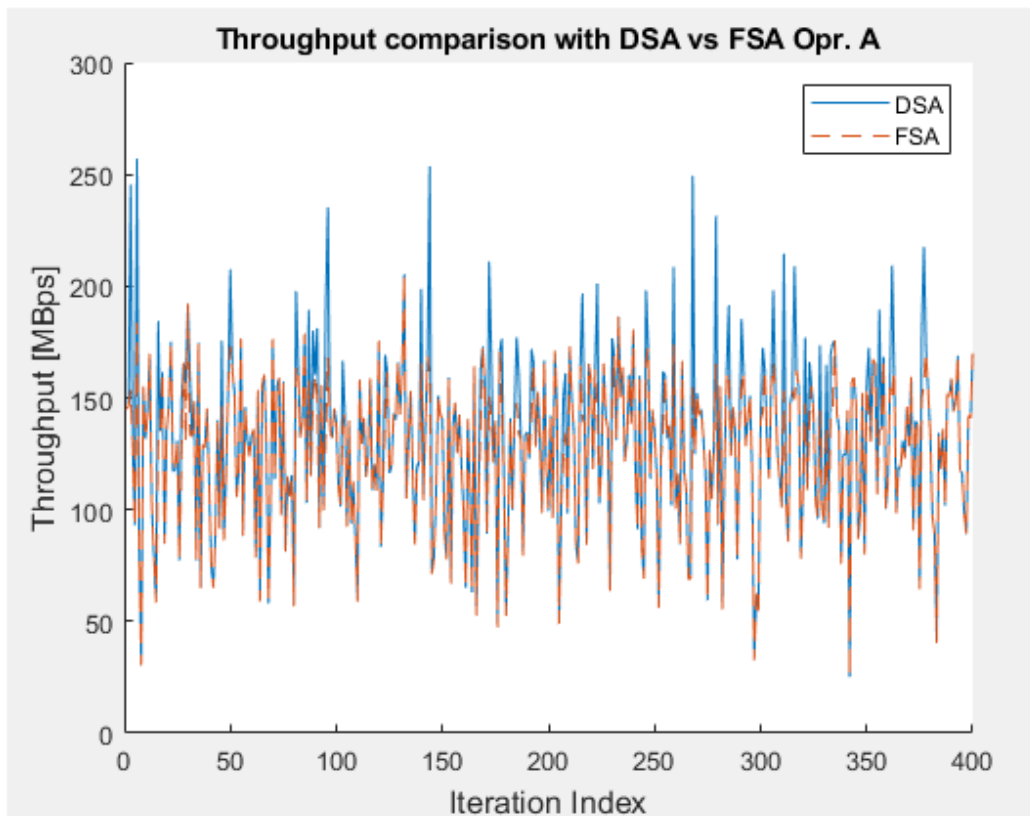


Figure 5.7: Throughput comparison with DSA and FSA for operator O_A with symmetric mean load case

in which the operators agreed to limit. Since Choosing small values can reduce the game, and large values can oppose the game benefiting the particular operators. With a selection of fitting value for the extra limit, the operators are able to uses resources with fairness; simultaneously keeping check on the operators' illegal requests for the unfair gain. And it can also be seen as with dynamic spectrum sharing, high load operator becomes able to increase its throughput in comparison with the orthogonal static allocation and also low load operators as shown in Table 5.3 for 60% shared spectrum. AS shown in this Table 5.3 the high load operator is O_B with mean load $N_b = 25$ and the throughput for DSA and FSA is better than low load operator O_A with a mean load of $N_a = 5$. Not only for that matter, but the throughput for the localized or small geographical area deployment cases have better throughput gain than higher access area. This meas when the serving area increase, the average throughput gain decrease as shown in the Table 5.3. All the average throughput gain results are normalized by dividing the throughput by the maximum theoretical capacity of the system. Hence, a normalized

Table 5.3: Average Throughput based on asymmetric Load of $N_b = 25$ and $N_a = 5$ for different simulation area

