Location-specific Spectrum Sharing in Heterogeneous Networks

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ABSTRACT OF THE
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The popularity of wireless mobile communication with enormous production of smart devices and applications increases the number of users in the wireless network. This increase of mobile users in the wireless network results insatiable demand for additional bandwidth. To improve network capacity of mobile operators efficient use of spectrum is critical. To improve the system capacity of operators and to provide flexible use of spectrum, we investigate a localized spectrum sharing between operators located at the same geographical area.

We provide a coordination mechanism for operators to form a common spectrum pool and to use it dynamically. The coordination between the operators is modeled using a game theoretical approach in a non-cooperative basis. We study the spectrum sharing at localized and non-localized level, where at localized level operators agree on spectrum sharing at small scale. In localized spectrum sharing operators share their spectrum at smaller areas, when compared to non-localized spectrum sharing.

Through numerical simulation, we analyze the performance of localized and non-localized spectrum sharing in comparison to the default orthogonal spectrum sharing mechanism. From the simulation results, we conclude that localized spectrum sharing outperforms non-localized spectrum sharing. Thus, spectrum sharing at smaller areas provides a better performance improvement than spectrum sharing at larger geographical areas.

Keywords: Spectrum sharing, co-primary, repeated game, DSA, HetNet

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Otaniemi, 15.11.2017

Sewda Biza

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Abbreviations

3GPP 3rd Generation Partnership Program. vi, 8

BS Base Station. vi

CC Component Carrier. vi, 17, 23, 27, 28, 34

CoMP Coordinated Multipoint. vi, 13

CSG Closed Subscriber Group. vi, 8

CSI Channel State Information. vi, 22

DSA Dynamic Spectrum Access. vi, 47

FAP Femto Access Point. vi, 23, 27

GSM Global System For Mobile Communication. vi, 1

HetNet Heterogeneous Networks. vi, 5, 6, 10, 32

ICIC Inter-cell interference coordination. vi, 13

LSA LicenseShared Access. vi, 15

LSP Limited Spectrum Pooling. vi, 16

LTE Long Term Evolution. vi, 1

MNO Mobile Network Operators. vi, 3, 23, 32, 47

MR Mutual Renting. vi, 16

NRA National Regulatory Authority. vi, 16

NTIA National Telecommunication and Information Administration. vi, 2

QoS Quality of Sevrice. vi, 3, 15, 17

SINR Signal to Interference plus Noise Ratio. vi, 27

UE User Equipment. vi

VoIP Voice Over Internet Protocol. vi, 1

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1 Introduction

1.1 Motivation

In the history of mobile communication, the first-generation mobile network appeared in the 1980s, GSM followed in the 1990s, 10 years later 3G arrived, LTE the 4th generation joined the industry in around 2010 and then 5G is on the way. Every ten years the mobile network technology shows an advancement, diffusing around the world rapidly. Following the evolution, wireless mobile communication has become widespread and an essential part of our day-to-day life. The invention of massive wireless devices, smart phones, tablets, and applications facilitates to enormous mobile network users to join the wireless mobile network communication. By 2021, it is expected that the number of internet-connected devices will be three times as high as the global population [9].

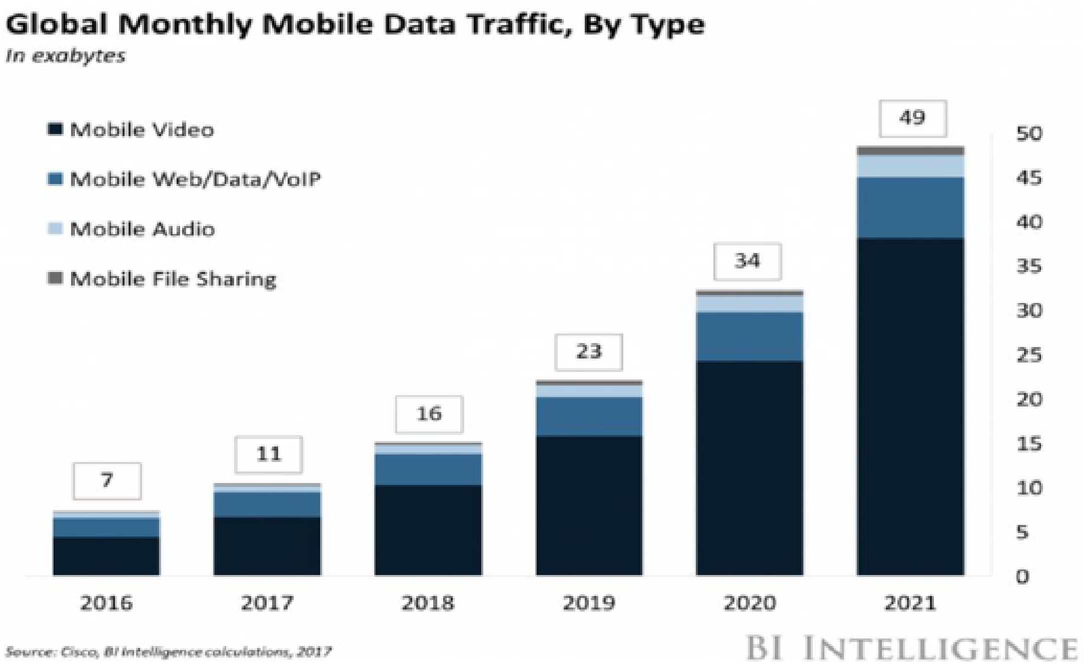


Figure 1: Global Monthly Traffic Forecast 2016-2021 [1]

According to the 2016 Cisco Mobile Visual Networking Index forecast [1], mobile data traffic will grow sevenfold from 2016 to 2021. The forecast estimates that the mobile data that accounted for 8% of internet traffic in 2016, will account for 20% by end of 2021. As shown in Figure 1, it is mobile video data that shows the highest growth reaching 38 exabytes per month followed by mobile web/Data/VoIP. The given forecast indicates that at the end of year 2021, the mobile video will account for 78% of mobile data traffic. This is due to the accelerated increment in the number of mobile users.

The exponential growth of wireless devices and wireless based applications increases the mobile data traffic globally. The bandwidth requirement for this huge data traffic in the network usually exceeds the available network capacity. To improve the end-user experience, it has become a necessity to extend the available network capacity. Thus, the explosive growth in data traffic is fueling the demand for more spectrum capacity daily. However, spectrum is a finite and nonrenewable scarce resource. Even though service providers are investing to remain competitive in the market of wireless mobile communication, it is very costly to get a license for new band of spectrum.

A most recent NTIA's report on frequency allocations in the United States, shows that within the current spectrum regulatory framework there is a huge scarcity of unallocated spectrum [10]. The chart given in Figure 2 shows the frequency allocation in the United States in September 2015. Traditionally, a portion of spectrum is statically assigned to a specific service or mobile operator to use it exclusively for a long time, which is called *Fixed Spectrum Allocation (FSA)*. In FSA, mobile operators typically own certain bands of spectrum dedicated to their own users. One can observe from the figure that there are huge blocks of spectrum dedicated to broadcasting and a lot of frequency ranges assignment relied on FSA policy.

This static allocation of the spectrum has limited flexibility of the spectrum usage and degraded spectral efficiency. Consequently, many researches and recent measurements indicate that there are part of assigned licensed spectrum left unused or underutilized for most of the time [11, 12]. In addition to the shortage of unallocated spectrum, inefficient spectrum utilization is the main reason for the current spectrum scarcity. This is due to the fact that lack of flexibility in the statically assigned spectrum bands results in low spectral efficiency. Spectrum allocation is one of the key issues to improve spectrum efficiency and has become the hot topic in the research of cognitive wireless network.

For decades, the FSA has been working well but nowadays the imbalance between available resource and demand growth has become a huge problem. It might be possible that at a certain time or place, the allocated spectrum for a system is unutilized, while at the same time there may be a heavily loaded system demanding for more bandwidth. In [13], it has been shown that causes a huge waste of resources. This ineffective utilization of the resource demands a better approach to get the best out of the available licensed spectrum. Spectrum sharing and heterogenous networks are two of the most promising solution to address the spectrum scarcity.

Spectrum sharing refers to the common use a specific range of spectrum simultaneously by multiple wireless system entities located at the same geographical area. Sharing of a spectrum allows operators or spectrum license holders to give access to their unused spectrum for other users under some agreed conditions [6]. This sharing strategy enables dynamic management of spectrum and maximizes spectrum utilization efficiency.

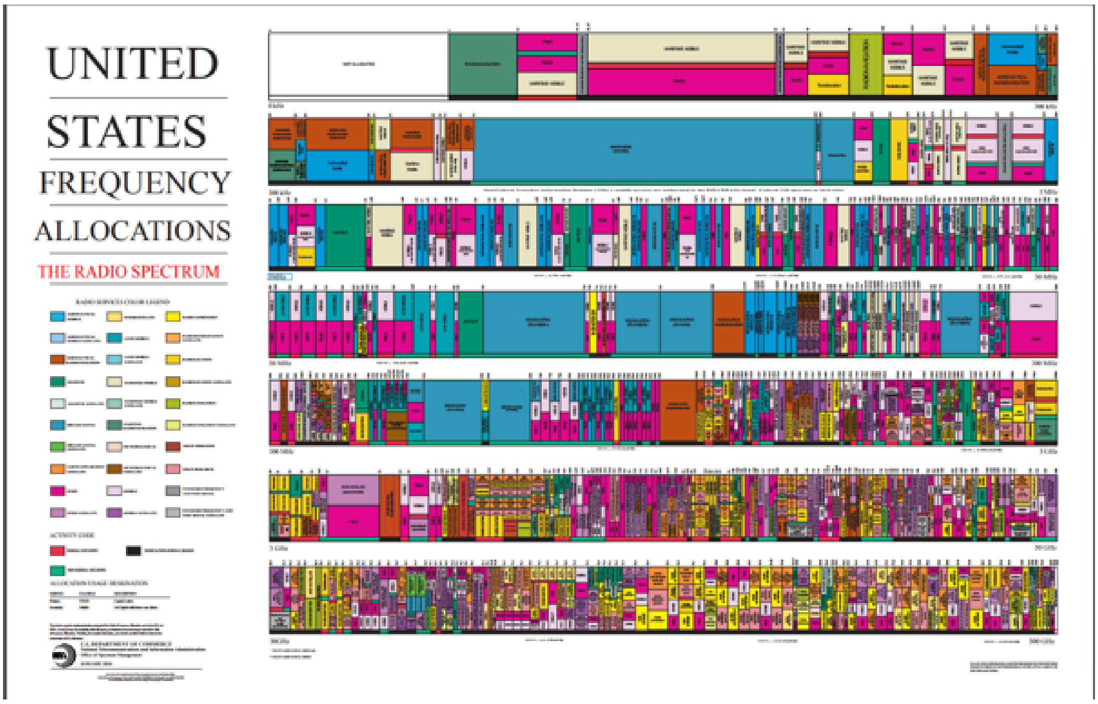


Figure 2: United States Frequency Allocation Chart [2]

Heterogeneous network (HetNet) is a network that comprises different types of cells with different downlink transmit powers and overlapping coverage areas. HetNet refers to the *densification* of small cells in the existing macro cell network. The instalment of these low power and less radius small cell base station in the network improves the network coverage. The spectrum sharing between the macro cell and the small cells in the network provides additional network capacity without need for extra bandwidth. Therefore, applying spectrum sharing in heterogeneous network environments brings solution for spectrum scarcity and utilization efficiency problem.

1.2 Objective of the Thesis

The problem of spectrum sharing between multiple operators located in the same geographical area is studied in this thesis. In small cell areas, especially indoors *e.g.* office, restaurant, shopping mall, and school, frequent variation of traffic is common. With dynamic spectrum sharing operators can improve their capacity as well as QoS delivered to end users. However, in a situation where operators operate in the same geographic area they will experience inter-operator interference on the shared spectrum. To minimize the risk of inter operator interference we propose a localized spectrum sharing mechanism to regulate the sharing of resources between MNOs.

We use game theory to coordinate the interaction between the operators. Game theory provides a mathematical framework to analyze interaction between independent decision-makers [14]. The interaction between the operators is assumed to be non-cooperative, *i.e*, operators act independently, because operators are competitive by nature and are not interested to share operator specific information.

In this thesis, localized and non-localized spectrum sharing mechanisms are studied among HetNet mobile operators that coexist in the same geographical area.

The main objective of this thesis is to investigate spectrum sharing in various geographical settings. The thesis aims to find out whether or not the spectrum sharing at small scale results in a better performance improvement than large scale spectrum sharing. The small-scale spectrum sharing defines the spectrum sharing at smaller areas which are summed up to form the large common geographic area which defines the large-scale spectrum sharing. The thesis aims to show to what extent small scale spectrum sharing makes a difference. To achieve the thesis objectives, we perform numerical simulation and observe the performance of the different spectrum sharing scenarios.

1.3 Thesis Outline

This thesis is organized into six chapters. Theoretical backgrounds related to this thesis is presented in Chapter 2 and Chapter 3.

Chapter 2 introduces the fundamental concepts in heterogeneous networks. The architecture and type of cells in heterogeneous networks are presented. This chapter covers also the advantage and challenges. Chapter 3 presents a brief introduction to the basic principles of a spectrum sharing and the game theory used for spectrum sharing.

In Chapter 4, the location-based spectrum sharing mechanism is introduced and explained in detail. The system model for the localized and non-localized spectrum sharing mechanism is presented in Chapter 4.

Chapter 5 focused on the simulation environment and the achieved results are discussed comparing to the static spectrum allocation scheme.

Chapter 6 concludes this work and envisions future work directions.

2 Heterogeneous Networks

2.1 Introduction

As the future forecasts, the number of networked devices and connection in the world will reach 24 billion by 2019 [15]. According to research and industry forecasts, the demand for cellular broadband data is increasing as the number of internet users and massive connected devices.

Ericsson envisions that there will be 50 billion connected devices by 2020 [16]. Users replace their home desktop with smartphones and tablets to make video calls, download videos, and transfer data and so on. These applications served by service providers consume more bandwidth than before. At the same time, users demand a high capacity, reliable and fast service with affordable price from their service provider regardless of their location and application they are using. 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. Over the past few years, network densification works as a solution. 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 Heterogeneous Network (HetNet) has emerge due to mobile operators necessity to get the ability to operate in networks which contain various radio access technologies in combiation with different types of cells with different sizes and formats operating seamlessly [17]. HetNet combines different radio technologies, base station types and transmission power levels to meet the growing demand of data capacity and improve network coverage. Presently more than 80% of mobile traffic originates from indoor users [18] and customers expect to receive a better network coverage irrespective of their location. Thus, with the deployment of indoor and outdoor small cells HetNet plays a significant role to achieve a better subscriber and user experience especially for indoor and cell edge users. Installing femtocell access points in residential buildings allows to improve indoor users experience. At hot spot and rural areas Micro base stations deployed to fill coverage holes and provide capacity demands. Pico base stations usually deployed at cell edge to deliver high quality services to cell edge users.

In HetNet architecture, several base stations of different sizes and transmission power level such as Macro cells and small cells, deployed throughout the whole network. Typical deployment of HetNet can be depicted in Figure 3.

