Frequency Selective Surface Assisted Dynamic Spectrum Access for the Wireless Indoor Environment

Elizar

MPhil

University of York

Electronics

October 2012

Abstract

This thesis investigates the impact of the use of Frequency Selective Surfaces (FSS) when applied to walls to improve the performance of indoor wireless communications. FSS controlled spectrum sharing is examined using a point-to-point network topology containing two different types of users, intra-room and inter-room, and considers a system with open spectrum access where all users have equal regulatory status. This approach is used together with FSS walls to smartly control resource assignment inside the building.

The FSS filter activation threshold is examined, using a threshold value measured from sensing interference in up to three spectrum bands. It is shown how using this threshold, and different FSS state activation strategies, can significantly improve the way an indoor wireless communications system can control its spectrum resources.

Different FSS activation strategies are explored. It is shown how the model where a specific value of FSS threshold is set and used throughout shows much better performance compared to situations where the FSS is either continually on or continually off. This performance can be further improved if a more deterministic value is used. This is achieved by using a sliding window average assessment of performance which aims to minimize the frequency of instantaneous FSS states changes; this means a statistical value is used to determine when to activate the FSS. The result shows that a longer sliding window tends to give a better performance for inter-room users without significantly decreasing the performance of intra-room users.

An analytical model of system performance using a two-dimensional Markov Chain is developed. Systems with One Available Spectrum (1AS) and Two Available Spectrums (2AS) have been analysed using a state-transition-rate diagram and global equilibrium expressions for both systems are presented.

Table of Contents

List of Figures

List of Tables

Acknowledgements

I would like to dedicate this thesis to my parents, as it is their continued endless love and encouragement that has inspired me to reach my dream to earn a better education and continue as far as I can go!!

I would also like to dedicate this thesis to my lovely wife Nana, my daughter Aisha and my baby boy Akhsan. Believe me, you all are the love of my life…

I would especially like to thank my first supervisor, Dr. David Grace for his invaluable advice, patience, constant support and insight throughout my research.

I am also grateful to my second supervisor, Dr. Paul Mitchell who offered me very useful comments and suggestions on this research work.

Further thanks go to my colleagues in the Communication Research Group for providing a pleasant environment to work and useful discussions. In addition, many thanks to all of my Indonesian friends in PPI York and all my Malaysian friends who were always cheering my day.

Declaration

All contributions presented in this thesis as original are as such to the best knowledge of the author. Acknowledgements and references to other researchers have been given as appropriate.

Chapter 1. Introduction

Contents

1.1 Overview

The significantly increasing demand of high data rate wireless communication services, as well as the continuous growth in the application and number of customers has resulted in an increase in demand for the frequency spectrum. This is a limited natural resource that may not be able to accommodate this fast paced growth in consumer demand.

The way the regulator overcomes this problem is by dividing the radio spectrum into non-overlapping small sections and assigning a specified frequency to an individual system by granting it license [1]. In this current spectrum regime, the regulator takes a maximum control approach to the management of the spectrum. They specify which band of frequencies can be used for which service, and which technologies should be used to deliver the service.

The conflict between inefficient use of the spectrum and the growth of spectrum demand calls for a more flexible and smart way to manage the spectrum resources. In the special case of an indoor environment, the use of *electromagnetic* (EM) shielding can be applied on the surface of an existing wall to further isolate interference between it and an adjacent coexisting wireless system. With the help of a material designed with a built in level of attenuation, when added with a special screening material such as Frequency Selective Surfaces (FSS) that can be fitted into the surfaces of wall, this could help in containing the leakage signal to be within the acceptable boundary. It is also possible to allow the required signal to propagate in the building and on the other hand to block an unwanted signal from propagating throughout the building.

1.2 Hypotheses

The rapid growth of wireless systems requires that coexistence between different heterogeneous technologies becomes more crucial and be addressed. The development of Dynamic Spectrum Access (DSA) enables the foundation of such mechanisms to allow Non-Priority Users (NPU) to share allocated spectrum subject to not imposing significant interference to Priority Users (PU) who own the frequency band.

We propose a cognitive coexistence framework of wireless indoor communication with the help of an external communication system entity called an FSS wall. The purpose of this thesis is to explore how FSS based spectrum sharing can be applied in such a communication system. This work concentrates on the way FSS works by exploiting the use of Dynamic Channel Assignment (DCA) to develop a robust scenario for communication between users inside the building.

FSS walls are walls with Frequency Selective Surface technology that have capability to continually observe and gain information from surrounding wireless indoor users and use that information to help the wireless indoor system significantly reduce interference between users. It is assumed that FSS walls have a restriction mechanism in place to work together with wireless indoor systems to increase the performance of the communication system.

We will firstly discuss the mathematical analysis of coexistence in spectrum sharing in an indoor wireless environment. This research provides the analysis of spectrum utilization for wireless indoor communication by using the Markov model. The system is modelled as a three-dimensional continuous time Markov model. Precisely specifying the state-dependent transition rate for each indoor user will lead to the understanding of the performance of users with different scenarios. The analyses provide a good understanding of how to measure the performance of wireless indoor communication with or without the presence of FSS.

In practice, the way the restriction mechanism of an FSS wall works is by having two different FSS state (FSS Continually ON and FSS Continually OFF) activations. Those two states can be activated by using instantaneous information gained from the system. FSS state activation can also be defined by using fixed interference thresholds also gathered from the wireless indoor system. This mechanism makes the FSS wall cognitively switch between two states depending on the interference analysis of the wireless indoor system. We will discuss those three activation mechanisms and compare which will give the best overall performance. Furthermore, this thesis will compare the performance of FSS fixed threshold activation mechanisms with FSS half dynamic threshold activation mechanisms in the form of interference analysis from look up table. The FSS threshold activation look up table is formed from the FSS wall activation categorization system based on the value of FSS_{thres}. FSS_{thres} itself is based on the value of Offered Traffic (OT) given by the system and it varies in the range of $0.5 \leq FSS_{thres} \leq 1$. FSS_{thres} value of 0.5 can be interpreted as the FSS wall ON state activation when the OT of the system has reached an instantaneous value 50% of the overall capacity of the system.