Sharing Mechanism	Average Throughput [Mbps]	Simulation Area
Operator A		
Fixed Spectrum Allocation	32.7631	100[m]*100[m]
Dynamic Spectrum Allocation	32.7631	
Operator B		
Fixed Spectrum Allocation	113.2582	
Dynamic Spectrum Allocation	232.0905	
Operator A		200[m] *200[m]
Fixed Spectrum Allocation	25.3946	
Dynamic Spectrum Allocation	25.3946	
Operator B		
Fixed Spectrum Allocation	140.403	
Dynamic Spectrum Allocation	120.0607	

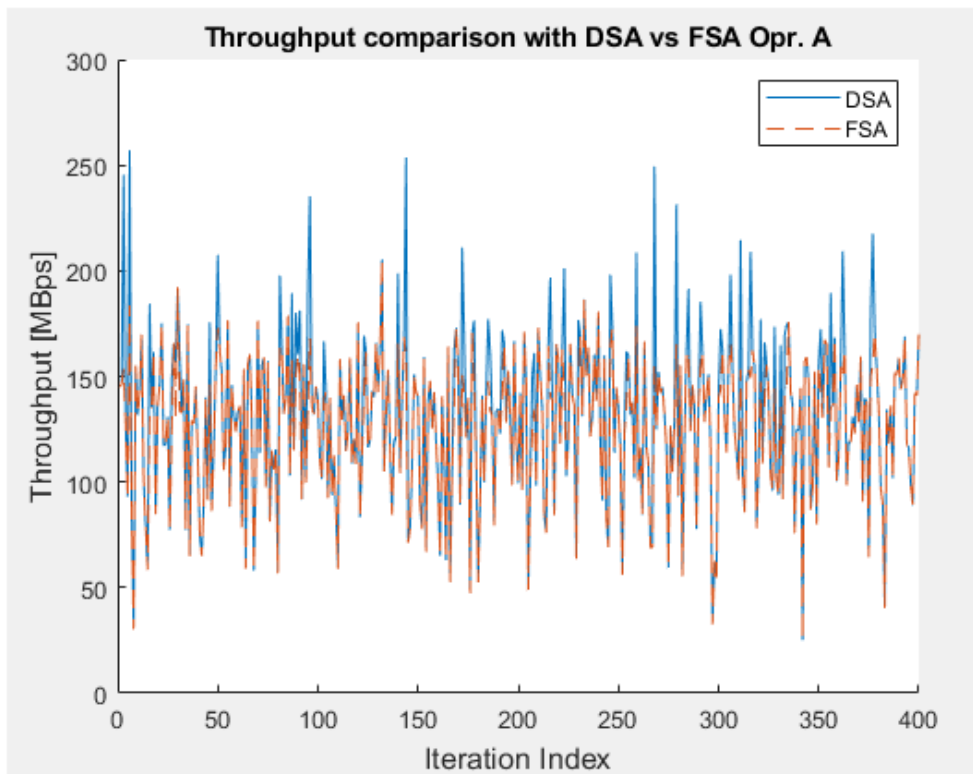


Figure 5.8: Throughput comparison with DSA and FSA for operator O_B with symmetric mean load case

throughput of 100% means that the theoretical capacity is achieved (transmission over the whole bandwidth at the maximum spectral efficiency of the system). Figure 5.11 shows the average throughput of operators O_A and O_B in mean load asymmetric cases. It can be seen that, with dynamic spectrum sharing, high load operator O_B becomes able to improve its delivered throughput in comparison with the orthogonal static allocation or FSA as shown in also Figure 5.12. Here also similarly as discussed in the load symmetric scenario the utility function which represents the system's performance level or QoS is strictly non-decreasing (monotonic) and concave function. But as we have seen in Figure 5.11, the gain of average cell throughput increasing for high load operator O_B , for operators' O_A load is $N_a = 5$ is constant for some stage games. And at some point game reached to its steady state and converges in its initial state. As we have said as for symmetric load scenario in the beginning of game, the values of the gain/loses thresholds are set arbitrarily some amounts for both operators with mean varying load scenario.