Small Cells

Small cell is an umbrella term for low power wireless access points. In HetNet Small cells are a vital component, which provides efficient and cost-effective solution for load balancing by offloading the macro cellular traffic. Small cell enhances cellular

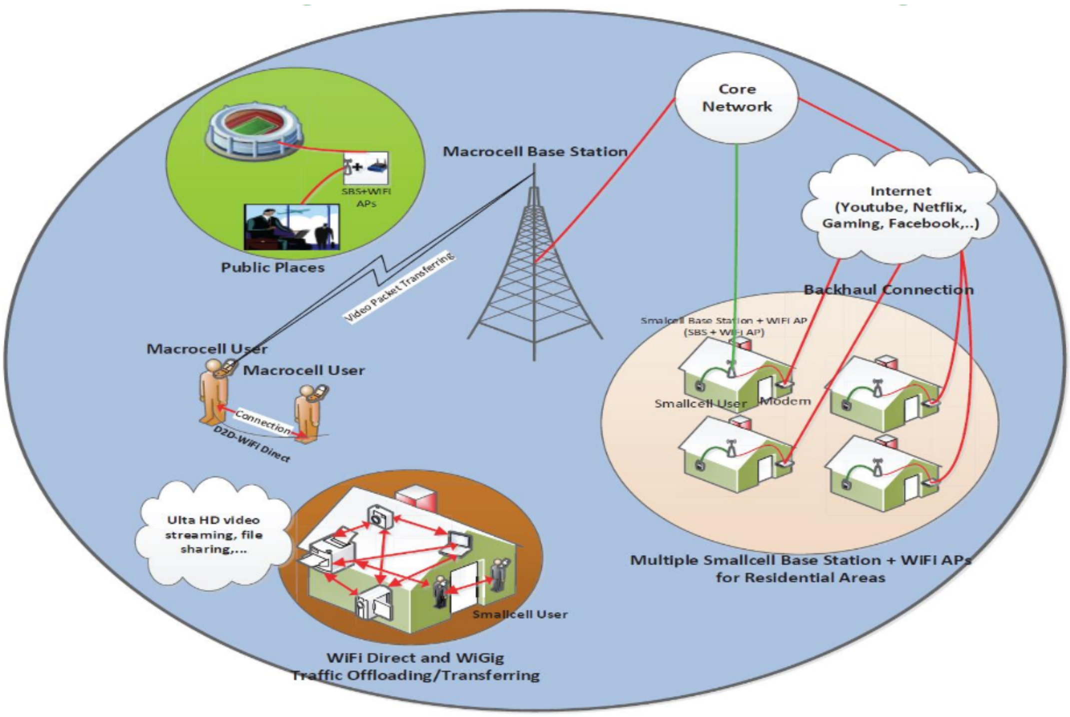


Figure 3: Heterogeneous Network [3]

capacity and network coverage for home users, small medium enterprises, and rural public places. Small cells are served by types of base station or node, which comes in variety of coverage ranges, transmit power and size different, decreasing order from microcell base station to Femtocell access point.

The integration of small cells with macro cell in a network brings an enhancement in overall system performance. For service providers, HetNet deployment is of special interest with the aim of guaranteeing high quality and improve network capacity for high data rate services to increasing numbers of users. Comparing with a homogeneous macro cellular network, a small cell-based heterogeneous networks is much more energy efficient and cost effective. In high macro cells, the power amplifier, which requires a fixed DC power supply, and a cooling unit consume more energy. However, the low power characteristics of small cells reduces this impact.

2.2 Heterogeneous Network Nodes

Macro Base Stations

Macro base stations are large cells providing the whole network coverage with powerful Macro base stations deployed by an operator. Macrocell is the backbone in the HetNet solution and provides a large coverage. Transmit power levels of macro base stations typically varies between 5 W and 100 W [3].

Micro Base Stations

Micro base stations are categorized under small cell base stations and gives coverage to the micro cell with lower transmit power than macro base stations over the backhaul. Micro base stations are regular base stations that are usually installed outdoors to fill macro coverage gaps in dense spot areas such as train stations. Microcells configured to operate in open access modes in which every subscriber can associate to the base stations.

Pico Base Stations

Pico base station is typically used in indoor public areas and offer good capacity in the range of tens of meters. It is difficult to distinguish Pico base stations, serving picocells, precisely with micro base stations but they are of smaller sizes and lower transmit power.

Femtocell Access Points

Femtocell access points are a small, low power access points designed to give coverage of about 10-20 meters. Users perform the deployment and configuration of FAPs at their own premises. Connectivity of femtocell access points with a core network is through consumer's own broadband connection (DSL or cable), which makes deployment of femtocells simple. They offer a better broadband service for residential users, small enterprises and good indoor network coverage. The deployment of femtocell access points allows service providers and operators to alleviate indoor mobile user problems and provide strengthened cellular signals. Hence, femtocells play a significant role for indoor and cell-edge users data capacity improvement and offloading macro cell.

2.3 Access modes

The use of access control mechanism in a cellular network supports various features of small cells including interference management, flexible deployment, mobility support and so on. It allows UEs to distinguish between femtocell and macro cell which reduces battery consumption due to cell search. Small cells can be configured with different access control methods.

There are three types of access control mechanisms where a base station or FAP can be configured to [19]:

- **closed access mode**
- **open access mode**
- **hybrid access mode**

Table 1: Types of base stations/ access points in Heterogeneous Networks [3].

Type	Typical deployments	power level(Indoor)	Power level(Outdoor)	# of Users	Cell Range
Macro	*Urban areas, Rural areas*	-	20-100 W	200-1000 users	1Km to 100 Kms
Micro	*Urban areas*	-	5-10 W	100 - 200 users	Few hundreds of meters
Metro	*Urban areas*	-	10-20 W	100 - 200 users	Hundreds of meters
Pico	*Public areas Indoors/Outdoor*	100-250 mW	1-5 W	32-100 users	Tens of meters
Femto	*Residential, enterprise environments*	10-100 mW	0.2-1 W	Residential Femto:4-8 users Enterprise Femto: 4-16 users	Tens of meters
WiFi	*Residential, enterprise environments*	20-100 mW	0.2-1 W	<50 users	Few tens of meters

Closed access mode

In closed access mode only closed subscriber group (CSG) subscribers can get a privileged access to the cell. A closed access configured cell also referred to as a CSG cell. A closed access cell denies access to a UE which is not under its CSG list. The concept of closed access subscriber group (CSG) defined in release 8 of 3GPP[20]. As an example, office and residential building small cells usually configured to closed access modes. Thus, the small cell allows CSG access to the residents, their guests and employees. Residential FAPS mainly operates on a closed subscriber group CSG.

Open access mode

An open access cell gives an access to all UEs equally. Open access cells are deployed by a service provider to fill coverage holes. This type of access methods can be applied for public areas like malls, airports, restaurants, etc. Femtocells configured to open access mode to offload microcells and macrocells. Open access femtocell improves network capacity but the negative issue is that it may lead to certain security risks.

Hybrid access mode

A hybrid access cell provides access to all UEs that either belong to CSG or not. A hybrid cell appears as a CSG cell for UEs under the CSG list and as a normal cell for other users. A hybrid access femtocell allows access to both roamers and home subscribers.

Figure 4 depicts a femtocells emplying with the three access control modes at different locations.

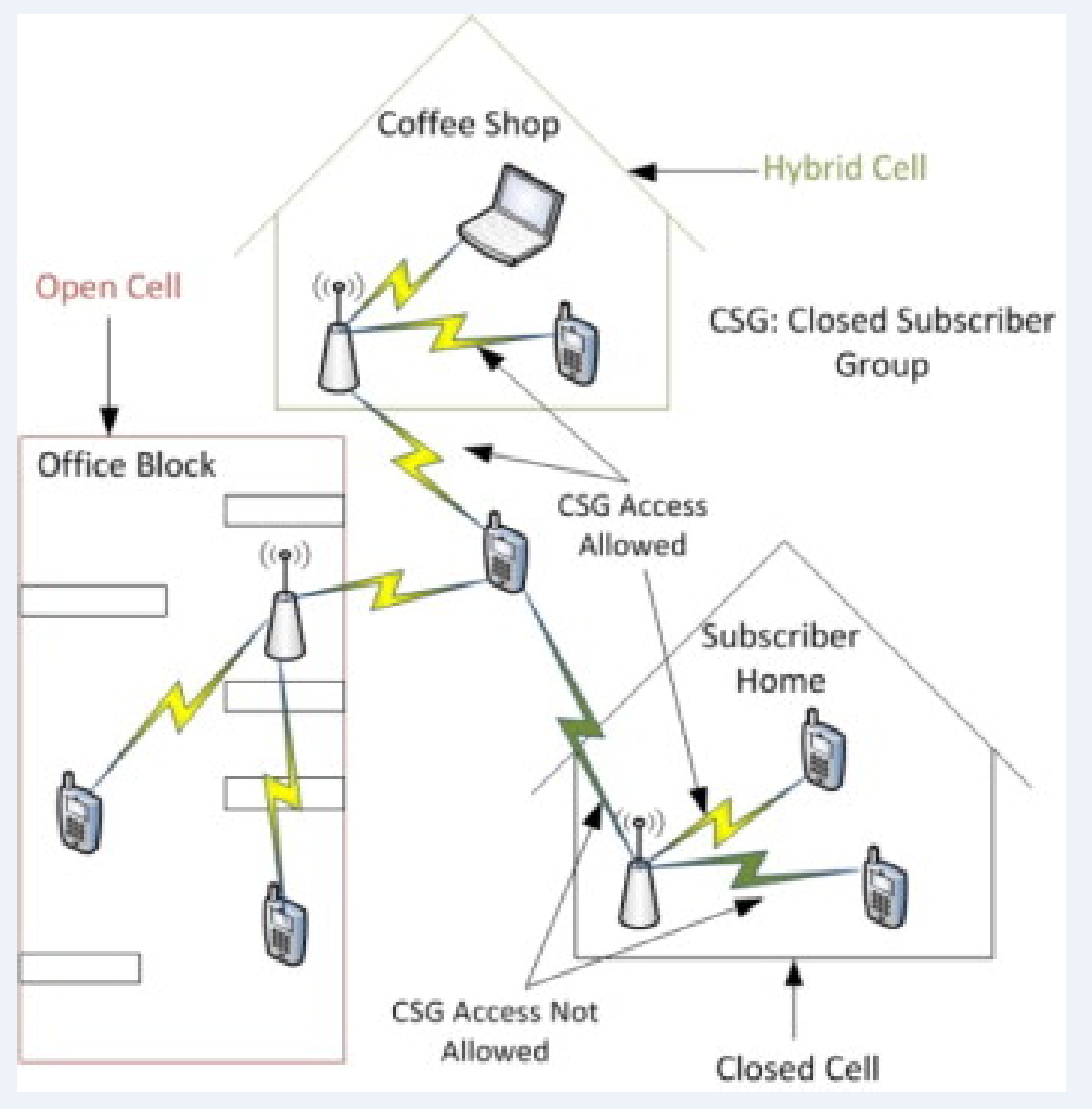


Figure 4: Femtocell access control modes[4]

2.4 Challenges of HetNets

The integration of small cells with macro cells creating a HetNet has a substantial benefit over the homogeneous network. Some of the benefits are mentioned below:

- Small cells assist and offload macro cells data traffic and minimize macro cell coverage holes.
- Enhances link quality by providing short transmitter-receiver distance.
- HetNet increases network coverage for hot spot and rural areas.
- Low power small nodes allows operators to minimize their power consumption.
- Improves spectral efficiency by using less coverage small cells, and so on.

Nonetheless, mass deployment of small cells introduces certain technical challenges that needs to be solved properly to maximize the benefits of HetNet. Backhaul, Mobility management, and interference are the main technical challenges that will be discussed in the following:

2.4.1 Backhaul

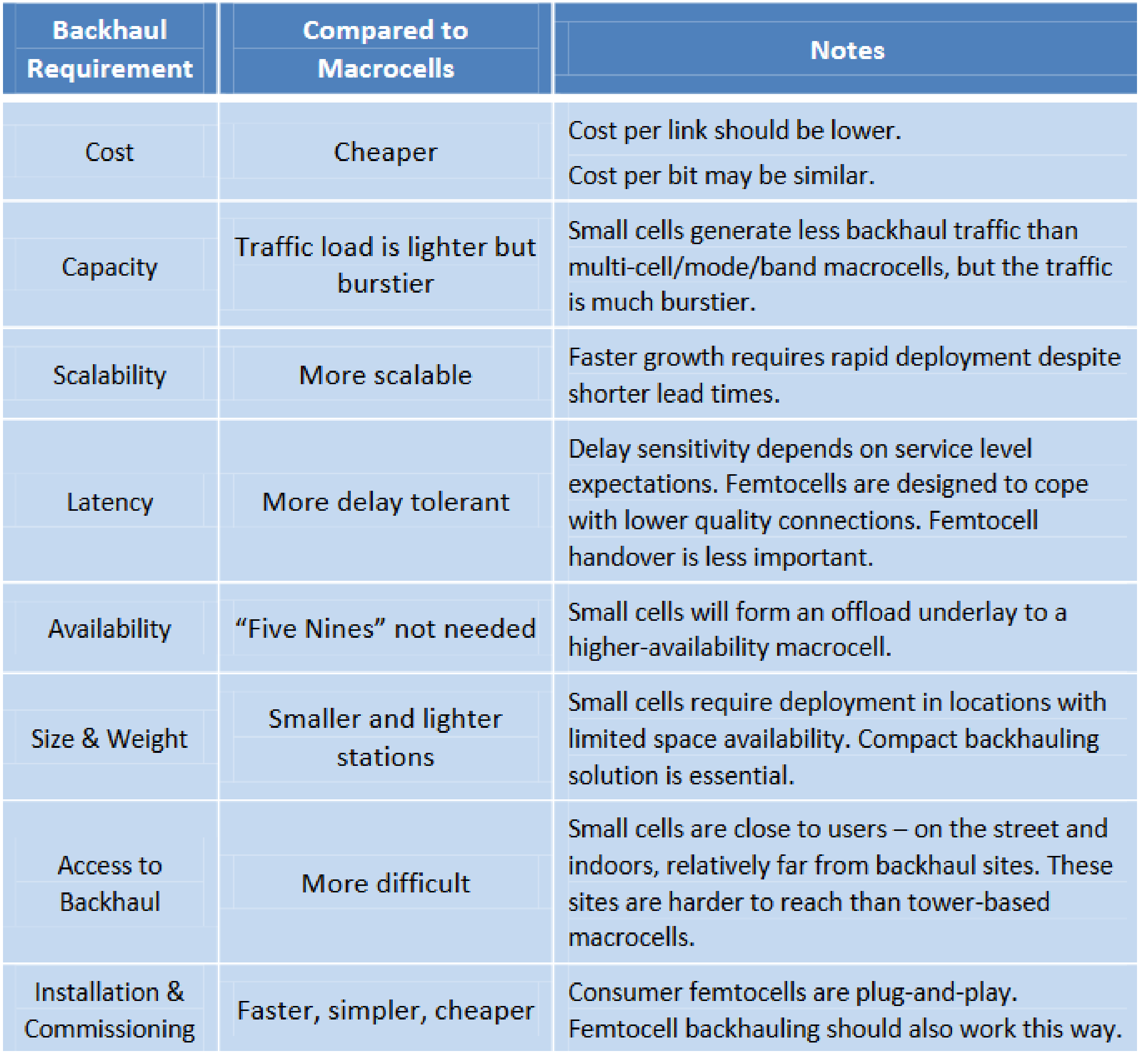
Small cells backhaul is a connectivity link between the small cells and the MNO's core network. Backhaul provides connectivity to the core network and other network. In case of Femtocells, it provides connectivity to the macro cell through the core network. Comparing to macro cell backhaul, small cell backhaul becomes more challenging for mobile operators. table1 provides a brief summary of small cell backhaul requirements.