This system works by grouping the OT into several categories; we will discuss that system in detail in chapter 5. FSS wall activation that is based on a look up table system is needed to minimize the effects of the use of instantaneous threshold value resulting in fast flipping state changes between FSS ON and FSS OFF state.

Finally, this thesis will introduce the FSS fully dynamic threshold activation mechanism with the use of a sliding window averaging the traffic load with a specific slot range. This model will record the measured traffic load every time activation is successful and average the sum of those recorded with a specific value of window size. Using averaged values of generated OT will minimize the effect of fast flipping state and increase the overall performance of the wireless indoor systems.

1.3 Prearrangement Spectrum Model

Generally we can prearrange the spectrum for all three models shown in Figure 1.1 and it is structured as follows:

- **One Available Spectrum (1AS)** model. This model has one spectrum available and that is spectrum f1. Inroom is their default *Priority User*, which means that it can occupy the entire channel with any restriction for all the time. In this model, Outroom is the opportunistic user, and does not have its own working spectrum. Outroom only works in spectrum f1 with a conditional set based on the availability of f1 channel.
- **Two Available Spectrums (2AS)** model. This model has 2 spectrum bands available, which are spectrum f1 and f2. Inroom is the default user of spectrum f1 and Outroom is the default user in f2. Inroom can only access the available channels in f1, however they can do so at any time, without any conditional restriction. On the other hand, Outroom can access both frequencies and find the availability of channel in f1 and f2. In the case of working in spectrum f1, Outroom is the opportunistic user and only works in spectrum f1 with a conditional set based in the availability of f1 channel.

- **Three Available Spectrums (3AS)** model. This model has 3 spectrums in total, which are spectrum f1, f2 and f3. Spectrum f1 has the availability of 12 channels, f2 with 6 channels and f3 with the availability of 12 channels in total. Inroom is the default player for both spectrum f1 and f2, so it has full access to both spectrums for the entire time. Outroom works in default in spectrum f3, but can access spectrum f2 and find the availability of channel in f2. In the case of working in spectrum f2, Outroom is the opportunistic user and only works in spectrum f2 with a conditional set based on the availability of f2 channel.

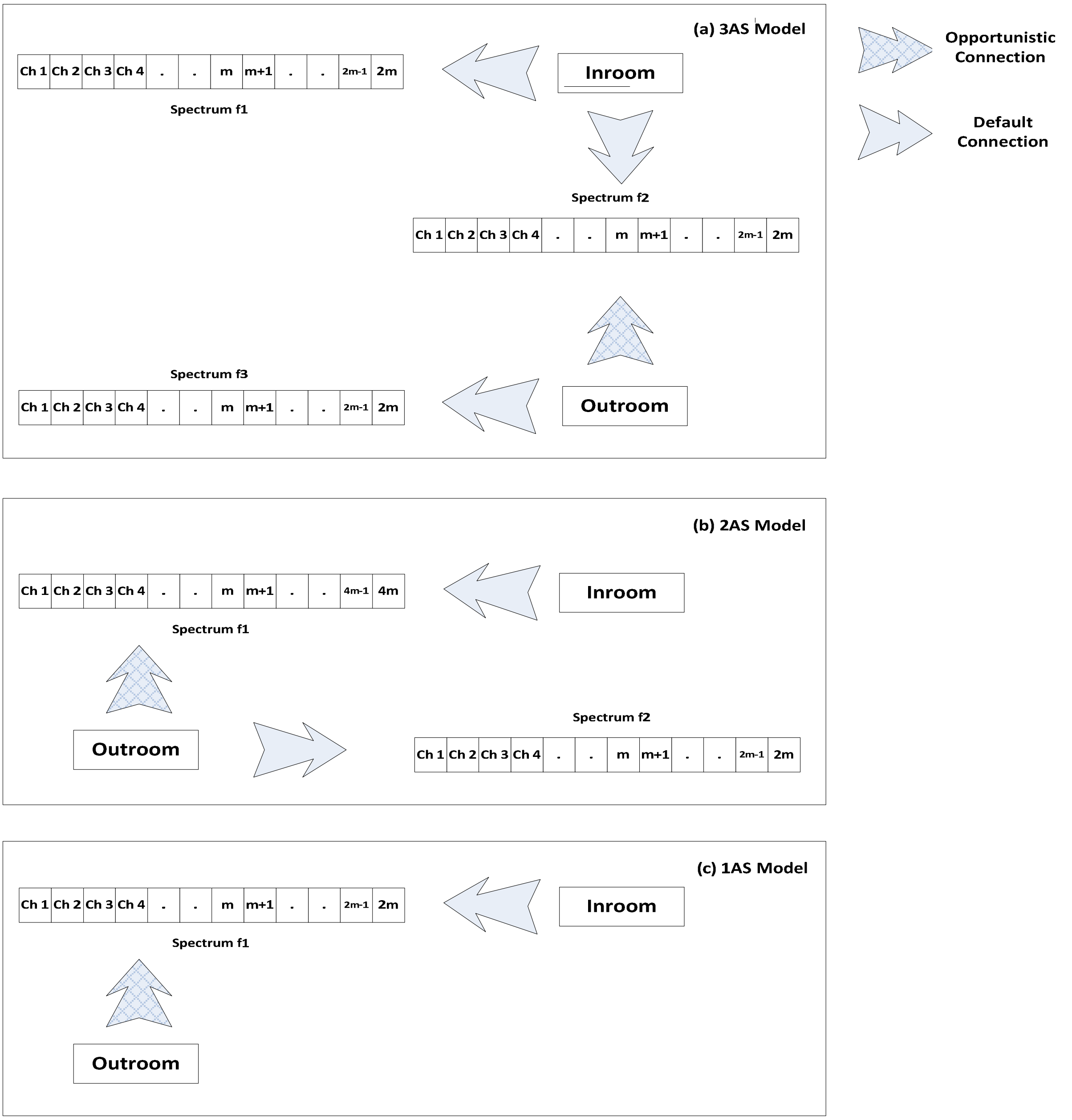

Figure 1-1.Prearrangement Spectrum Model

1.4 Organization of the Thesis

The remainder of this thesis is comprised of the following chapters:

- **Chapter 2.** This chapter introduces the basic background of several concepts that are used in the thesis. First, an overview of wireless coexistence in the context of wireless standards is presented. Then it will give a brief introduction to *Dynamic Spectrum Access* (DSA). Next it continues in discussing *Cognitive Radio* (CR), and, afterward, some basic principles of the smart building environment and their application to improve indoor communication by using *Frequency Selective Surfaces* (FSS). The last part of this chapter is devoted to the description of the basic of interference model together with the indoor propagation models that are widely used in this research.

- **Chapter 3.** This chapter gives a brief introduction to the simulation techniques and the simulation and analytical tools that have been used to evaluate the performance of the system scenario. The parameters used to evaluate the performance are also described. It then determines the suitable Channel Proportion (CP) to be used and the discussion continues to describe the performance range of each scenario. Finally, simulation validation in comparison with *Engset Distribution* is then presented.

- **Chapter 4.** This chapter will introduce the mathematical analysis of coexistence in spectrum sharing in indoor environments. Firstly it will begin with the Markov analysis of the *No Restriction* model and continue the analysis with a model that imposes the restriction mechanism, including the FSS based restriction mechanism and users own spectrum occupancy based restriction mechanism. The analysis will cover all state-transition-rate diagrams together with the blocking probability equation analysis for each mechanism.

- **Chapter 5.** This chapter introduces the FSS based spectrum sharing in smart indoor environments which define the better and more efficient usage of spectrum and increased performance for users. All models presented in this chapter were developed to further investigate the system performance where FSS continually ON and FSS continually OFF are used to measure the performance in relation to the *Offered Traffic*. We continue the discussion with proposing the model with FSS Fixed Threshold, which performed much better when compared with FSS continually ON and FSS continually OFF for both Inroom and Outroom users.

- **Chapter 6.** This chapter will introduce the use of dynamic table, this table functions as a look up table for use by the FSS to determine the state activation. The use of this table can reduce the instantaneous FSS threshold value, as it incorporates the better catagorization of the FSS threshold value in relation to its respective *Offered Traffic*.

- **Chapter 7** This chapter provides some ideas to take the research in this thesis forward.

- **Chapter 8** The main conclusions and the novel contributions of this work are summarized.

Chapter 2. Background Theory

Contents

This chapter will firstly discuss wireless coexistence in the context of the wireless standards that are designed to operate in the indoor propagation environment. Then it will give a brief introduction to *Dynamic Spectrum Access* (DSA) in the virtue to discuss more complex spectrum sharing in a new regime spectrum management, next it continues in discussing *Cognitive Radio* (CR), and afterwards with some basic principles of the smart building environment and their application to improve indoor communication by using *Frequency Selective Surfaces* (FSS). Finally, it also explains the basic of interference model together with the indoor propagation models that are widely used in this research.

2.1 Wireless Coexistence in Homogeneous Network

Indoor wireless systems are very popular for low cost connectivity in workplaces and in home applications. At the moment, most of the applications use the unlicensed ISM band, which becomes a problem as those bands are expected to be overcrowded.

The wireless standards that are working with this unlicensed ISM band are inherently designed to take into account the coexistence issues. However, they only provide active mechanisms within a homogeneous network. Most indoor wireless devices use standards such as 802.11a/b/g, Bluetooth, and Zig-Bee which share the same spectrum and will often be located in close physical distance to one another.

Technically, most of these standards work to avoid interference between each other by virtue of their use of spread spectrum techniques. In the context of 2.4 GHz, the spectrum where most of these technologies operate, the presence of interference is almost always confined to a reduction in the data rate as more packets need to be resent [2].

Bluetooth uses the Frequency Hopping Spread Spectrum (FHSS) and is allowed to hop between 79 different 1 MHz channels also in 83 MHz ISM band. When the Bluetooth transmission occurs on a frequency that lies within the frequency space occupied by a simultaneous 2 Wireless LAN 802.11 transmission, some levels of interference can occur, depending on the strength of each power radiated by the source transmitter [3].

Zig-Bee uses the Direct Sequence Spread Spectrum (DSSS). It has an output power of as low as 0 dBm, the lowest of all other technologies. It has 16 channels (11 – 26) centered on one channel with bandwidth of 2 MHz. In the case of Zig-Bee performance under varying Wireless LAN 802.11 interference patterns, Zig-Bee is critically affected by coexistence as its output power is much lower than Wireless LAN 802.11 networks [4].

The other Wireless LAN standard family of 802.11 also uses Orthogonal Frequency Division Multiplexing (OFDM) for its physical layer. The 802.11a operates in 5 GHz spectrum, using OFDM combined with a *Binary Phase Shift Keying* (BPSK), *Quadrature*

Phase Shift Keying (QPSK), and *Quadrature Amplitude Modulation* (QAM), depending on the chosen data rate. Operating frequencies for the 802.11a OFDM layer fall into the following three 100 MHz unlicensed national information structure (U-NII) bands: 5.15 to 5.25 GHz, 5.25 to 5.35 GHz, and 5.725 to 5.825 GHz [5]. The 802.11g standard with OFDM also operates in the 2.4 GHz spectrum, the same spectrum as with the previous 802.11b standard with backward compatibility, though it can provide higher data rate of up to 54 Mbps.

2.2 Dynamic Spectrum Access

The most important resource for wireless communications is spectrum. This spectrum is not an infinite resource, so it needs to be regulated. These regulations are designed to ensure the efficient use of the spectrum and provide many benefits to society. At present, spectrum is regulated by governmental regulatory agencies like OFCOM, FCC, BRTI, etc. An example of the OFCOM frequency allocation chart is shown in Fig. 2.1 [6].