The same is true here as we said earlier, for our whole simulation stages, the

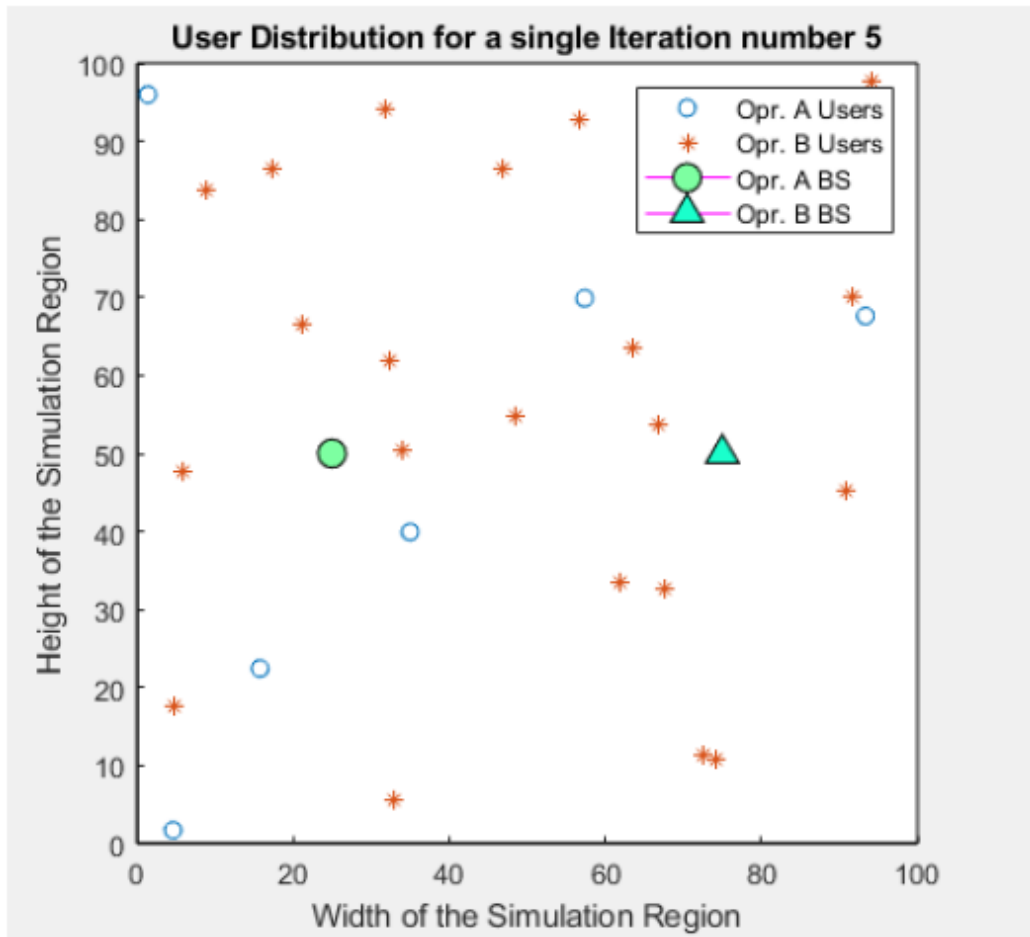


Figure 5.9: User Distribution of Operators O_A and O_B with mean Loads of $N_a = 5$ and $N_b = 25$ in their access are for inter-operator spectrum sharing

operators' probabilities for asking and granting favors are recomputed in every 50 stage games, considering all stage games. Due to this, the decision thresholds are updated by solving the optimization problem maximizing the utility function. Unless the strategy profile in the end of the game reached to its steady state (converge), due to full probability as show in Figure 5.11.

Low load operator average cell throughput will decrease or constant, but operators in this case do not thought of as losing their resources low load conditions if they are do in advance benefits for their difficult conditions in the future since the load gets reversed. The comparison of the proposed DSA and existing allocation schemes for load asymmetric case, which means load of operator $N_b = 25$ and load of operator $N_a = 5$ is depicted in Figure 5.16 which indicates the performance gain in terms of average cell throughput is significant compared to traditional way. If we reverse this load to operator O_A the result is the same to the illustrated one