There are some ways to provide small cells connectivity to the core network, including wireless backhaul, using DSL, or fiber [21]. However, each of these methods have advantages as well as drawbacks. In residential and small enterprise femtocells, the backhaul connectivity is through the DSL/copper cable but this provides limited data rates to end users. Another option is the use of fiber, which provides the highest throughput and operators would like to apply it to their small cells. But this can be expensive and is not a cost-effective solution for small cells. Wireless backhaul for small cells, on the other hand, attracted a lot of attentions and many solutions have emerged in recent years [22]. Applying wireless backhaul for indoor small cells have a limitation of maintaining line of sight connectivity. There are some viable options for small cell backhaul [23, 24, 25] yet it remains a challenge to conduct cost effectively and without performance sacrification.

2.4.2 Mobility management

Handover and mobility management are essential to provide seamless connectivity for mobile UEs[d]. Depending on where the handover intelligence resides, mobility decisions can be a UE- or network-initiated. In LTE, a handover is typically triggered

Table 2: Small Cell Backhaul Requirements [8]



Backhaul Requirement	Compared to Macrocells	Notes
Cost	Cheaper	Cost per link should be lower. Cost per bit may be similar.
Capacity	Traffic load is lighter but burstier	Small cells generate less backhaul traffic than multi-cell/mode/band macrocells, but the traffic is much burstier.
Scalability	More scalable	Faster growth requires rapid deployment despite shorter lead times.
Latency	More delay tolerant	Delay sensitivity depends on service level expectations. Femtocells are designed to cope with lower quality connections. Femtocell handover is less important.
Availability	"Five Nines" not needed	Small cells will form an offload underlay to a higher-availability macrocell.
Size & Weight	Smaller and lighter stations	Small cells require deployment in locations with limited space availability. Compact backhauling solution is essential.
Access to Backhaul	More difficult	Small cells are close to users – on the street and indoors, relatively far from backhaul sites. These sites are harder to reach than tower-based macrocells.
Installation & Commissioning	Faster, simpler, cheaper	Consumer femtocells are plug-and-play. Femtocell backhauling should also work this way.

by base station [26].

Handover is a process of which a user is transferred from the serving cell to another cell to maintain quality of service and ensure that a UE is connected to the best serving cell [27]. Handovers triggered based on signal strength measurements on the UE. In addition, handovers triggered for traffic load-balancing purpose in which a UE connected to a highly congested cell can be handed to a less loaded cell.

Nevertheless, in heterogeneous network environments due to dense deployment of different size small cells with different backhaul links handover management is challenging. In [28] and [29] handovers between macro cell and femtocell have been studied. The studies emphasize the challenges of optimizing handover with short-range femtocells. The short range of femtocells leads to short stays and frequent handover by UEs. Frequent handover comes at the expense of signaling overhead at the system and increases probability of handover failures, which in turn result in user outages.

Access control mode of small cells is another challenge for efficient mobility in HetNet. The ability of CSG cells to deny access to non- CSG users prevents a UE from connecting to the closest cell.

2.4.3 Interference in HetNets

Integration of small cells with macro cells alters the existing network topology, introducing a multi-layer also called multi-tier hierarchical cell network. This deployment of small cells in the network, as discussed above, enhances capacity and network coverage. However, the main technical challenge with the mass deployment of small cell increases an interference. The interference takes place within and between tiers and can be distinguished in two types: co-tier interference and cross-tier interference [5].

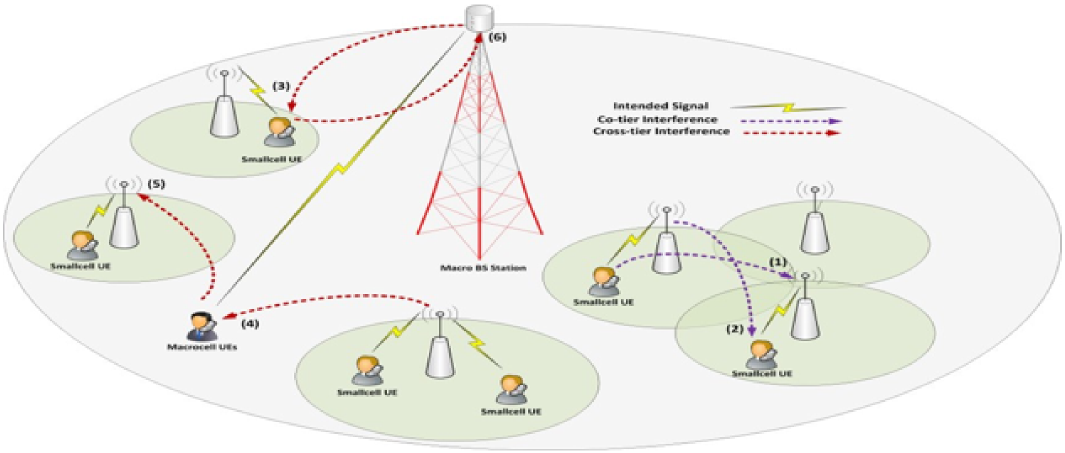


Figure 5: Co-tier and Cross-tier Interference in a Heterogeneous network [5]

Co-tier Interference

Co-tier interference also known as co-layer interference refers to an interference which takes place between cells belonging to same network layer. The interference caused by a femtocell to neighbor femtocell users or interference caused by microcell to adjacent microcell is an example of co-tier interference.

Cross-tier Interference

Cross-tier interference refers to the interference between base stations belonging to different layers in the network. The downlink interference from femtocell FAP to microcell and macrocell users or vice versa is a cross-tier interference.

To realize the advantage of HetNet, the co-tier and cross-tier interference in a network should be managed properly by applying different interference mitigation techniques. In 3GPP LTE specification some features are added to mitigate interference problem in HetNets. Some of the techniques are Inter-cell interference coordination (ICIC), carrier aggregation with cross carrier scheduling and coordinated multipoint (CoMP). One simple but expensive way to avoid cross-tier interference between macrocell, microcell and femtocell is to assign a dedicated channel to femtocell subscribers. However, this approach reduces the spectral efficiency and expensive regarding spectrum usage. Hence, sharing spectrum between microcell and femtocell is an appropriate approach and a common trend to improve spectral efficiency.

3 Spectrum Sharing

3.1 Introduction

Spectrum is a fundamental prerequisite for the success of wireless mobile communications. For over many years, static assignment of dedicated and exclusive licenses has been the main approach that national regulatory authorities use to allocate new spectrum bands. In exclusive access, only one operator has the right to use and control the given range of frequency band. This static assignment guarantees interference protection between frequency bands through licensing, allowing mobile operators to assure high quality of service and reliability to the subscribers.

As the mobile data traffic growing fast, alongside the inexorable demand for spectrum has placed pressure on mobile operators to ensure adequate capacity performance and a need for greater flexibility of spectrum access. The traditional static allocation often leads to a low spectrum utilization due to the reason that operators' spectrum demand may vary over time and location. Especially in small cells networks with variable load and spectrum demand, exclusive access may result inefficient spectrum utilization. The variation of demand, scarcity and low utilization of spectrum has created a need for greater flexibility in addition to the current licensed and unlicensed approach. Though exclusive access will be the dominant strategy in mobile communications, spectrum sharing is an efficient regulatory option for enabling high capacity, flexible usage and better Quality of Service.

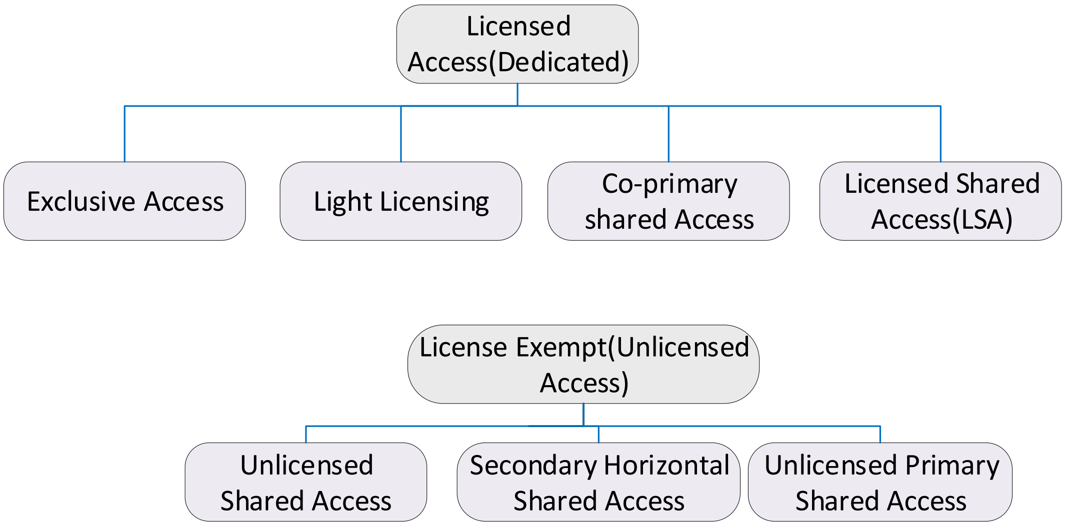


Figure 6: Spectrum access and authorization schemes [6]

Spectrum sharing refers to the collective use of a specific range of frequency by multiple wireless systems. Spectrum sharing can be realized in several dimensions;

time, space and geography. Spectrum sharing opens opportunities for mobile operator to have access to currently underutilized spectrum and to meet the growing data rate requirement of the current and future mobile communication market. A classification of spectrum access modes and sharing scenarios are derived as shown in Figure 6.

3.2 Licensed Spectrum Access

In dedicated(licensed) access, National Regulatory Authority (NRA) grants a license for using a spectrum to mobile network operators. The provided license would be valid for a given frequency range, geographic area and for fixed time usually for a decade. The following different spectrum access modes and sharing scenarios can be defined under licensed or dedicated spectrum access: exclusive access, Light sensing, Co-primary shared access, and Licensed shared access (LSA). Among the listed licensed sharing scenarios, we will discuss co-primary shared access and license shared access.

3.2.1 Licensed shared access

LSA is a spectrum access model in which licensees get access to a specific band usage right from a primary license holder under certain rules and conditions defined by the regulator. The LSA concept defined in [1] as “An individual licensed regime of a limited number of licensees in a frequency band, already allocated to one or more incumbent users, for which the additional users are allowed to use the spectrum (or part of the spectrum) in accordance with sharing rules included in the rights of use of spectrum granted to the licensees, thereby allowing all the licensees to provide a certain level of QoS.”. As defined by ETSI, Figure 7 illustrates the LSA System Architecture.

LSA scheme involves a regulator, the incumbent – the primary license holder, and the LSA licensees - LSA spectrum usage license holders which shares the spectrum with the incumbent on a basis of sharing agreement. For LSA licensees to get spectrum access right from incumbents, they need to have the LSA spectrum usage license, which would be granted by the regulator, and a sharing agreement. The framework for LSA spectrum grant policy is formulated by national regulator authority. The spectrum sharing activities between the incumbent and LSA licensees monitored by the regulator. Providing a long-term sharing agreement between incumbent and licensees, LSA guarantees investment security and Quality of Service at a given frequency band, time period and geographic area. The main use case for LSA technology relates to the extension of cellular capacity below 6GHz in Europe. For the initial deployment of LSA in Europe, the 2.3-2.4 GHz has been identified.

3.2.2 Co-primary shared access

Co-primary shared access refers to a spectrum sharing, where multiple primary license holders agree for a joint use of their licensed spectrum or fragment of it. This co-primary sharing requires mutual agreements between spectrum holders and

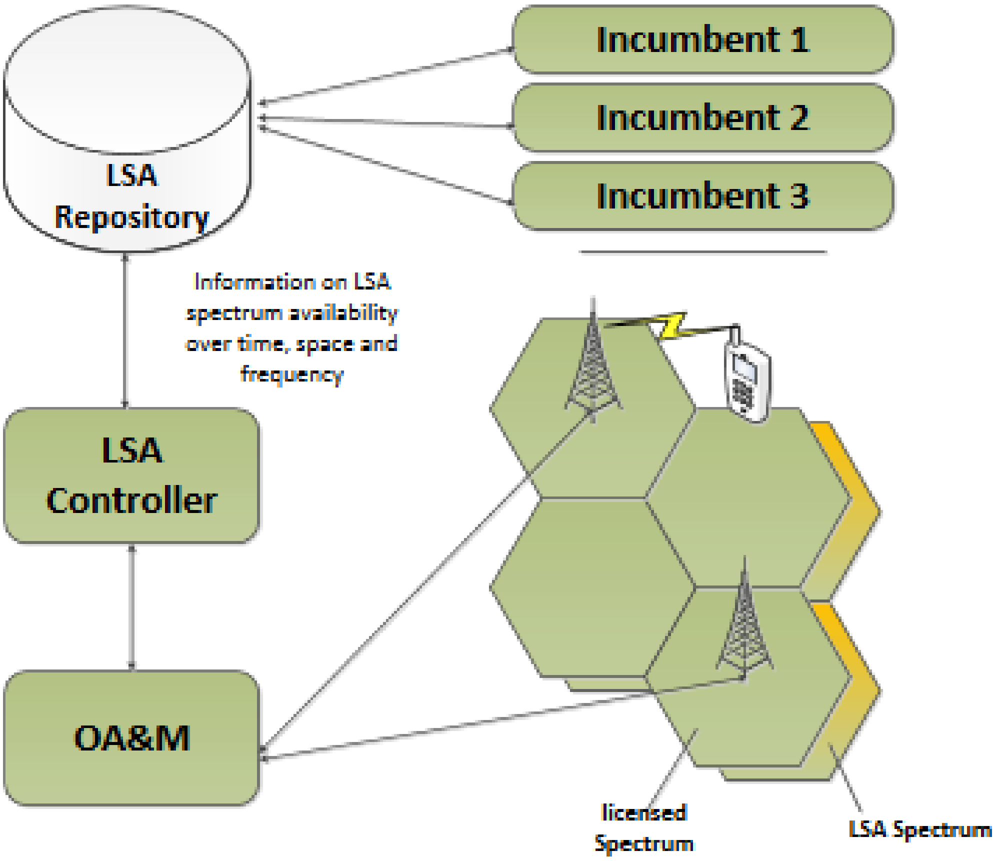


Figure 7: Licensed Shared Access System Architecture [7]

explicit priori usage policies (conditions) to define the common usage rules. In this sharing model, there is no hierarchy of use and users have equal access rights with no priorities. Co-primary shared access and related works are analyzed in detail in the next section. The two co-primary shared access schemes are limited spectrum pooling LSP and mutual renting MR.