Currently, the regulation in frequency allocation applies the maximum control allocation model by providing an exclusive assignment of a fixed frequency block for each communication service. In addition to the spectrum allocation, the regulator is also regulating the spectrum usage by specifying the type of service and the maximum transmission powers. It is also awarded for a long time interval to an exclusive licensee and, normally, over large geographical areas such as an entire country. The main motivation is to avoid unwanted interference between transmitters which requires having transmitters operating on non-overlapping spectrum bands.

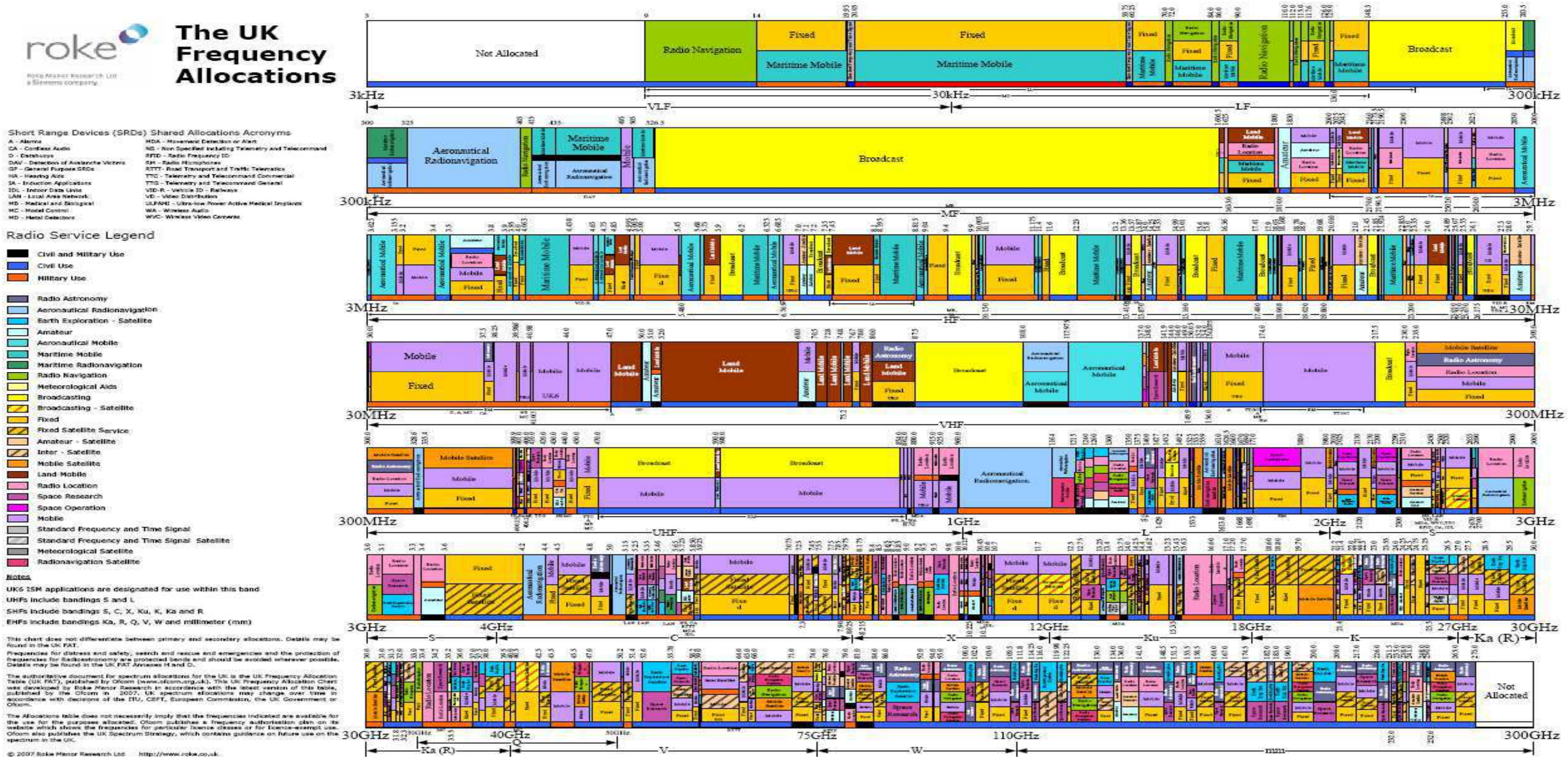

Figure 2-1. UK Frequency Allocations Chart (directly reproduced from [6])

A study reported in [7],[8],[9] shows vast temporal and geographical variations in the usage of the allocated spectrum. As an example, from a report in [7] which was conducted in part of the Greater London area, as shown Fig. 2.2. It clearly showed the variation of spectrum usage; the spectrum can be congested in one area, such as Central London, while it is being under-utilized in another area, such as Heathrow. A study conducted in the city of New York, as reported in [10], has shown that, on average, only 13% of spectrum opportunities were utilized. This static and inflexible spectrum licensing scheme leads to the inefficient use of the spectrum in terms of spectral efficiency as the licensed users who have the permission to use a certain portion of the spectrum cannot necessarily exploit this resource at all times or locations. At the same time this prohibits other users or service providers from accessing the unused spectrum, resulting in wasted bandwidth and making what it is available become expensive.

There are two different types of model for the study of Dynamic Spectrum Access (DSA) [11]: the Hierarchical Access Model and the Open Sharing Model. HA model considers two hierarchical users which are primary and secondary users. The primary user is a *Priority User* (PU) aka the existing system or the one which was granted a licence from the regulator, and the secondary user is a *Non-Priority User* (SU) which is the user that needs to share the spectrum, provided that the *Non-Priority User* defers whenever the primary needs the spectrum. The HA model considers two different spectrum sharing scenarios, the underlay and overlay approaches.