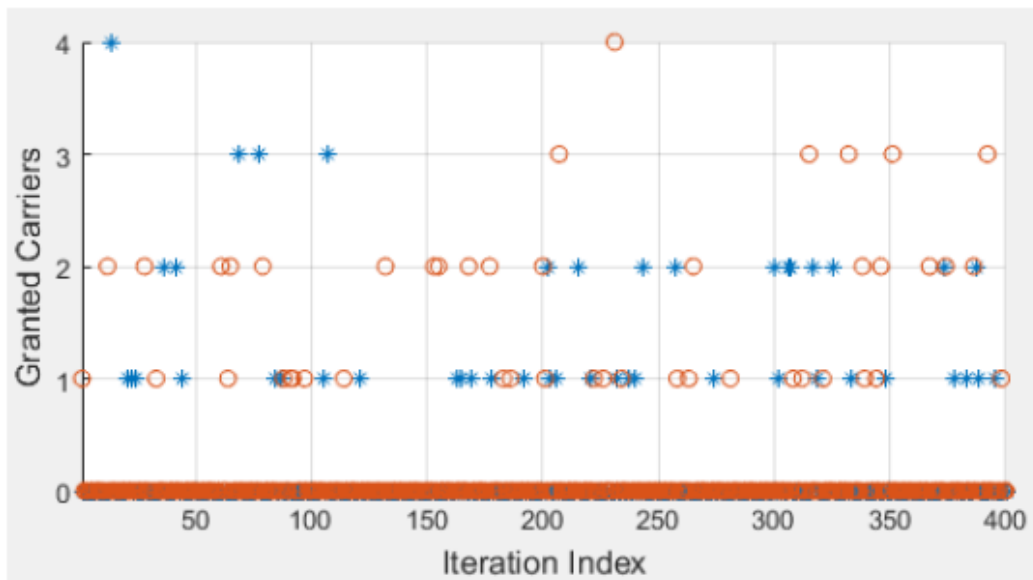


Figure 5.10: Exchanged favors during simulation for Operator O_A and Operator O_B with Asymmetric mean load case

for both operators that is we want to show only for one operator.

The comparison of the average throughput gain for operator O_A and O_B in symmetric and asymmetric load factors is measured for various fraction of shared carriers. The Proportionally fair average cell throughput gain is from 7.69% up 51.89% for 40% of sharing in the proposed DSA obtained for both cases than FSA. The performance for the proposed scheme is better than that of the exclusive one. And also this implies that during spectrum sharing the performance of the high loaded operator outperforms than the low loaded operator, since the low loaded operator grants more spectrum.

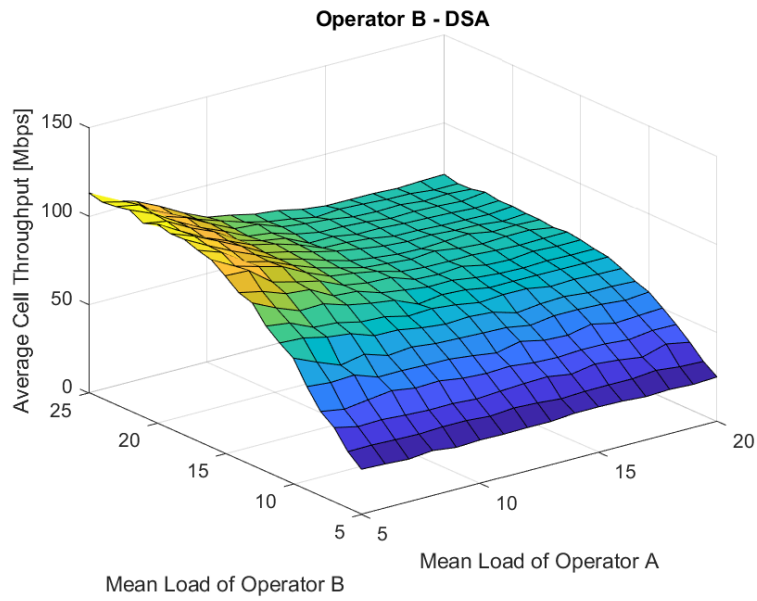


Figure 5.11: Average Throughput gain of Operators O_A and O_B with mean Loads of $N_a = 5$ and $N_b = 25$ based on users distributed in in their access area based on Dynamic Spectrum Allocation