Limited spectrum pooling

In Limited spectrum pooling (LSP), NRA grants a group license for several operators that allow them to access a common pool of spectral resources. This group license allows an operator to have equal access right on a shared basis with other known authorized operators over the spectrum pool. This sharing scheme does not guarantee a minimum amount of spectrum for immediate access, however the license holders make a prior agreements that the individual operators has a predictable minimum value in the long-term share. It is envisioned that each operator owns exclusively some piece of spectrum (primary component carriers) while there is also another piece of spectrum to be shared among operators (secondary component carrier). Mutual agreements allow operator with low traffic load using few secondary CCs for satisfying their QoS while remaining carriers can be utilized by operators with high traffic load.

Mutual Renting

In Mutual Renting (MR), licensed operators for an exclusive use of frequency bands mutually allowed to rent parts of their licensed unused resources to their peers based on prior requests. Instantly, an operator can rent resources from more than one peer operators. For a given range of frequency, the actual owner has always a strict priority.

3.2.3 Light Licensing

Light licensing access method is simpler and less expensive way of issuing spectrum to users compared to the exclusive access method. In light licensing access mode, operators/users are given the right to access bandwidth either with a very small price compared to the fully exclusive allocation price or free, and they may be required to follow usage terms and conditions set by NRA [30]. Light licensing access provides a guarantee for better quality of service than unlicensed access and equal sharing among license holders with a nominal cost. It is intended as a solution to apply flexible spectrum allocation. However, there is a possible interference among nearby licensees. In order to avoid or keep the interference at lower level, it requires interference avoidance mechanisms.

3.3 License-Exempt Access

The unlicensed access allows several users to utilize the allocated frequency as a common and shared resource without an individual license. It is unregulated approach but sharing parties are subject to certain mandatory restrictions such as limited transmitted power and fulfill required hardware configuration. Unlicensed spectrum usage provides unpredictable QoS and system performance but the spectrum cost is relatively low, typically zero. unlike licensed access there is no protection rights for unlicensed bands. The best-known example of the unlicensed spectrum is industrial, scientific, and medical radio (ISM) band at 2.4GHz. Multiple technologies are used in unlicensed spectrum such as LTE unlicensed, Wi-Fi, and Bluetooth. Under unlicensed access, the following access modes and sharing schemes can be defined: unlicensed shared access, unlicensed primary shared access and secondary horizontal shared access.

3.3.1 Unlicensed Shared Access

In unlicensed shared access, multiple users acquired an equal access to the license-exempt frequency bands in which no priority service is assigned. In the unlicensed shared access, guarantee for interference protection and quality of service is not provided. To minimize the interference among nearby users, transmission over these frequency bands subject to limited transmission power [31].

3.3.2 Secondary Horizontal Shared Access

Secondary horizontal shared access is the same as the unlicensed shared access except that it provides a prioritized access to users. In this access, users with higher priority, primary users, share the given frequency bands with unlicensed low priority users called secondary users. Multiple unlicensed secondary users get the access in an opportunistic manner with low access guarantee and protection from interference. In horizontal shared access, there may be a requirement for secondary users to be registered in a database, such as geolocation database, to get access to the shared frequency bands [6].

3.3.3 Unlicensed Primary Shared Access

In unlicensed primary shared access, a primary service is allocated in a frequency band and all services using the same technology can get access to these frequency bands. A typical example of this access scheme is Digital European Cordless Telecommunications (DECT) operating in the 1880- 1900MHz band as a primary user through mobile service allocation [6].

3.4 Game Theory For Spectrum Sharing

As is discussed in section 3, balancing the demand for wireless bandwidth with its availability has become very challenging for mobile network operators. Because of the inherent characteristic of wireless bandwidth being limited resource, the competition between service providers becomes severe. Service providers always tries to maximize their user's throughput and are selfish by nature. Therefore, the competing interaction among these self-interested mobile operators sharing a common resource can be modeled as a game. Using the game theoretical model, the outcome of the interaction and the system performance of the operators can be predicted. Nowadays game theory has been widely used in the area of mobile communication.

Game theory [14, 32, 33, 34] is a mathematical framework used to model and predict possible outcomes of a cooperative or conflict (competing) strategic interaction between multiple decision makers. The strategic interaction indicates that the decision or action of one player affects the outcome of others. Game theory provides a set of analytical tools to study or analyze the decision-making process when self-interested players interact. Originally, game theory was invented in the field of economics and mathematics. But today, game theory becomes widely applied in different research areas such as engineering, law, economics, and sociology.

3.4.1 Strategic Games

A game in a strategic form consists of three entities; a set of Players, set of strategies, and utility function. A game involves a finite set of players P. A game with only one player is called a decision problem. A set of strategies S which consists of strategies of each player. Each player has a non-empty set of actions they select strategically at each stage of a game. The utility function represents the outcome of the game for each player with the selected strategy profile. strategy profile is a set of strategies one for each player.

Definition

A strategic game mainly consists of three components:

- A set of players $P = \{1, 2, ..., N\}$,
- A set of strategies $S = \{S_1, S_2, ..., S_N\}$, in which each stratey S_i consists of a set of possible alternatives for player i. Where $i \in N$
- A utility function (also called as payoff function) $U_i(S)$, which represents the outcome of player i for choosing strategy S.

In a strategic game, the strategy represents one of the possible choices available for each player. Thus, when player i participates in every distinguishable state of the game it chooses one of the actions from the set S_i. In game theory, there is a generalized assumption that the players are rational. A rational player means that a player selects a strategy which maximizes its payoff. Thus, game theory is used to analyze and predict the interaction between these rational players.

For clear understanding of what a game between players represents, let us discuss the best-known example of prisoner's dilemma game.

Introductory example

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 could not 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.

		Player 2	
		Confess	*Refuse*
Player 1	*Confess*	$(-2,-2)$	$(0,-6)$
	Refuse	$(-6,0)$	$(-1,-1)$

Table 3: The Prisoner's Dilemma Game

To predict what a player chooses to minimize its payoff at a prison lets observe prisonner1 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 player1 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*.

3.4.2 Nash Equilibrium

In a game theory, Nash Equilibrium is a concept used to describe the steady state of a game. Nash Equilibrium (NE) [34], also called strategic equilibrium, can be defined as a strategy profile which no player maximizes its utility by unilaterally deviating from this strategy profile. Thus, as long as the other player's strategy remains the same no player will change its strategy and get a better payoff.

In the above prisoner's dilemma, for example, the strategy profile (C,C) is the Nash Equilibrium of the game. Given the other prisoner strategy known to be Confess, the only strategy for the other prisoner that maximizes its payoff is to confess. Therefore, the strategy profile (C,C) will capture the steady state of the game and no player has an incentive to unilaterally change its strategy selection.

Definition: A strategic game G's Nash equilibrium can 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:

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

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 other than s_i^* that yields a better utility, given that all other players strategy is s_{-i}^*.

3.4.3 Cooperative/ Non-cooperative game

The distinction between cooperative and non-cooperative game is the major division branch in game theoretic approach [35].

In a cooperative game, the game participants are able to make a coalition and act according to the binding agreement. So that for a player in a cooperative game, selecting a strategy must abide the prior agreement. Whereas, in a non-cooperative game each player acts independently in the absence of coalition and without collaboration with others. Players in a non-cooperative game act rationally and committed to their own strategies.

4 Location-based Spectrum Sharing between Co-located MNOs

Recently co-primary spectrum sharing gets many research work attentions. In many researches, the interaction between operators modeled as a game where operators are players with individual strategy of maximizing their own sum utility. In [36, 37] a cooperative game model is studied for spectrum sharing, in which operators exchange their operator specific information such as CSI. However, the exchange of operator specific information between operators would result signaling overhead and requires a link between operators. Since operators are competitive by nature, it is not wise to design a cooperative game model.

A non-cooperative spectrum sharing game has been done in [38, 39, 40, 41]. In a non-cooperative game, operators do not exchange any operator specific information and make decisions independently. Among these works, the main motivation for this thesis is [42]. In [42] the authors proposed a non-cooperative repeated spectrum-sharing model. The interaction between operators is based on history of their utility gain/loss. The idea is that when an operator experiences a high inter-operator interference on the shared part of the spectrum pool, the operator will ask for a spectrum usage favor. The spectrum usage favor is exchanged when one operator requests for favor and the other operator accept the request and give permission. The exchange of the usage favor results a utility gain for an operator and utility loss for the other. For an operator, giving a favor is losing the right to use the given part of the spectrum for some time. However, operators participate in the game willingly.

In our approach, we follow exactly the same coordination mechanism as [42] but for a fair regulation of the common spectral pool, we proposed location based spectrum exchange. We assumed that operators subdivide their common operational area into small areas, in which clusters of BSs exist. Operators exchange a small or a big favor. A big favor is exchange only at the worst case, where there is a huge inter-operator interference or an operator experiences a heavy load. By proposing an option for a small favor, we are able to minimize the utility loss of an operator. At a given instant of time when an operator gives a small favor the operator can still have the right to use the common pool in sub areas where the inter-operator interference is low.

The aim of this study is to show how operators coordinate to minimize inter-operator interference and benefit from the joint usage of a spectrum. We show that for operators getting an option of small or big favor enables them to improve user rate and minimize the excess utility loss.

4.1 System Model

We considered a downlink co-primary spectrum sharing between HetNet MNOs. The MNOs comprises a microcell and femtocells. Each operator has a licensed frequency band composed of P component carriers (CCs). The micro cells can transmit over all P CCs, Microcells of each operators share their spectrum orthogonally. The operators mutually agree to use their spectrum jointly for efficiently utilize the available resource. For the construction of the common spectrum pool, each operator contributes equal number of CCs. Femto access points of each operator are then allowed to transmit over the common pool whereas, the micro base stations share their frequency orthogonally. Fig.8 shows the spectrum allocation for micro and Femto cells as well as the common spectrum pool for the case of two operators. For simplicity, we consider two operators participating in our spectrum-sharing model, but it can be expanded to number of operators.

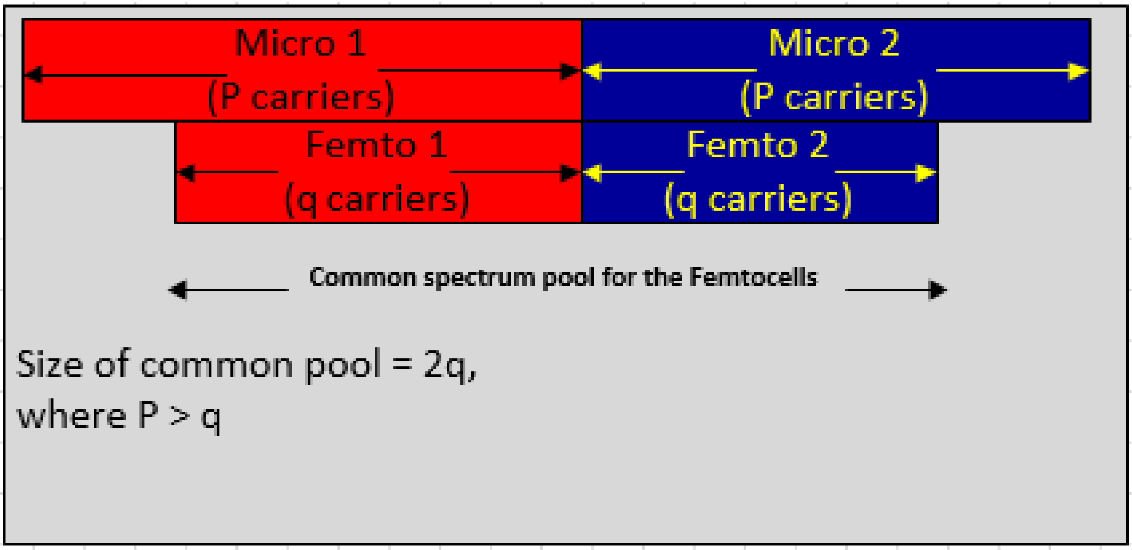


Figure 8: Spectrum allocation between femtocell and microcell and construction of a common spectrum pool for femtocell of operator 1 and operator 2.

Due to the common utilization of the spectrum pool, inter-operator interference exists between the operators (OP1 and OP2). Over the $2q$ CCs the Femto-connected users (FUE) suffer from Femto to Femto inter-operator co-tier interference. Femto access points (FAP) of OP1 generate inter-operator cross-tier interference to micro-connected users (MUE) of OP2 over $(2q \cap P)$ CCs. Also, FAP of OP2 will generate cross-tier inter-operator interference to MUE of OP1 over $(2q \cap P)$ CCs.

To minimize the inter-operator interference and to benefit from spectrum sharing, a coordination between femtocells and microcells of the operators is expected. For this purpose, the operators agree on prior rules for the regulation of the spectrum pool usage. Based on interference profile and traffic load, operators ask each other a spectrum usage favor for exclusive use of some CCs of the common pool. The spectrum usage favor refers to, when one operator asks the other operator to discontinue its transmission over some of the component carriers of the common spectral pool for some time [42]. In our approach, to avoid the co-tier and cross-tier inter-operator interference the microcell and femtocell of an operator can ask a spectrum usage favor from femtocell of the other operator. It is possible for both operators to request and grant a spectrum usage favor at the same time and the utilization of the common pool may even become orthogonal. An operator can ask a spectrum usage favor for a maximum of the number CCs it provides to the common pool.

Our model follows the same coordination mechanism as [42] but for the fair regulation of the common spectral pool we introduced a more localized spectrum sharing option of 'small' and 'big' favor. For this purpose, the common coverage area divided into smaller subareas. Each subarea contains a number of base stations of both operators. The subareas known commonly by the operators as A1, A2..., An. The dimension of each subarea agreed at priori between the operators.

A small favor represents a favor from FAPs in one of the subareas whereas, big favor constituents all FAPs in all subareas. The mutually agreed spectrum sharing rules between the operators includes the decision-making mechanism rules, favor validity time, dimension of subareas, and the default state. The default state represents the state at which both operators' femtocells are utilizing the common pool. When an operator granted a favor, the exchanged favor is valid for the certain interval of time called, favor validity time. Favor validity time is fixed and in the range of seconds. As the granted favor entails to exit from the default state, the expiration of the favor validity time returns the usage of the common pool to the default state.

In the considered repeated game, the interaction between the operators is based on book keeping of the exchange of favors. At a given stage of the game, an operator is willing to give a spectrum usage favor if and only if the other operator is going to pay it back with equal amount of favor in the future. Since the repeated game encounters a large set of equilibrium points, it is hard to find and analyze its unique NE point. Therefore, we follow heuristic threshold based strategies [42] to obtain long-term reciprocity. The threshold value keeps monitoring the exchange of favors between the operators. Therefore, the decision-making procedure depends not only on the result at a given stage game, but also in the history of previous reward exchanges.