In the underlay approach, SU devices have been imposed with severe constraints on transmission power to keep the interference level they generate on the primary system below the noise floor. The best examples of this approach are the Ultra Wide Band (UWB) [12], [13], and the interference alignment system which are applied in MIMO systems [14].

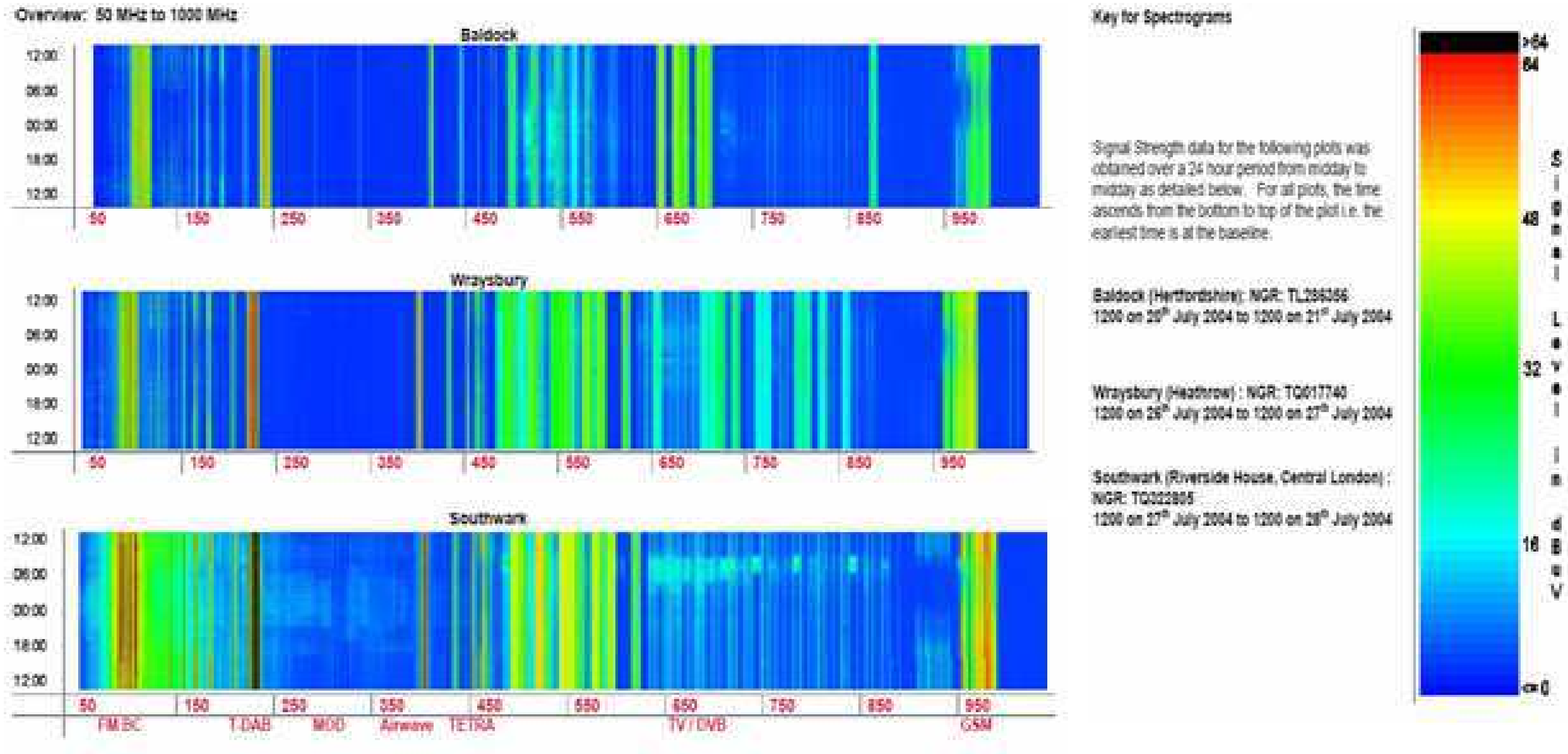

Figure 2-2. Temporal and Geographical Variations in the Usage of Allocated Spectrum (directly reproduced from [7]*)*

Differing from spectrum underlay, the overlay approach does not impose rigorous restrictions on the transmission power of secondary users, but rather puts restriction on how and when the secondary can transmit. Secondary users will commence sensing for the idle channel which is not being used by the primary users and opportunistically allow for the repossession of that channel during the unoccupied period[15], [16]. However, a secondary user will actively detect when the primary user accesses a channel that it is using and start to either move to any other available idle channel or be dropped by the system. This approach requires that both the PU and the SU do not transmit simultaneously in the same spectrum.

The PU, as a licensee who has been allocated frequency bands by the regulatory agencies, is not using them all of the time in all locations. At the same time, the spectrum regulation will create barriers to others who want to use spectrum locally but do not have the right to use the corresponding frequencies. What is clearly needed is a sharing policy such as Opportunistic Spectrum Sharing (OSS) which accommodates SUs to operate in corresponding spectrum without the consent of PUs of this band, as long as they do not interfere with the primary system[17], [18].

A reliable detection of the presence of the primary user still becomes a major problem for the implementation of the OSS system. In previous research findings, different types of spectrum sensing mechanisms have been explored for the ability to detect the presence of primary users, as in [19], they measure the power received signal during a predefined time period and a frequency channel and use that measured value as a threshold to decide the presence of the primary user.

Typically, secondary users can opportunistically access an idle channel in the form of non-occupied time slots in Time Division Multiple Access (TDMA)[20], frequency slots in Frequency Division Multiple Access (FDMA)[21], spatial direction in Spatial Division Multiple Access (SDMA)[22], tones in Orthogonal Frequency Division Multiple Access (OFDMA)[23] or even spreading codes in Code Division Multiple Access (CDMA)[24].