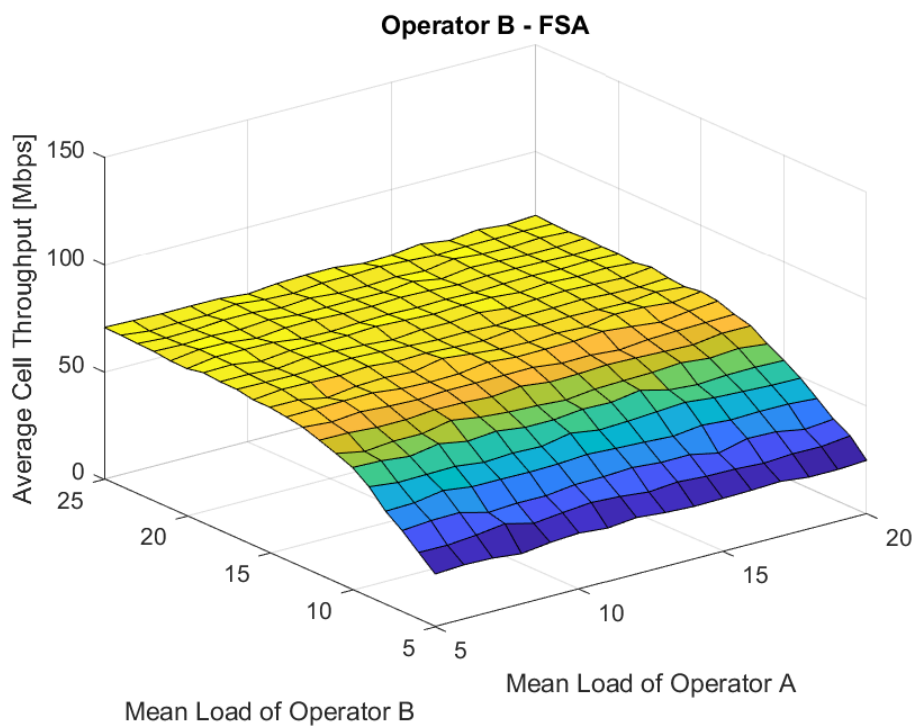


Figure 5.12: Average Throughput gain of Operators O_A and O_B with mean Loads of $N_a = 5$ and $N_b = 25$ based on users distributed in in their access area based on Fixed Spectrum Allocation

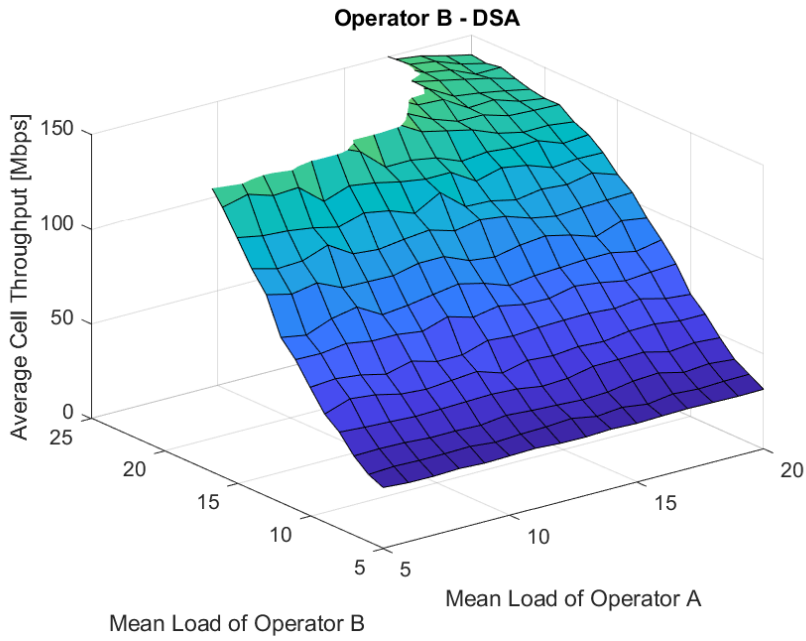


Figure 5.13: Average Throughput gain of Operators O_A and O_B with mean Loads of $N_a = 25$ and $N_b = 5$ based on users distributed in in their access area based on DSA