4.2 Location based spectrum sharing mechanism

Initially the usage of the common spectrum pool is at the default state. At the given state, to determine whether to request or grant a favor, an operator needs to estimate the utility gain/ loss of its own for asking/ granting a favor respectively. The utility represents the satisfaction of users for the services offered by the serving operators. The system architecture for the co-primary spectrum sharing is shown in Figure 9. To calculate the utility gain/ loss, an operator needs to identify the level of the inter-operator interference. For the estimation of the interference level from the other operator network, one operator may request its UEs to make a measurement of the interference from the other operator and report to the serving base station. Normally a UE is able measure the signal strength and quality of the neighbor cells

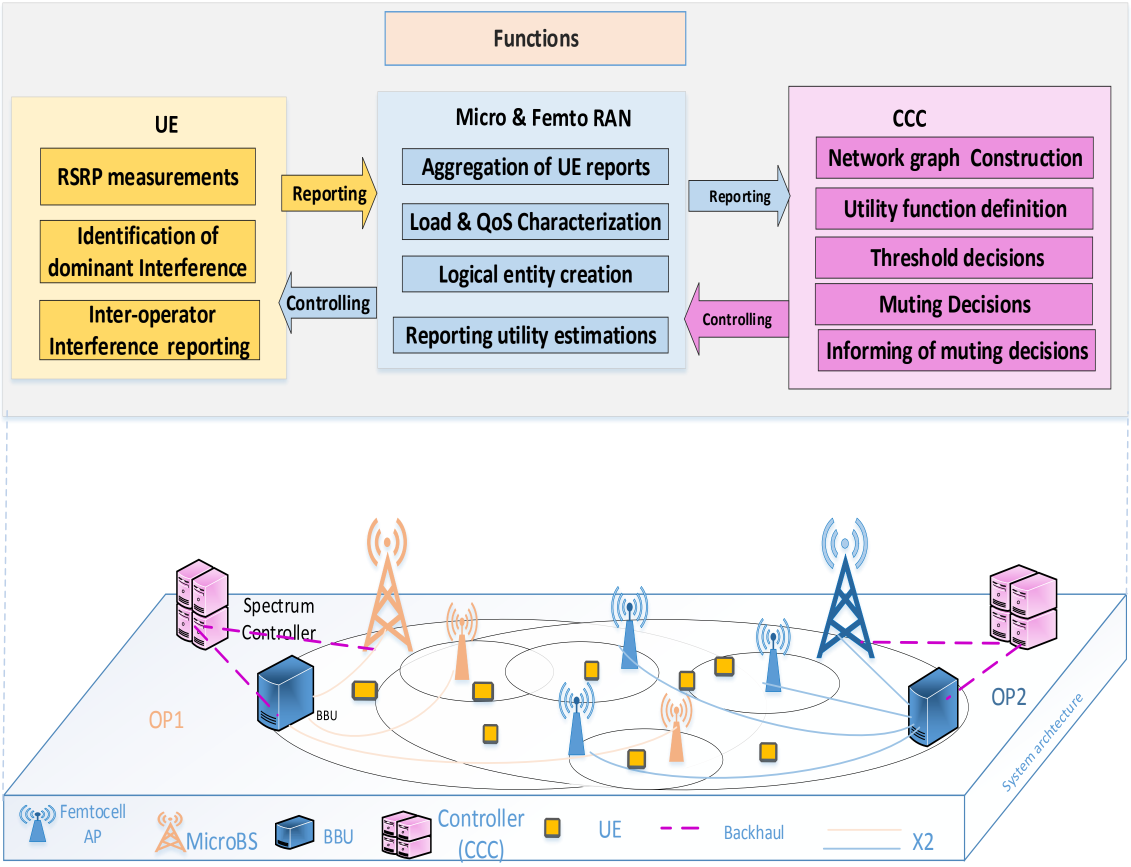


Figure 9: System architecture for co-primary spectrum sharing between mobile network operators

of own operator network through reference signals for cell selection/reselection and handover purposes [43]. With the same procedure, we assumed that it is feasible for a UE to measure the total interference from the other operator network. The UE then reports the total inter-operator interference to the serving base station. Upon receiving the total inter-operator interference from all UEs in its cell range, a small cell can estimate the impact of the inter-operator interference. Aggregating the received reports, a base station/ FAP will send it to the spectrum controller. Once this information is retrieved, the spectrum controller sums up the aggregated small cells report in each sub areas and sorts the sub areas based on the impact from the inter-operator interference. The spectrum controller selects a sub area with highest interference from other operator networks. In case the level of inter-operator interference in all subareas is almost the same, then the spectrum controller of operator O selects the total area to make favor request from opponent operator to stop using some of the q ccs it contributes to the common pool. Once the area is selected, the spectrum controller evaluates its network utility gain/ loss of a presumed favor comparing with its utility in the default state.

To make a decision whether to grant or request a favor the operator (OP1) then compares its instantaneous utility gain of the current stage game with the threshold values. In case the instantaneous utility gain is greater than the threshold value (expected utility loss) for the given component carrier, then OP1 will ask a favor from OP2. An Operator always attempts to ask the maximum number of component carriers, so that its instantaneous utility gain will be greater than the corresponding threshold. OP2 then accepts the spectrum usage favor request if its immediate utility loss for giving the required spectrum usage favor on the given CC is less than the expected utility gain (threshold value). Then OP1 and OP2 will update their corresponding threshold values.

4.2.1 Algorithm

The algorithm for operator $O \in \{OP1, OP2\}$ to ask or grant a favor on i CCs in the form of pseudocode is below:

Algorithm 1 Co-Primary Spectrum Sharing

```
 1: procedure Ask Favor(Operator O selects area $A \in \{A_x or \sum_{x=1}^{n} A_x\}$to ask a
    favor on i CCs for $i = 1, 2, ..., q$)
 2:     Step 1 Operator O
          Calculate utility gain for the presumed favor
          $U_{O,i}^{gain} = U_{O,i}^{hyp} - U_{O,i}^{default}$
          Compare $U_{O,i}^{gain}$ with the respective threshold value:
 3:     if $U_{O,i}^{gain} > \theta_{O,i}$ then
 4:         $S_O$ =ask a favor on i-ccs                      ▷ $S_O$–Operator O strategy
 5:     else
 6:         $i = i - 1$,
 7:         go to 2
 8:     end if
 9: end procedure
10: procedure GRANT Favor(Upon being asked to give a favor on i CCs i = 1,
    2, ..., q)
11:     Step 1 Operator O
          Calculate utility loss for the required favor
          $U_{O,i}^{loss} = U_{O,i}^{default} - U_{O,i}^{hyp}$
          Compare $U_{O,i}^{loss}$ with corresponding threshold value:
12:     if $U_{O,i}^{loss} < \lambda_{O,i}$ then
13:         $S_O$ = Grant a favor on i- CCS
14:     end if
15: end procedure
```

4.3 Model of Wireless Network

Suppose the common area, A, shared by two operators OP1 and OP2 is divided into n subareas $A = \{A1, A2...An\}$. The FAPs of operator $O \in \{OP1, OP2\}$ installed in subarea Ax gives a service for n_{Ax} number of users. The micro base station of operator O gives coverage for n_M users.

The downlink signal to interference plus noise ratio SINR of the n-th users of operator O on the i-th CC can be defined as:

$$SINR_{n,i} = \frac{\beta_{O,i} S_{O,n,i}}{I_N + \beta_{O,i} I_{O,n,i} + \beta_{-O,i} I_{-O,n,i}} \tag{1}$$

During orthogonal sharing of spectrum between the operators, the SINR is:

$$SINR_{n,i} = \frac{\beta_{O,i} S_{O,n,i}}{I_N + \beta_{O,i} I_{O,n,i}}. \tag{2}$$

Note $I_{-O,n,i} = 0$ where $S_{O,n,i}$ is the downlink received signal power, I_N is the noise power, and $I_{O,n,i}$ and $I_{-O,n,i}$, respectively represents the intra- and inter-operator interference on the i-th cc. In the above expressions, the allocation indicator beta (β) indicates whether operator O is using the i-th CC. At the default state, both operators are utilizing the spectral pool, $\beta_O = 1$ and $\beta_{-O} = 1$, whereas in case of favor exchange if the femtocells of operator O stops using the i-th CC $\beta_O = 0$.

For the n-th UE of operator O the transmission rate on the i-th cc can be calculated as:

$$R_{n,i} = w_{n,i} BW_i \log_2(1 + SINR_{n,i}) \tag{3}$$

where BW is bandwidth of CC and $w_{n,i}$ is the time scheduling weight of the n-th user on the i-th CC.

4.3.1 Utility Function

Initially the operators are at the default state, where both operators' femtocells utilize the common spectral pool. Therefore, at each stage game operators first calculate the network utility at the default state. We assumed both operators use a proportionally fair utility function. The logarithmic proportional utility function maximizes the overall utility of user rates by providing a compromise between user fairness and maximum throughput [44]. The network utility of operator O, U_O defined as:

$$U_O = \sum_{n=1}^{n_{A1}} \log\left(\sum_{i=1}^{2q} R_{n,i}\right) + \sum_{n=1}^{n_{A2}} \log\left(\sum_{i=1}^{2q} R_{n,i}\right) + ... + \sum_{n=1}^{n_{An}} \log\left(\sum_{i=1}^{2q} R_{n,i}\right) + \sum_{n=1}^{n_M} \log\left(\sum_{i=1}^{p} R_{n,i}\right) \tag{4}$$

$$U_O = U_{O,A1} + U_{O,A2} + ... + U_{O,An} + U_{O,M}$$

The utility function of operator O Equation 4 is a function of β_O and β_{-O} through Equation 1 and Equation 3:

$$U_O = U_O(\beta_O, \beta_{-O})$$

Thus the utility function of operator O at the subarea A_x :

$$U_{O,Ax} = U_{O,Ax}(\beta_{O,Ax}, \beta_{-O,Ax}) \tag{5}$$

At the default state both operator are transmitting over the 2q CCs, thus $\beta_O^{2q} = 1$ and $\beta_{-O}^{2q} = 1$ where $\beta^{2q} = (\beta_1, \beta_2, ..., \beta_{2q})$

4.3.2 Area Selection

This option of area selection is made for a more localized spectrum sharing mechanism, where operators agree and select subareas to avoid the interference from nearest base stations and the interference from other sub area base stations assumed to be negligible.

As we have discussed in subsection 4.2, the operator selects a subarea or the total shared area to make a favor request. Thus, the interference level at each area is compared with the interference level over the total area. The interference level over the total shared area I_A can be calculated as:

$$I_A = I_{A1} + I_{A2} + ... + I_{An} \tag{6}$$

Where I_{Ax} is the interference at each sub area Ax. The interference over subarea A_x summed up as:

$$I_{Ax} = \sum_{i=1}^{m} I_i \tag{7}$$

Where I_i the interference report from users served by base station i, and m is the number of base stations housed in subarea Ax. Then to select the subarea with the highest interference level the sum interference at each subarea will be compared to the total area sum interference. If $I_{Ax} > \mu I_A$, where μ is set as a selection coefficient. For example, if $\mu = 0.6$, then a sub area which contains 60% of the total interference from the other operator is selected. After the selection if the utility gain for the assumed favor is much less than the case where the total area is selected, then other sub area will be considered to make a favor request.

4.3.3 Small Favor

Based on the measurement report from its UEs, let us assume that operator O selects subarea A_x to ask a favor from operator -O to stop using q CCs from the common pool. Then operator O estimates its utility gain taking an assumption that Operator O's FAPs in the selected subarea Ax stops transmitting over these CCs and the interference coming from the neighboring subarea FAPs are considered negligible. Thus, the assignment indicator of operator -O for subarea A_x will be zero over the given CCs. The immediate utility gain of operator O for the assumed small favor over q CCs can be calculated as:

$$U_O^{gain} = U_O^{hyp} - U_O^{default} \tag{8}$$

$$U_O^{gain} = U_O^{hyp}\left(\beta_O, \beta_{-O}\right) - U_O^{default}\left(\beta_O, \beta_{-O}\right) \tag{9}$$

At the hypothetical state, the assignment indicator for Operator -O:

$$\beta_{-O}^{2q} = \beta_{-O,Ai}^{2q} = 1,$$

Where $i = 1, 2, ..., n$ and $i \neq x$
For $i = x$ the assignment indicator can be re-written as $\beta_{-O}^{2q} = \left(\beta_{-O}^{q}, \beta_{-O}^{2q-q}\right)$, where $\beta_{-O}^{q} = (\beta_{-O,1}, ..., \beta_{-O,q})$ and $\beta_{2q} = (\beta_{-O,q+1}, ..., \beta_{-O,2q})$. Thus, the assignment indicator of Operator -O for the subarea Ax is $\beta_{-O,Ax} = (0^q, 1^{2q-q})$.

Deducting Equation 8 the utility gain of operator O at the given stage of game for getting a small favor from operator -O in the q-th cc on the subarea Ax can be estimated as:

$$U_O^{gain} = U_{O,Ax}\left(1^{2q}, \left(0^q, 1^{2q-q}\right)\right) - U_{O,Ax}\left(1^{2q}, 1^{2q}\right) \tag{10}$$

Each operator selects a strategy to maximize its utility, but at a single stage of a game, an operator may experience a loss for granting a favor. However, an operator will get the favor back in return in the near future. Upon being asked, Operator -O estimates its utility loss for the required favor over the subarea Ax before granting a favor:

$$U_{-O}^{loss} = U_{-O,Ax}\left(1^{2q}, 1^{2q}\right) - U_{-O,Ax}\left(\left(0^q, 1^{2q-q}\right), 1^{2q}\right) \tag{11}$$

4.3.4 Big Favor

An operator considers a big favor when the interference from opponent operator affects its utility over all the area shared by both operator. In such a case, an operator selects the whole area to request for a favor. Let us assume operator O selects the given common shared area A, to ask a favor from operator -O over q CCs. The utility gain of operator O estimated, taking in assumption that the FAPs of Operator -O installed over the shared area stops using q CCs of the common pool. Thus, the utility gain can be estimated from Equation 8 and the assignment indicator of for operator -O at the hypothetical state assumed to be:

$$\beta_{-O}^{2q} = \beta_{-O,Ai}^{2q} = 1,$$

for all i=1,2,...,n.

Therefore, the utility gain of Operator O for getting a big favor from Operator -O over q CCs estimated as:

$$U_O^{gain} = U_O(1^{2q}, (0^q, 1^{2q-q})) - U_O(1^{2q}, 1^{2q}) \tag{12}$$

Similarly, operator -O estimates its utility loss for the required big favor:

$$U_{-O}^{loss} = U_{-O}(1^{2q}, 1^{2q}) - U_{-O}((0^q, 1^{2q-q}), 1^{2q}) \tag{13}$$

One can observe from the above equations the difference between a small favor gain/ loss and a big favor gain/loss is that, the change in the utility for small favor is only over the area selected for a given favor. Whereas for a big favor the gain/loss of the operator's utility calculated over all the shared area.

4.4 Non-localized Spectrum sharing

The location-based spectrum sharing in subsection 4.2 discusses a localized spectrum sharing between two operators in common coverage area. By classifying the shared area into subareas, we introduce a more-localized spectrum sharing between the operators. Let us consider a common geographic area which encompasses N multiple independent set of coverage areas such as buildings. The term independent used to mean that, the transmission in one building do not interfere with the transmission in the other building. Thus, in a given common geographic area the operators play N-stage repeated location-based spectrum sharing game, where a single stage game refers to a game in one building.

The non-localized spectrum sharing involves operators in a single stage game over the total geographic area instead of localized game into buildings or more-localized game to smaller areas. Now consider a single stage game where the operators Op1 and OP2 exchange spectrum sharing favors based on the network load or interference profile over the total coverage area. Each operator asks or grants a favor on i, i=1,2,...,q CCs. Unlike location-based spectrum sharing, in Non-localized spectrum sharing the exchange of favor affects the user's throughput over all the geographic area. When operator Op1 grants a favor of i CCs for operator Op2, all base stations of operator Op1 stops transmitting over the i-th CCs.