Some of the research being carried out considers the protection of the *Priority Users* (the user holds regulatory permission to operate in spectrum of interest) in order not to be interrupted by *Non-Priority Users*. For example, by determining the allowable transmitting power (power control) to guarantee a protected radius to *Priority Users* [17]. By using this approach, spectrum sharing between primary and *Non-Priority Users* will be enabled. The other approach is taken by constructing the system with equal regulatory status. In this type of approach, most research, such as in [25], [26] uses game theory concepts to better achieve distributed transmit power allocations.

2.2.1 Coexistence and cooperation

Currently, a potential trend in the current Telco industrial structure is the emergence of alternative spectrum management regimes, the so called unlicensed bands. With these new regimes, new technologies can be developed if they fulfil some of the very simple and relaxed “spectrum etiquette” rules to avoid excessive interference on existing systems.

Any device with different technology can be deployed in an unlicensed band without explicit permission, provided that the device operates in accordance with the rules. Today, regulators control access to the spectrum by granting licenses or establishing rules in an unlicensed band [27], [28]. However, the general development in spectrum management is toward increased flexibility and a more liberal approach to the assignment and management of the spectrum.

That is why coexistence between different heterogeneous systems becomes crucial—it makes mutual interference become a crucial problem when the systems use a shared radio spectrum. SU devices might attempt to coexist with the primary, when its presence goes unnoticed, and it then opportunistically accesses the spectrum. It can exist with the use of advanced interference sensors or Cognitive Radio techniques [29]. A guaranteed QoS for *Non-Priority Users* can only ensure it if the PU promises not to interfere. However, it can only be possible if it is also benefiting the PU, most likely for a fee, with a grant for static access to use the available spectrum for a longer period of time or a grant for dynamic access to the momentarily idle spectrum for small period of time [26].

Co-existence between indoor wireless standards within the same frequency spectrum is essential to ensure that each wireless technology maintains and provides its desired performance requirements. This research addresses coexistence issues simulating the interference network model in a smart building environment. It considers a system where all users have equal regulatory status, providing open access for all perspective users, and uses this approach in a more cognitive way to control spectrum sharing.

Alternatively, a SU device may cooperate with the PU. It could be through an explicit signalling protocol, where the SU device learns when it can operate safely without interrupting the PU device. As reported in [30], [31], cooperation between users can achieve a better system capacity and increased spectrum utilization.

In addition to the goal of maximizing the overall spectrum utilization, for good spectrum sharing we should also think of a way to achieve fairness among dissimilar users and of how to coordinate their access to lighten interference with each unlicensed user and avoid conflict with the *Priority Users*.

2.3 Cognitive Radio

Cognitive Radio (CR) is an emerging idea to implement this kind of spectrum sharing because of their ability to sense the spectrum and dynamically allocate their usage accordingly. CR is also considered a novel approach in dealing with the problem of spectrum scarcity in wireless communication system [15]. CR involves several parts of communication systems and uses some intelligent strategies so they are capable of responding autonomously to the changes in their communication environment.

Joseph Mitola, in his PhD dissertation [32], is the first person to propose the concept of Cognitive Radio. In his previous paper [33], he defined a Cognitive Radio as *"A radio or system that senses, and is aware of, its operational environment and can dynamically and autonomously adjust its radio operating parameters accordingly"*. This is essentially a Software Defined Radio (SDR) system with artificial intelligence, sensing capability and reacting according to its environment.

The term cognition itself traditionally has been used to describe a human thinking process in reference to their awareness of their surroundings and that they somehow react to any changes by learning, elaborating and adjusting. In this way, a human will keep memories, working to understand languages, problem solving and making decisions. Similarly, for a radio system to match the criteria of cognition it needs to include the process to learn from previous events, gain knowledge, and dynamically adjust communication parameters to improve their system performance. As such, all those criteria are in line with the definition of Cognitive Radio suggested by ITU-R [27] as follows '*a radio system employing a technology, which makes it possible to obtain knowledge of its operational environment, policies and internal state, to dynamically adjust its parameters and protocols according to the knowledge obtained and to learn from the result obtained*'.

The FCC, on the other hand, describes a Cognitive Radio [28] as a system which *"could negotiate cooperatively with other spectrum users to enable more efficient sharing of spectrum. A cognitive radio could also identify portions of the spectrum that are unused at a specific time or location and transmit in such unused 'white spaces,' resulting in more intense, more efficient use of the spectrum while avoiding interference to other users"*

A CR user is an independent unit in a wireless communication environment and in order for it to use the spectral resource efficiently, it should:

- Sense the interference; normally it will use the interference as a main sensing object to sense spectral environment over a wide bandwidth.
- Implement the communication etiquette and be fair to other CR users; normally it will adapt its power level or transmission bandwidth to avoid interference with other CR users.
- Keep the *Priority Users* (spectrum licensee) informed, at the least, it should detect their presence.
- Be self-modification capable; normally it will learn from previous experience to optimize the use of the spectrum and deal with new conditions.
- Apply a knowledge base as databases to support a learning and reasoning engine to optimize future output.

A CR intelligently optimizes its own performance in response to user requests and its communication environment. The way a cognitive radio responds to the requirement of the environment is not necessarily predictable, due to its ability to learn and update its intelligence based on its past experiences. Thus the CR then is able to cleverly bring forward certain transmissions depending on the availability of resources.

2.4 Smart Building Environments

A smart environment can be defined as '*a system that is able to acquire and apply knowledge about the environment and its inhabitants in order to improve their experience in that environment'*[34]. The ability to acquire and apply the knowledge can be gained from the automation process which can be viewed as a cycle of perceiving the state of the environment, completing the task, and acting upon the change of the state of the environment.

On the other hand, a smart or intelligent building can be defined as '*a building that utilizes the use of information technology and control systems to make the functioning of the building more useful to its occupants, in relation to its management, or in respect to the building's operational purposes'* [35].

A smart building environment is essentially a building which implements an automation system that can perceive the state of the environment through the use of information technology and control systems, and can apply that knowledge to improve the experience of the building occupants. The cutting edge of this distributed automation system is the use of sensors which are situated throughout the building walls and transform the infrastructure into an intelligent wall.