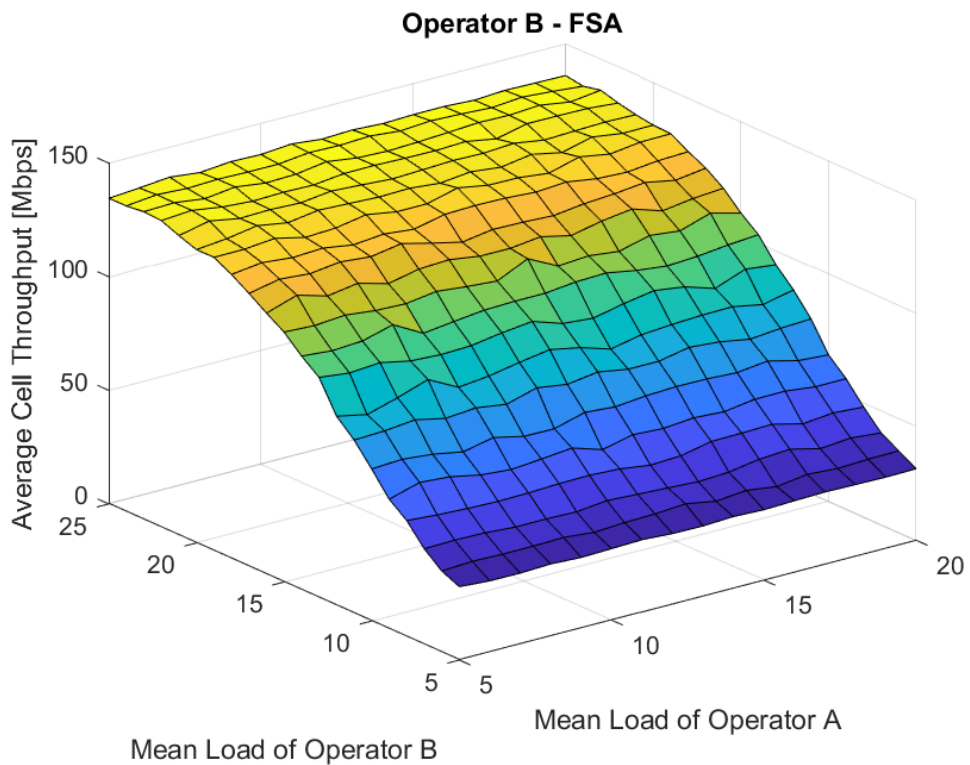


Figure 5.14: Average Throughput gain of Operators O_A and O_B with mean Loads of $N_a = 25$ and $N_b = 5$ based on users distributed in in their access area based on FSA