For an operator O, to ask/ grant a favor it estimates its utility gain/ favor in each building and takes the summation. For N buildings in a given common geographic area, the total utility gain for operator O for getting a spectrum favor over i CCs estimated as:

$$U_{O,i}^{gain} = \sum_{j=1}^{N} \left(U_{O,i,j}^{gain} \right) \tag{14}$$

Where $j = 1, 2, ..., N$ and $U_{O,i,j}^{gain}$ is the utility gain of operator O in the localized area j and can be estimated using Equation 12. Similarly, the utility loss of operator O for granting a favor of i CCs estimated as:

$$U_{O,i}^{loss} = \sum_{j=1}^{N} \left(U_{O,i,j}^{loss} \right) \tag{15}$$

Where $j = 1, 2, ..., N$ and $U_{O,i,j}^{loss}$ is the utility loss of operator O for granting i CCs favor over localized area j from Equation 13.

In Non-localized single stage spectrum sharing game, both operators utilize the common spectral pool at the default stage. In a single stage game, the operator's utility loss/ gain depends on the strategic decision made by each operator at this stage of the game. The available set of strategies for each operator are: ask a favor, grant a favor or do nothing. To maximize their utility, it is clear that both operators will ask a favor and never grant a favor. Therefore, the equilibrium solution for this single stage game is for both operator to ask a favor. However, since both operators never grant a favor, both operators utilizing the common spectral pool is the logical decision.

5 Numerical Results

MATLAB-generated simulation results are discussed in this chapter. The performance of the obtained results with the localized and non-localized spectrum sharing mechanism is evaluated and compared to the orthogonal spectrum sharing scheme. In addition, the localized per half-building spectrum sharing with free selection of small or big favor analyzed in comparison to the localized per building spectrum sharing scheme.

5.1 Simulation Scenario and Parameters

The system under consideration as discussed in previous chapter consists of two HetNet MNOs participating in the spectrum sharing simulation.

The simulation environment considers the example deployment of Figure 10, assumed to have 400 buildings laid out in Manhattan-like grid model. The dimension of each building covers 100 m x 100 m and inter building distance of 30 m. Each building allocates to both operators. In each building we consider the deployment of Figure 11, comprising five indoor Femto access points (FAP) per operator. The micro base stations of both operators deployed outside of the building to give coverage to the outdoor users as well as some indoor users. The indoor installed FAPs give coverage to indoor UEs and assist microcells of the operator. The given UE selects the serving base station of home network based on the strongest reference signal received power.

For the localized per building spectrum sharing, each building is considered for each single stage game. For the localized per half building, the area of a building is divided into two sub areas $A = (A_1, A_2)$. Both operators know the sub areas at priori as area1 (A1) and area2 (A2), in which the exchange of favors in these subareas referred to us a small favor. Subarea A1 covers for 50 m x 50 m left half of the building whereas; subarea A2 covers right half of the area. Layout of the simulation scenario is shown in Figure 11 and Figure 10.

For the indoor and outdoor signal propagation, we consider a simple power-law distance based propagation path loss model at a carrier frequency of 2.6 GHz. We assumed modern buildings with external thick wall, hence due high wall attenuation the interference from indoor FAPs to outdoor users assumed to be negligible. However, the micro cell transmission interferes the indoor Femto-connected users received signal. For outdoor-to-indoor propagation, we use 17dB wall attenuation.

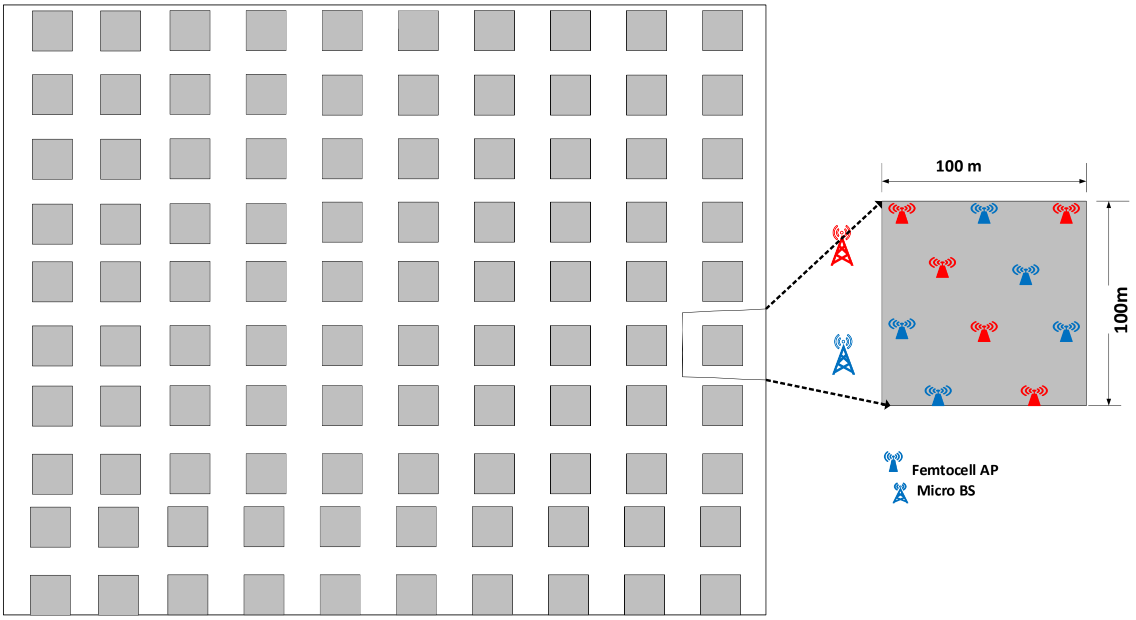


Figure 10: Multi building simulation environment.

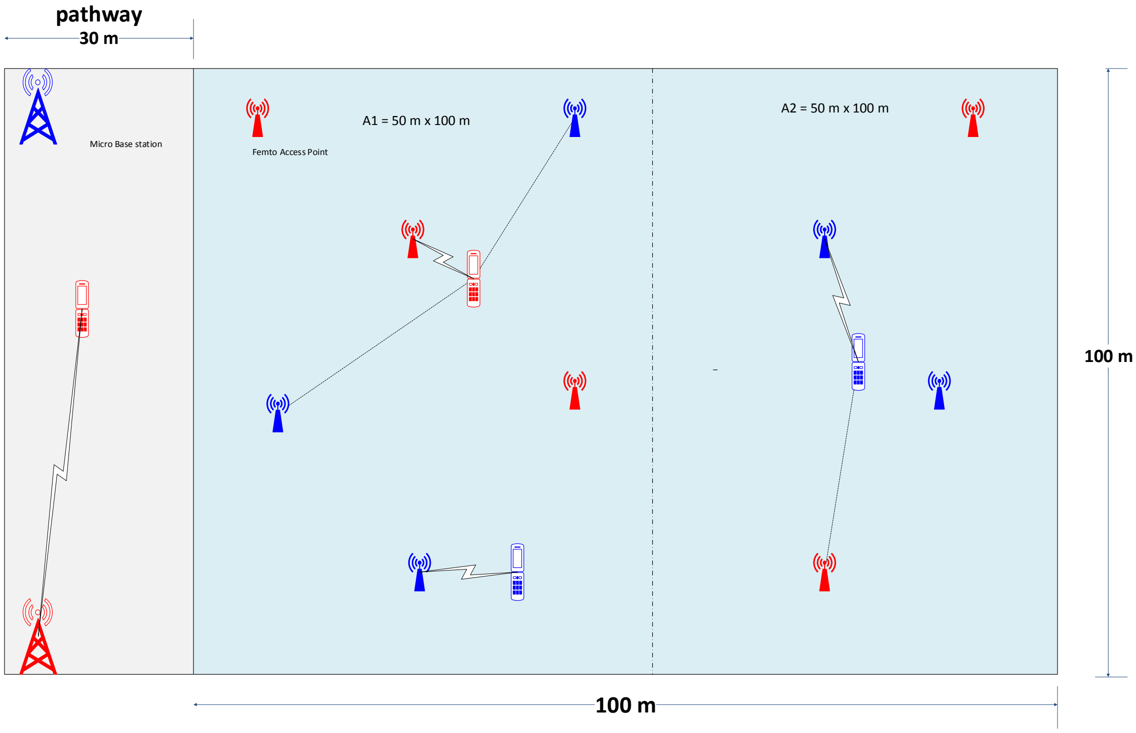


Figure 11: Micro base station and FAPs deployment scenario

Each operators' licensed frequency bandwidth of 30 MHz is divided into 3 equal CCs of 10 MHz each $BWc = 10$ MHz. The outdoor deployed Micro base station of each operator can transmit their signal over 3 CCs of own operator's license with the available power budget of 30 dBm per CC. During orthogonal spectrum sharing, FAPs of the operators can use only two CCs of own operator license to serve femto-connected UEs, see also Figure 8.

Table 4: Simulation Parameters

Number of Operators	2
Number of FAPs/operator	5/building
Number of Micro BSs/operator	1/building
Number of Indoor and Outdoor UEs	Poisson distributed with mean N_i per operator per the shared geographical area
Carrier Frequency	2.6 GHz
Total Bandwidth/operator	30 MHz
Number of Component Carriers/operator	3
Spectrum pool size	4 Component carriers
Carrier Bandwidth	10 MHz
Transmission power in Femtocell	20 dBm
Transmission Power in Microcell	30 dBm
Scheduler	Proportional fair
Number of buildings	400
Inter-building distance	30 m
Building dimension	$100m \times 100m$
Indoor Layout	Single Story
Number of Sub Areas	2
Sub Area dimension	$50m \times 50m$
Path loss model	power law distance based path loss Cd^{-A}
Path loss exponent	$A = 3.7$
Attenuation Constant	$C = 8.435 \times 10^{-5}$
Wall Attenuation	17dB

For the construction of the common spectral pool, both operators contribute 2CCs of the femtocells, providing a total size of a pool 4CCs. Thus, as discussed in previous chapter, the FAPs can access the common pool simultaneously with the available power budget of 20 dBm per 10 MHZ at default state. However, due to the coexistence of the operators, micro-connected UEs experience an interference from FAPs of the opponent operator from half of the spectral pool. In addition, Femto-connected UEs experiences Femto-to-Femto interference. Details of simulation parameters are given in Table 4.

5.2 Spectrum Sharing Schemes Performance Evaluation

Before investigating the actual simulation results, let us first observe allocation of the common pool for localized per half building spectrum sharing case when one operator asks and the other grants a favor. Assume operator OP1 requests a favor over subarea A2 to get an exclusive use of 2ccs the common pool. OP2 has two FAPs on subarea A2 and 3FAPs on sub area A1. When OP2 grants the required favor, FAPs of OP2 installed on sub area A2 stops using 2 CCs from the common pool. At the given stage game, as shown in Figure 12, FAP1 and FAP2 of OP2 can use only 2CCs of own operator. The rest FAPs of OP2 and all FAPs of OP1 share the spectrum pool simultaneously. After the expiration of favor exchange valid time, utilization of the common pool returns to default state.

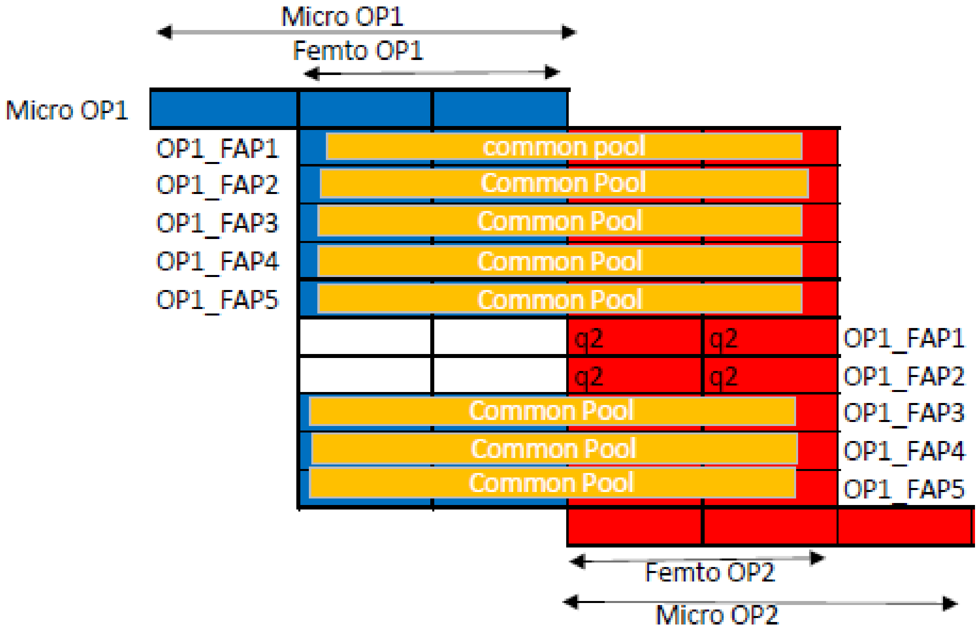


Figure 12: An example where Operator 2 turned off its femto1 and femto2 in the selected area from the common pool due to the granted favor for Operator1.

5.2.1 User Distribution

During the simulation, the number of users follow Poisson distribution with mean N_{OP1} for Operator 1 and N_{OP2} for Operator 2. We observe two scenarios where the operators have equal and unequal mean number of users for the given whole area of 400 buildings. For the first considered scenario when the operators have symmetric mean network load, we take a mean number of users for both operators $N_{OP1} = N_{OP2} = 800$. In the second scenario, the simulation carried out with the operators having asymmetric mean number of users in the shared area. For this case we set $N_{OP1} = 800$ and $N_{OP2} = 1200$.

As we have discussed in the previous chapter, with spectrum sharing game, an operator can get a spectrum usage favor from lightly loaded operator and improve its performance. On the other hand, less loaded operator deteriorates its user throughput for giving a favor for the other operator. In case of asymmetric mean number of users between operators, thus a load reversal considered to balance the exchanged number of favors between the operators. In the first 200 rounds of the simulation, we set the mean load for operator OP1 is 1200 and 800 for operator OP2. Then for the latter half of the simulation, the mean load for operator OP1 is 800 and 1200 for operator OP2.

5.2.2 Simulation Results

The performance of localized and non-localized spectrum sharing mechanisms evaluated in the Manhattan-like grid model of 20 x 20 buildings. Users distribute inside and outside of the buildings according to the used distribution model discussed in subsubsection 5.2.1. The assumed repeated spectrum sharing game between the operators (OP1 and OP2) performed in a 400-stage game, where a single stage game represents an exchange of favor in one building. Operators' load and inter-operator interference varies in each building. The gain/ loss of each operator recorded in each building and the threshold values updated in each round. Thus, the gain/loss of an operator at one building affects the decision of the operator at the next building. Initially the threshold values are set arbitrarily equal to $\lambda_{O,1} = \lambda_{O,2} = 1$ and $\theta_{O,1} = \theta_{O,2} = 1$.

Simulation results are presented in terms of the cumulative distribution function (CDF) of the throughputs obtained in all the spectrum-sharing scenarios, generated according to the aforementioned parameters. The user rate CDFs are plotted for operators OP1 and OP2 with respective symmetric and asymmetric Poisson distributed mean number of users.