The intelligent wall itself, as reported in [36], can be defined as *'a self-configuring and self-optimizing part of a pre-installed collaborative autonomous infrastructure which uses Distributed Artificial Intelligence (DAI) to help dynamically control a Frequency Selective Surfaces (FSS) multipath propagation and energy focused towards certain part of building'*. The sensor and DAI in intelligent wall will work together and merge with the CR algorithm, to achieve better performance of the wireless indoor communication.

2.4.1 Frequency Selective Surfaces (FSS)

Frequency Selective Surfaces (FSS) are the most influential part of an intelligent wall. In general as defined in [37], FSS is *'an array of periodic apertures in a conductive surface that, when illuminated by an electromagnetic wave, exhibits total transmission around the resonance frequency'*.

The FSS structure will perform a filter operation depending on its physical construction. So, it can be behave either low pass, high pass, band pass or band stop, and is tuned to a bandwidth that covers the frequencies of interest. Typical FSS types and their responses are shown in Fig 2.2.

The FSS can be beneficial in creating small isolated zones by delimiting the space of use. It can be an advantage for Wireless LAN systems as it can raise their performance by increasing the spectrum re-use.

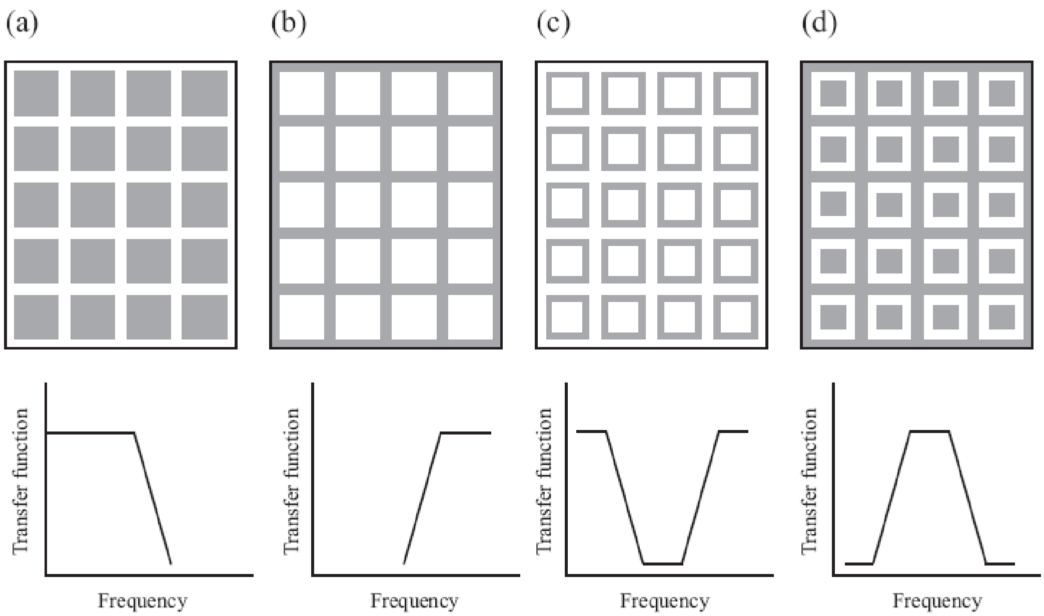

Figure 2-3. Typical FSS Types and Their Responses (directly reproduced from [23])

2.4.2 Some FSS Research in Wireless Technology

Modelling FSS in wireless environments has been reported in [38]. This research has simulated a building facility as an office environment partitioned with three isolated offices with support from Wireless LAN both at 2.4 GHz and 5.2 GHz. It is assumed the wireless communication occurs within a relatively short distance (<10 m).

In this research, the FSS walls were made from two layers separated by a spacer, each layer using a dielectric core of extruded polystyrene. The thickness dimension of both layers, plus cladding also made from dielectric material, was about 30 mm.

Their objective was to achieve the selectivity of frequency by allowing the signal of the user of 2.4 GHz to across a physical boundary and to block the signal of the user of 5.2 GHz. The separation between frequencies with appropriate shielding from FSS structure has proved that the 45 dB attenuation can be achieved in the stop band, with only 2–3 dB attenuation in the pass band.

In research reported in [39], the researchers made a simple wallboard from custom-designed band stop FSS as a cover of wall surfaces. This structure is constructed and tested by setting up the floor plan of two rooms. This structure was made to isolate the undesired 5.8 GHz and to allow 2.4 GHz signals to pass through. The transmitting antenna was located in the centre of room 1 and a receiving antenna with 30 different locations was used to measure the performance of Frequency Selective wall at various incident angles (0° - 55°) in the azimuth plane.

The measurement showed that this structure exhibited a band-stop response with attenuation of 15 dB at 5.4 – 6.0 GHz compared to an unmodified wall. This additional attenuation in the stop band is considered to be significant and beneficial for interference reduction. On the other hand, the pass band region of 2.4 GHz exhibited additional attenuation of less than 5 dB compared to the unmodified wall.

Mostly, research investigating the effect of FSS in indoor environment is based on the simulation of an FSS system in a ray tracing model. One example is a study reported in [40]. They have proposed a method of controlling signal coverage based on changing electromagnetic properties of FSS like intelligent walls. In this case they simply set the scenarios into a two wall state of ON and OFF. All scenarios were simulated using 3D ray tracing-based model simulation. They have shown that the intelligent walls have a positive influence on controlling the signal coverage and managing the level of service of the communication system in the building.

In another study reported in [41, 42], they also used 3D ray tracing model to study the effect of deploying FSS by simulating a simple scenario with or without FSS. The simulation was performed at 2 different frequencies (2.4 and 5.2 GHz) to highlight the frequency selectivity behaviour of the deployed FSS. The FSS that was simulated was a square-loop design tuned to 2.4 GHz and assumed to be constructed in FR4 dielectric material. They showed that FSS effectively reduced the interference to any other wireless systems operating at the same frequency outside of the external containing wall. They also confirmed that wireless systems operating with different frequency other than the FSS-tuned frequency can be used without any significant effect on its radio propagation characteristics.