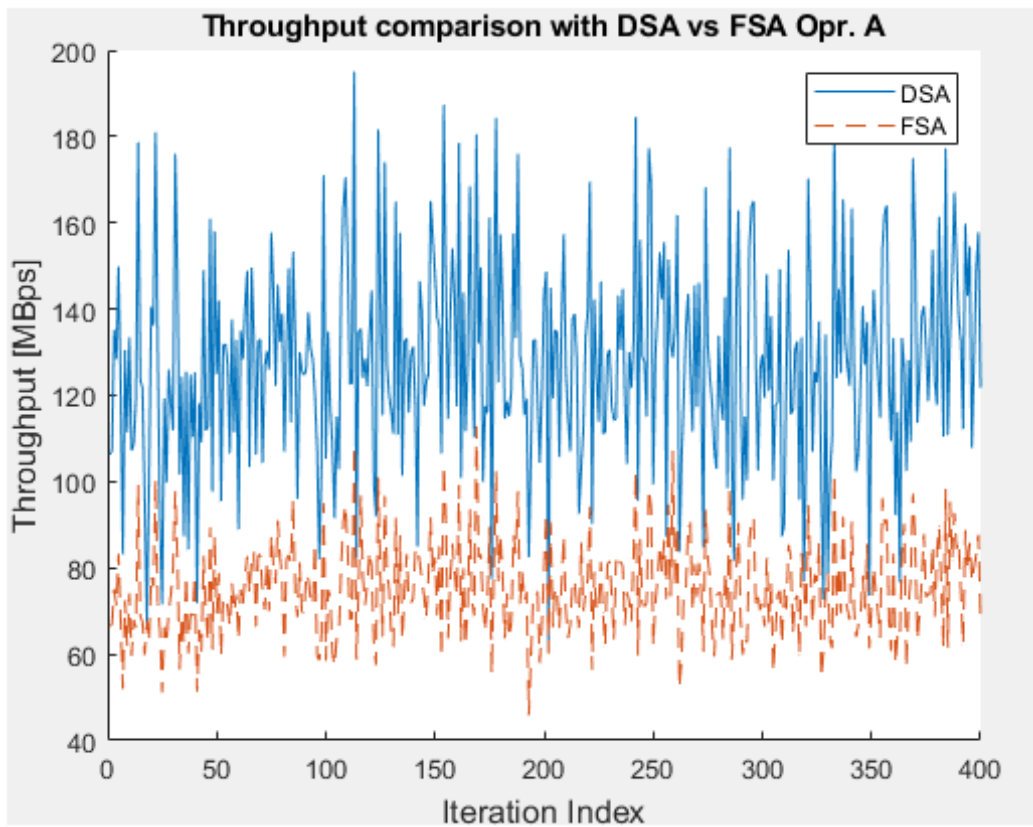


Figure 5.15: Comparison between DSA and FSA for operator O_A with asymmetric loads

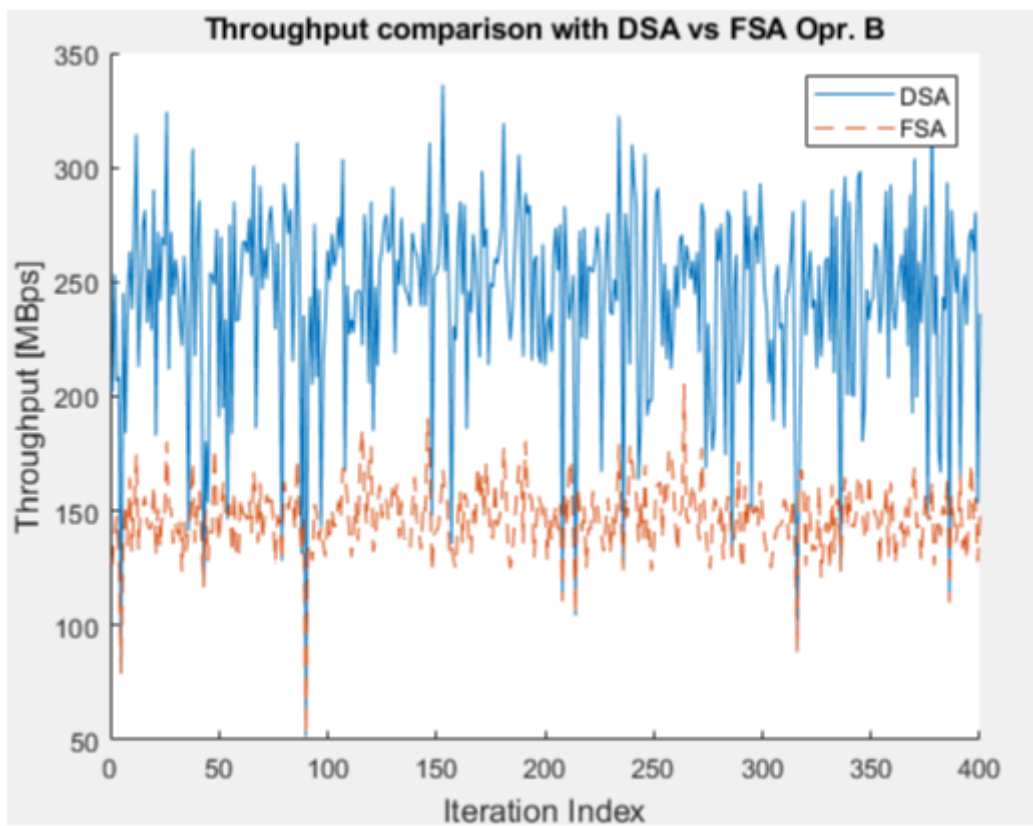


Figure 5.16: Comparison between DSA and FSA for operator O_B with asymmetric loads