The simulation results depict the following spectrum sharing scenarios:

- **Orthogonal spectrum sharing (Orthogonal-SS):** The operators utilize their own spectrum orthogonally.
- **Non-Localized spectrum sharing (Non-Localized-SS):**The sharing of the common spectrum pool agreed at the total geographic area level thus, both operators utilize the common spectrum pool jointly over the shared area.

- **Localized per building spectrum sharing (LocalizedBuilding-SS):** The operators agree exchange of spectrum favor per building level i.e. operators exchange always a big favor.
- **Localized per half-building spectrum sharing (LocalizedHalfBuilding-SS)**: The exchange of spectrum usage favor is agreed per half building. The spectrum sharing favor consists an option of either small or big favor.

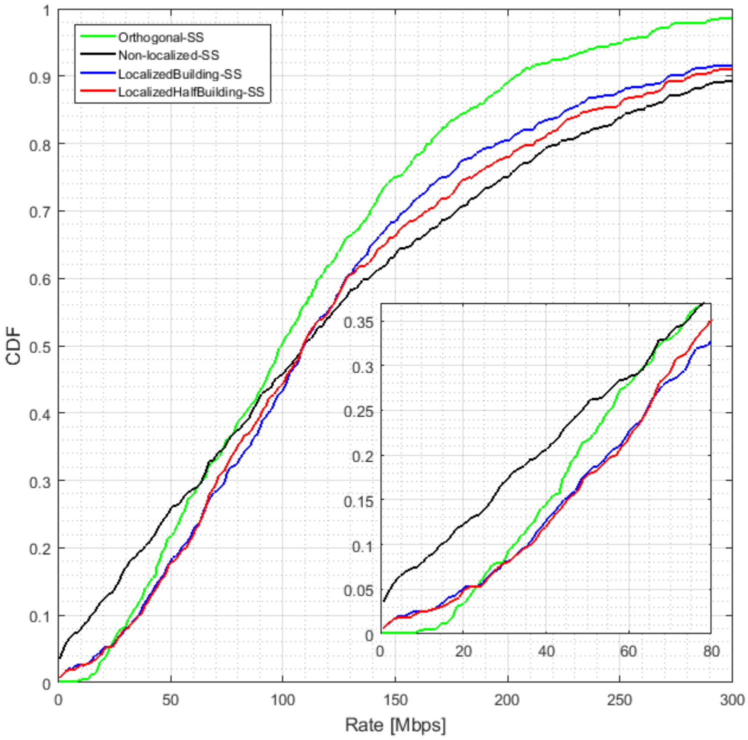


Figure 13: User rate distribution of Operator 1 for symmetric mean loads.

In Figure 13 and Figure 14, the simulation results for Operator 1 and Operator 2 with orthogonal, non-localized, localized per building, and localized per half-building spectrum sharing mechanisms are depicted. The results for the considered spectrum sharing mechanisms are obtained in a situation where the operators have equal mean number of users, $N_{OP1} = N_{OP2} = 800$, in the shared geographical area. The simulation results in Figure 13 and Figure 14 are tabulated with the user rate at the 5th percentile and mean throughput variables for all the considered spectrum sharing scenarios in Table 5.

The results for Operator 1 and Operator 2 with the non-localized, localized per building, and localized per half-building spectrum sharing shows a significant improvement compared to the results of orthogonal spectrum sharing. In Figure 13, the non-localized spectrum sharing in comparison to the orthogonal static allocation,

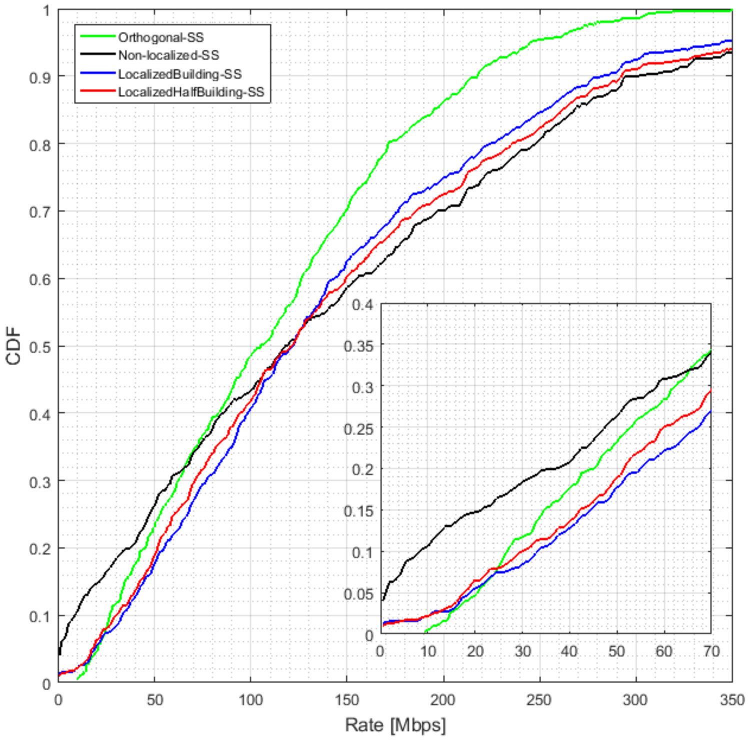


Figure 14: User rate distribution of Operator 2 for symmetric mean loads.

Table 5: Mean throughput and 5th percentile user rate for symmetric mean loads

Sharing Mechanism	Mean throughput[Mbps]	User rate at the 5% of the CDF [Mbps]
	Operator 1	
Orthogonal-SS	111.47	23.00
NonLocalized-SS	140.65	2.94
Localized per Building-SS	135.83	20.54
Localized per halfBuilding-SS	139.83	21.31
	Operator 2	
Orthogonal-SS	114.32	20.80
NonLocalized-SS	146.59	1.49
Localized per Building-SS	144.94	20.14
Localized per halfBuilding-SS	148.52	18.00

delivers an improvement to the user rate distribution. Nonetheless, for 50 percent of the users the non-localized spectrum sharing introduces a significant loss, while the remaining 50 percent of users can benefit from the sharing mechanism. At the 5th percentile user throughput decreases from 23 Mbps to 3 Mbps when compared to the orthogonal spectrum sharing. With the non-localized spectrum sharing mechanism, 50 percent of users can achieve throughput above 120 Mbps.

Similar patterns are captured for Operator 2 in Figure 14. The result showed that around 54 percent of Operator 2 users' rate deteriorates with non-localized spectrum sharing, while the rest 46 percent users achieve a significant gain. At the 5th percentile Operator 2 users' throughput decreases from 20 Mbps to 1.5 Mbps when compared to the orthogonal spectrum sharing. This user rate deterioration in the non-localized spectrum sharing happens due to the inter-operator interference when the operators access the spectrum pool jointly. For the users located close to interference sources orthogonal utilization of spectrum yields a better throughput.

On the other hand, from the localized per building and per half-building spectrum sharing, almost all users of both operators enjoy a better data rate. At the fifth percentile, users attain almost equal throughput as of the orthogonal spectrum sharing mechanism. With localized per building and localized per half-building spectrum sharing mechanisms, 95 percent of users of both operators achieve a throughput of above 20 Mbps and 18 Mbps respectively.

Users' data rate distribution with the localized per building and localized per half building spectrum-sharing shows a minor dissimilarity of approximately 1-2 percent difference. This is due to the fact that, for users located near their serving base stations the localized per half building refines the closest interferences and results a better data rate. In case of localized per building spectrum sharing, it gives a better data rate for users located close to interferences and far from their serving base station. Thus, averaged over the total area the localized per building and localized per half-building spectrum sharing results almost the same performance improvement to the operators. Overall, from the simulation results we observed that the non-localized spectrum sharing introduces more performance loss to operators' user rate compared to the localized spectrum sharing.

In Figure 15, the exchange of favors between the operators for the localized per building and localized per half building spectrum sharing is depicted. During the localized spectrum sharing per building, Operator 1 receives exclusive access to the spectrum pool (part of it) for 41 percent of the buildings and it grants an exclusive access of the spectrum pool for 42 percent of the buildings for Operator 2. In the localized per half building spectrum sharing, the exchanged favor can be either for the half building or for the whole building. As the operators exchange more number of small favors the negligible difference in users' rate that we observed in Figure 13 and Figure 14 with the localized per building and localized per half-building spectrum sharing will become siginificant. In 17 percent of the buildings both operators utilize the spectrum pool jointly this is due to the fact that the operators have equal mean number of users.

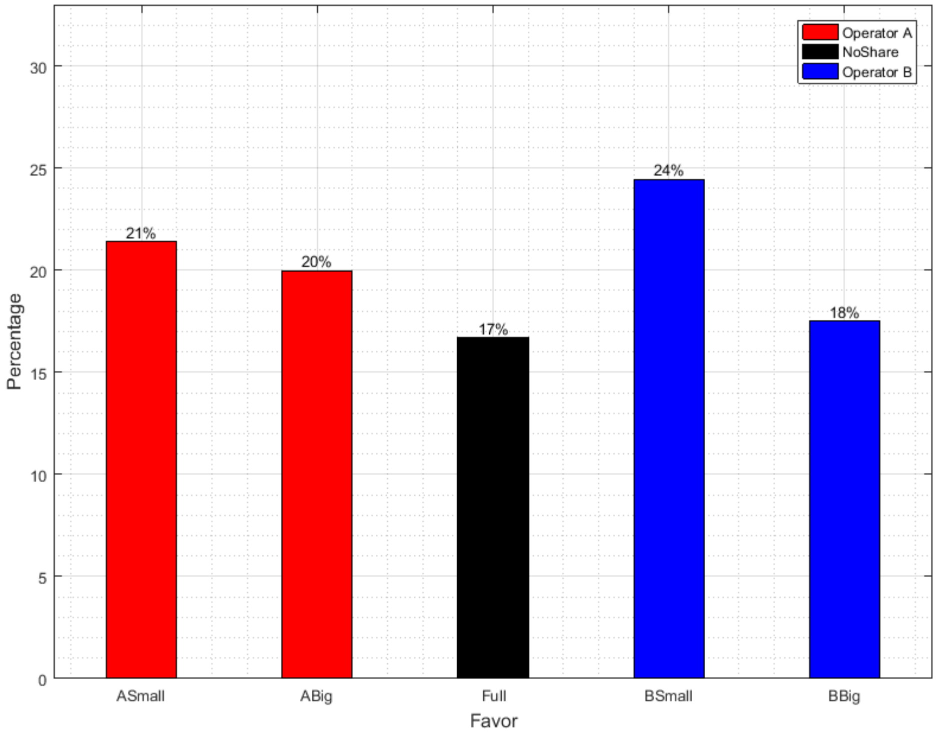
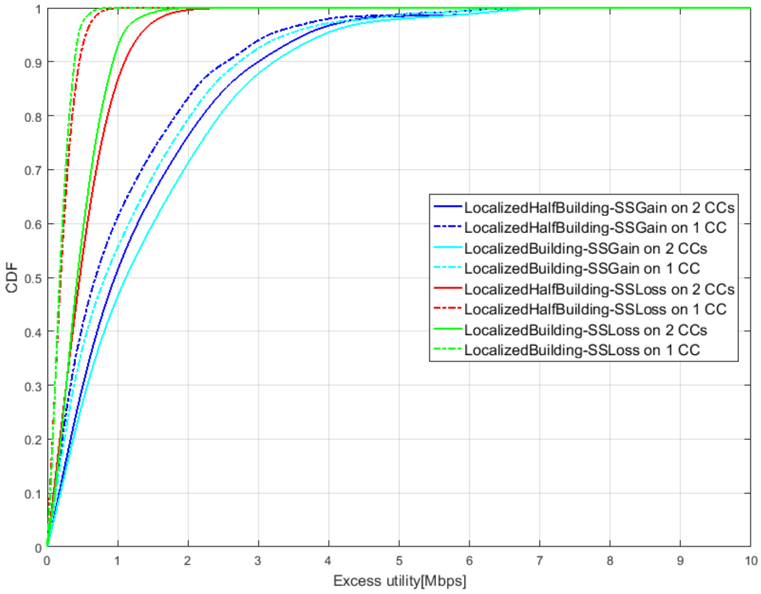


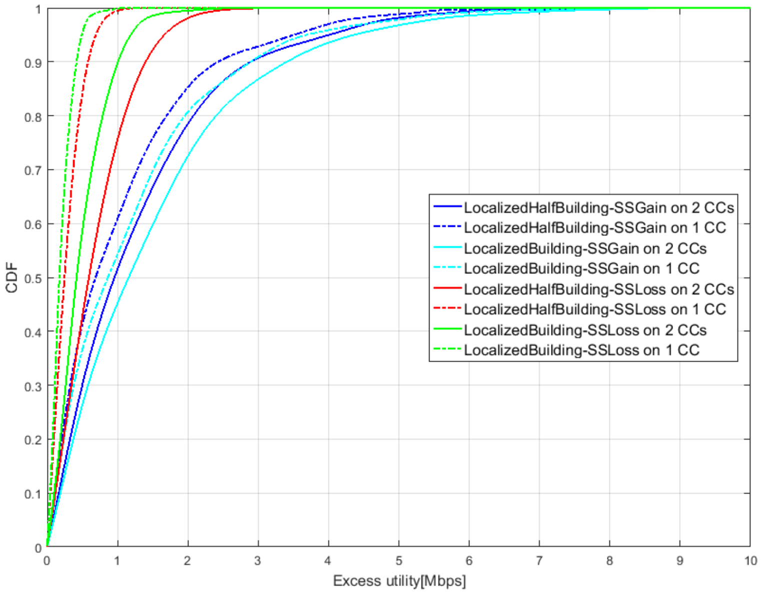
Figure 15: Share of different favors for Operator 1 and Operator 2 with symetric mean load case

In localized per half-building spectrum sharing case, the operators minimize their utility loss by favoring spectrum for the half of the building and maximize their utility gain by asking a spectrum usage favor over the building. On the other hand, in the localized per building spectrum-sharing case, the operators can ask and grant a spectrum usage favor for the whole building which maximizes their utility gain and utility loss as well. This characteristics is captured in 16(a) and 16(a). 16(a) and 16(a) shows the excess utility loss and gain of Operator 1 and Operator 2 for the localized per building and localized per half building spectrum sharing mechanisms with the exchange of 1 and 2 CCs. In case of localized per half building spectrum sharing, the more operators exchange a small favor the more the operators minimize their utility loss.

Next comes the second simulation scenario for the case when the operators have asymmetric mean number of users over the given shared geographical area. Figure 17 and Figure 18 shows the simulation results for Operator 1 and Operator 2 with orthogonal, non-localized, localized per building, and localized per half-building spectrum sharing mechanisms. The results obtained for Operator 1 and Operator 2 with mean number of users Nop1=800 and Nop2=1200 in the first half of the simulation and Nop1=1200 and Nop2=800 in the last 200 rounds of the simulation.



(a) Operator 1 Excess utility



(b) Operator 2 Excess utility

Figure 16: Excess utility loss and gain of Operator 1 and Operator 2 with 1 and 2 CCs and symmetric mean load between the operators

The users rate at the 5th percentile and the mean throughput for both operators with all the considered spectrum sharing scenarios tabulated as shown in Table 6.

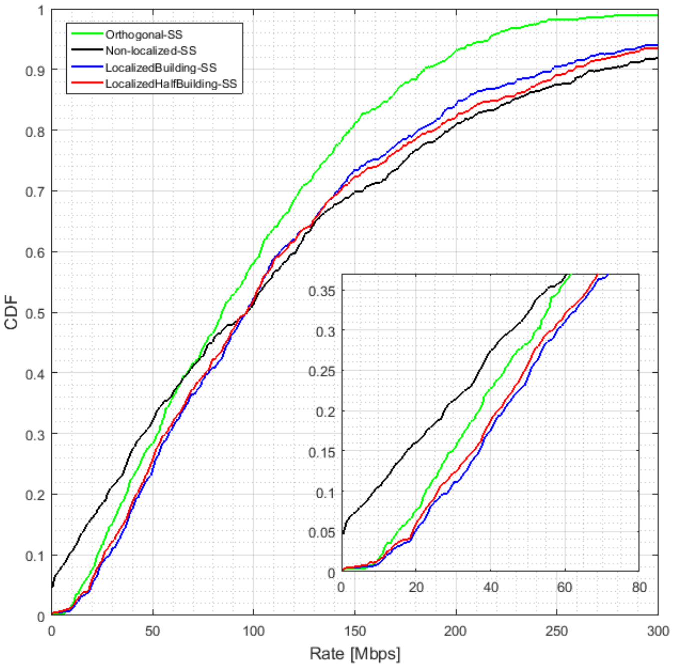


Figure 17: User rate distribution of Operator 1 for asymmetric mean load scenario.

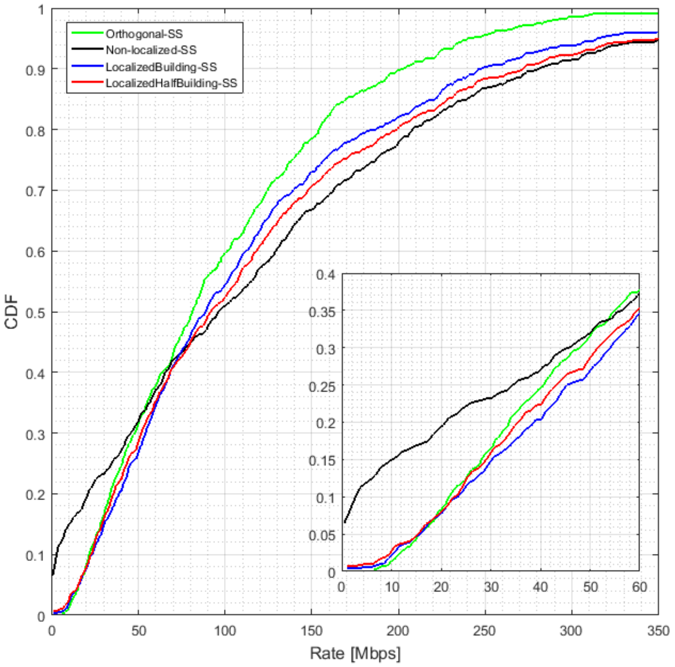


Figure 18: User rate distribution of Operator 2 for asymmetric mean load scenario.

Table 6: Mean throughput and 5th percentile user rate for asymmetric mean load scenario

Sharing Mechanism	Mean throughput[Mbps]	User rate at the 5% of the CDF [Mbps]
	Operator 1	
Orthogonal-SS	96.11	15.15
NonLocalized-SS	120.36	1.07
Localized per Building-SS	119.88	20.57
Localized per halfBuilding-SS	121.33	19.50
	Operator 2	
Orthogonal-SS	98.84	15.79
NonLocalized-SS	126.26	0.72
Localized per Building-SS	119.36	16.33
Localized per halfBuilding-SS	125.78	15.97

From Figure 17 and Figure 18, one can observe that the considered spectrum sharing mechanisms provide a better user rate for both operators. In Figure 17, when compared to orthogonal spectrum sharing results, 50 percent of Operator 1 users experience a lower throughput from the non-localized spectrum sharing scheme. However, it is shown clearly that the rest 50 percent of the users achieve 15 to 52 percent performance gain compared to the orthogonal spectrum sharing results. Users rate at the 5th percentile shows that non-localized spectrum sharing results 5 percent of users receive a user rate of less than 1 Mbps and the rest 95 percent of the users receive a throughput of grater that 1Mbps.

Similarly, from the non-localized spectrum sharing scheme, about 45 percent of Operator 2 users faces a considerable performance loss when compared to the orthogonal spectrum sharing. It is depicted in Figure 18 that the rest 55 percent of users achieve 20 to 46 percent performance gain from the non-localized spectrum sharing scheme. At the worst-case, 5 percent of users will get a throughput of less than 1 Mbps, whereas the rest 95 percent users achieve a user rate of greater than 1 Mbps. This loss to user rate in the non-localized spectrum sharing is due to the inter-operator interference introduced to each other because of the operators accessing the spectrum pool simultaneously. Even though this spectrum sharing scheme provides a better performance for about 50 percent of users, the user rate deterioration for the rest 50 percent of users is an acceptable.

It is showed in Figure 17 and Figure 18 that from the localized per building and localized per half building spectrum sharing mechanism both operators achieve a better user throughput. From the localized per building and localized per half building spectrum sharing, Operator 1 users achieve 15 to 50 percent improved user

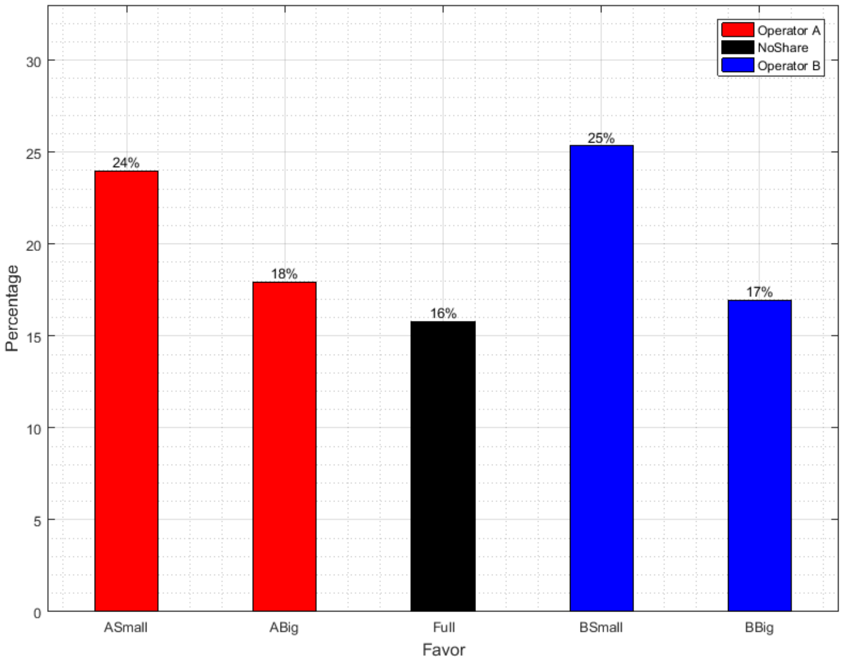
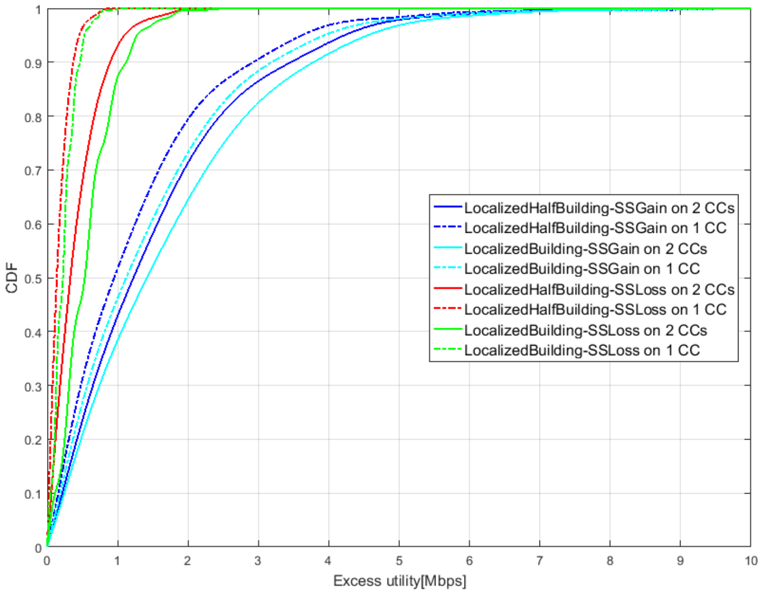


Figure 19: Share of different favors for Operator 1 and Operator 2 with asymmetric mean load case

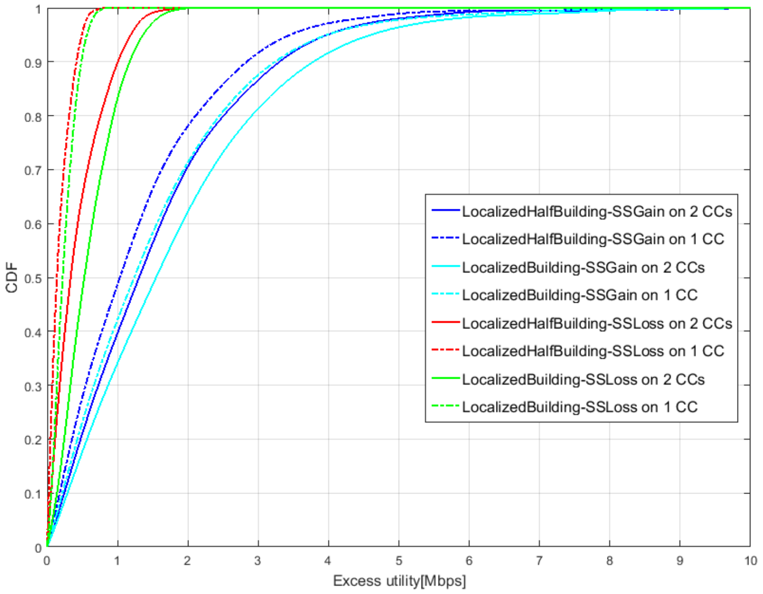
rate when compared to the orthogonal spectrum sharing mechanism. Likewise, Operator 2 users obtain 5 to 45 percent improved user rate. The results from the localized per building and localized per half building show a minor dissimilarity due to users' location and the number of small and big spectrum usage favor between the operators.

In Figure 19, the shared percentage of favors between Operator 1 and operator 2 during the localized spectrum sharing scheme is depicted. Out of the 400 buildings in the simulation environment, Operator 1 receives a spectrum usage favor for 42 percent of the buildings and Operator 2 receives a spectrum usage favor for 42 percent of the buildings as well. The rest 16 percent of the buildings the operators either have equal number of users or estimate high utility loss to grant a favor, thus both operators access the spectrum pool jointly. In localized per half-building spectrum-sharing case, the operators receive a spectrum usage favor for the entire building or half of the building. By granting a favor over half of the building, an operator can access the spectrum pool simultaneously at the other half of the building. Thus, the exchange of small favors facilitates a fair utilization of the spectrum pool between the operators.

Due to the choice of either a small or big favor in the localized per half-building spectrum sharing, the operators are to minimize their utility loss than that of the localized per building spectrum sharing where the operators exchange only big favors. 20(a) and 20(b) shows the excess utility loss and gain for Operator 1 and Operator 2



(a) Operator 1 Excess utility



(b) Operator 2 Excess utility

Figure 20: Excess utility loss and gain of Operator 1 and Operator 2 with 1 and 2 CCs with asymmetric mean load between the operators

with the localized per building and localized per half-building spectrum sharing case. As the percentage of small and big favor an operator becomes almost equal, the excess utility loss and gain from the localized per building and localized per half-building spectrum sharing scenarios shows a slight difference.

5.3 Summary

We have discussed a spectrum sharing at a building, half-building, and a big geographic area which consists of a number of buildings. We have evaluated and discussed the simulation results for each considered spectrum sharing mechanisms in comparison with the default orthogonal spectrum sharing scheme. From the simulation results, we have observed that both operators benefit from both the localized and non-localized spectrum sharing mechanism.

In the non-localized spectrum sharing case, it provides a major performance gain for half of the users. However, the performance loss it results for almost 50 percent of the users is unacceptable. The localized spectrum sharing, on the other hand results a significant user rate improvement for both operators. There is a slight difference between the results from the localized per half building and localized per building spectrum sharing scenarios. This difference in the simulation results occurs due to the distribution of the users in the given area.

In a situation where users dispersed throughout the building, a localized per building spectrum sharing delivers more performance improvement to the system than localized per half building. The more the users located close to their serving base station, the more the localized per half-building spectrum sharing results a better performance. Concerning a fair utilization of the spectrum pool between the operators, the localized per half building spectrum sharing provides the best result for both operators. Generally, we observed that during a spectrum sharing between operators the difference in number of user of the operators at a building level makes more difference than per big geographical area.

Overall, we can conclude that small scale spectrum sharing provides system performance improvement than spectrum sharing at a big geographic area level.

6 Conclusions and Future Work

6.1 Conclusions

This thesis work presents a study of spectrum sharing between mobile network operators. In the recent years, the concept of spectrum sharing has gained much attention and popularity in the area of wireless mobile communication. Driven by the enormous growth of wireless based applications and capacity starved UEs, MNOs showed a significant interest towards DSA and flexible use of spectrum instead of the traditional fixed spectrum allocation.

In this thesis, we study the problem of spectrum sharing between heterogeneous mobile operators located at the same geographical area. We propose localized and non-localized spectrum sharing between the operators based on the dimension of the geographic area used for sharing. Without revealing operator specific information, the operators participate in a repeated spectrum sharing game in a non-cooperative basis. The main aim of the study was to demonstrate how spectrum sharing improves MNOs delivered throughput. We intended to show how localized spectrum sharing outperforms the non-localized spectrum sharing through numerical simulation. The performance of these spectrum-sharing mechanisms evaluated in comparison to the static orthogonal spectrum-sharing scheme.

Through simulation localized and non-localized spectrum sharing shown to provide significant performance improvement in terms of user throughput in comparison to the static orthogonal spectrum sharing. From the simulation results, we observe that the performance of the spectrum sharing mechanisms affected by the operators' network traffic load, interference profile and users location. The main contribution of this thesis was to show through simulation the performance gain obtained by the localized spectrum sharing over the non-localized and orthogonal spectrum sharing. In the simulation results, we observed that the localized spectrum sharing outperforms the non-localized spectrum sharing mechanism. We conclude that sharing a spectrum at small scale provides a better performance, due to the fact that the variation of operators network load at smaller areas makes difference than large geographical area.

6.2 Future Work

Based on what we have done in our research work, there are possible directions we recommend for future work.

1. In the simulation, single story buildings have been considered for the case of localized spectrum sharing. It could provide more interesting results, if more challenging environment is taken, *e.g.*, walls inside the buildings, corridors.
2. During the simulation, the interference from the indoor femto access points to the outdoor users neglected with the assumption of thick outdoor walls.

Considering this interference could lead to new avenues to the research and could provide interesting find outs.

3. Increasing the number of operators participating in the spectrum sharing game is one possible direction for future work. The simulation has been performed with two operators instead it could provide a better improvement if it has been performed for N operators.

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