CONCLUSION AND FUTURE WORK

This research work give the report for the findings of the main objectives of modeling the problem of spectrum sharing schemes with non-cooperative game theoretic approach to mitigate interference and improve system capacity and QoS. In order to achieve this objectives,define and evaluate different scenarios and parameters where spectrum sharing is considered in the context of two operator's operating in the same geographical area with the same frequency bands. We discuss in this chapters the finding of the research works.

6.1 CONCLUSION

Due to the low traffic demand and the command and control regulation, most mobile network operators following the exclusive allocation policy to the radio spectrum. This allocation schemes are static, inefficient and not flexible to deploy new technologies. So spectrum sharing is emerged to overcome the inflexibility of this traditional schemes. Spectrum sharing is using the available spectrum simultaneously between operators operating in the same geographic area with the same frequency bands. But if the operators fail to cooperate in the radio frequency planning the inter-operator interference is the main problem that affects the performance of the networks adversely.

An example of CBI which motivates for this research work is in the eastern border of Ethiopia, where networks of ethio telecom in border town of Togochale get impacted by emissions across the border from telecoms operators of So-Telesom, SOM60 and SOMTEL in Somali-Land and mitigated traditionally. So we need to explore another techniques that the operators can share the available spectrum dynamically. Dynamic spectrum allocation is a technique with the best capability which each operator can share the available spectrum according to their needs

from the limited spectrum pool.

We have investigated the power of game theory for spectrum sharing problem between competitive, selfish but with the self-interested behavior of two mobile network operators. The problem is modelled via game theoretic approach for an efficient DSA. It is based on spectrum pool in addition with privately owned orthogonal frequency bands which is allocated for both is called FSA, the shared part called DSA. In the later cases the operators operate simultaneously for the scarce resources from a common spectrum pool and there is an interference if no coordination. It is based on a coordination protocol of tit-tat-strategy for exchanging favors during equal load and variation loads in order to use efficiently the available carrier and in order to mitigate interference.

For the purpose of performance analysis, a scenario has been considered, comprising of two operators with their neighboring RANs in small area. Each operator has one BS, and the BSs are geographically separated by small distance. The operator's loads are Poisson distributed, but their locations are uniformly distributed within their access area. There are total 10 available carriers which is divided in to exclusively called FSA and DSA. The secondary component Carriers or pool have 4 carriers in common as a base line and the remaining's are allocated equally and exclusively. The performance of the specific techniques is strongly dependent on several system parameters, and the rational outlook of the operators. The operators opportunistically share carrier and maximize their average-throughput non-cooperatively with an energy to converge the ideal cooperative solutions.

Our numerical results show that appropriately modeled games provides a significant gain in terms of system-level mean throughput, when compared with traditional or exclusive allocation scenarios over the time. The comparison of the average throughput gain for operator O_A and O_B in symmetric and asymmetric load factors is measured for various fraction of shared carriers. The Proportionally fair average cell throughput gain for example for 40% of spectrum sharing is from 7.69% up 51.89% in the proposed DSA obtained for both cases than that of FSA. In this thesis, the simulation results shows, the performance of the proposed

algorithms achieving dynamic spectrum sharing overtakes the traditional exclusive allocation schemes under variable load factors. More importantly, the gains are significant when the number of users or mean loads is relatively large by an operator.

6.2 FUTURE WORK

Based on what we have done in our research work, there are possible directions we recommend for future work since we didn't expect this work as it is complete.

1. In this thesis simulations, we have been considered only two operators each have one BS, have been considered for simplicity. Increasing the number of operators participating in the spectrum sharing game is one possible direction for future work. It can lead to interesting findings in terms of interference management.
2. In thesis simulation, we considered the deployment scenario for suburban in Sparsely populated scenario which participates a small number of users with small area. But possible to model and consider the game for densely populated are in single story buildings deployed a femtocell. It could provide more interesting results, if more challenging environment is taken, e.g., walls inside the buildings.

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