2.5 FSS Wall Panel

Apart from FSS research which employs simulation to evaluate the FSS performance, there are some researches that specifically design and evaluate a physical FSS structure. Most of the designs are reflect/transmit FSS structure and all of them are still ongoing laboratory prototype and not in the market yet.

As reported in [43], they have been constructed a 2.1 m x 2.1 m x 0.7 m FSS panel made from three interlocking panel. They named it as Tetra Mode Conversion – FSS (MS-FSS) Panel because it was designed to resonate at 870 MHz (Tetra service band in some countries). The design use substrate material made from 9.5 mm plasterboard and an 80 mm air layer supported by a wooden frame with a total of 54 dielectric elements.

Performance of MS-FSS panel was evaluated by placing the panel in the right-angled corridor and in 2 scenarios, with or without the MC-FSS panel. They have proved that, at the design frequency 870 MHz, the MS-FSS panel generates an average signal level of -43.5 dB, which is 13.5 dB above the case when the MS-FSS panel not in placed.

In [40, 44], they have made a simple and low cost FSS wall by covering a building wall with a custom designed FSS cover. The FSS cover was constructed using conducting aluminium foil square loop and tuned at 2.4 GHz WLAN signals. Under such a scenario, they have achieved the attenuation of about 30 db greater than that of an uncovered wall at the resonant frequency. The achievable attenuation has allowed FSS structure to decrease a significant interference between users and thus achieve much better system performance.

In another project from Kajima Technical Research Institute [45], they have designed FSS glass structure printed with tripoles element made from silver past print (silver paint with 95% Ag) and tuned at 1.9 GHz. This FSS glass structure has obtained more than 35 dB attenuation at the resonant frequency. This design has proved to shield only 1.9 GHz device signal and let others to pass through.

Different from previous mentioned research, the project reported in [46, 47] have designed and tested a novel absorb/transmit FSS panel working for 5 GHz WLAN application as shown in Figure 2.4. The FSS structure divided into 2 layers, the first one is conventional conducting cross dipole with circular aperture in the centre and the second layer is made from resistive cross dipole. The absorption capability in stop band help reduce additional WLAN multipath, delay spread and resultant fading causes by typical reflect/transmit FSS structure, thus this panel have the potential as a security isolation wall for 5 GHz WLAN.

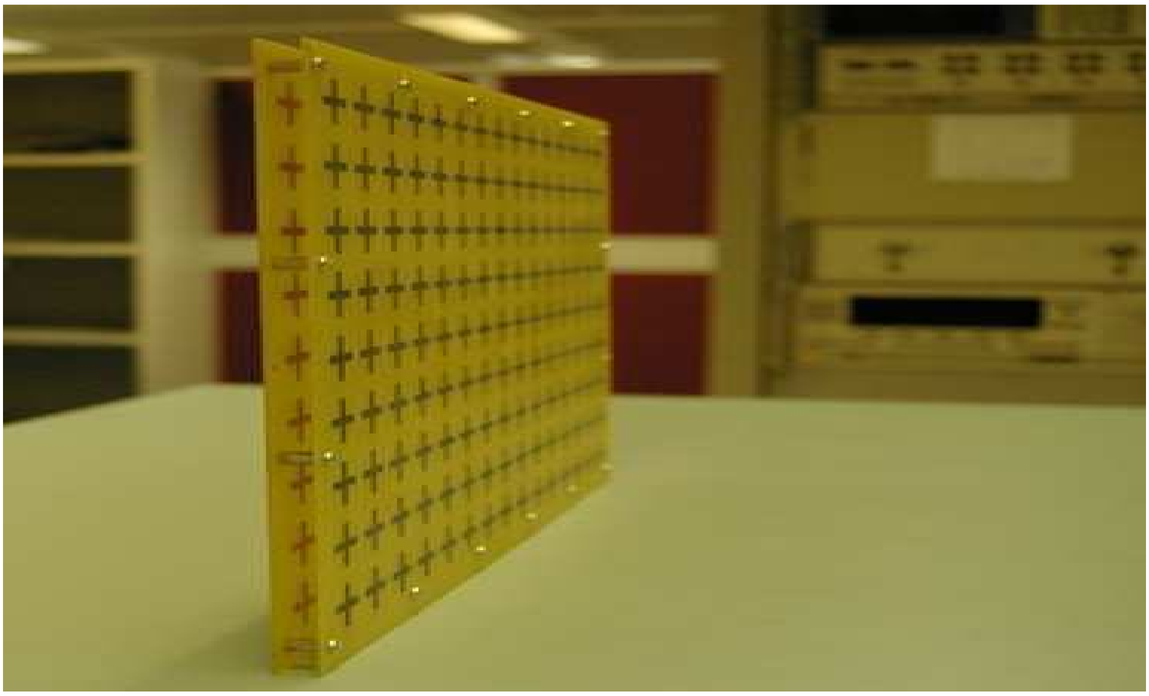

Figure 2-4 Absorb/Transmit FSS Panel (directly reproduced from[48] *)*

The latest publication reported in [49] have successfully designed a switchable FSS structure that can provide a better reconfigurable solution to enhance spectral efficiency and capacity of indoor wireless communication system. The design is constructed in FR4 dielectric material and based on square loop aperture geometry, with four PIN diodes across the aperture for each cell at 90 degree intervals. Figures 2.5 and 2.6 show the front and rear close view of the switchable FSS prototype. The overall size of FSS panel is 45 cm x 30 cm and the thickness of FR4 substrate was 1.6 mm. PIN diodes can be switched between forward and reverse bias to obtain an average of 10 dB additional transmission loss for both polarization at normal and oblique incidence. Positive dc biasing is applied from the front side of FSS and diagonal negative biasing came from the reverse side of the FSS prototype.

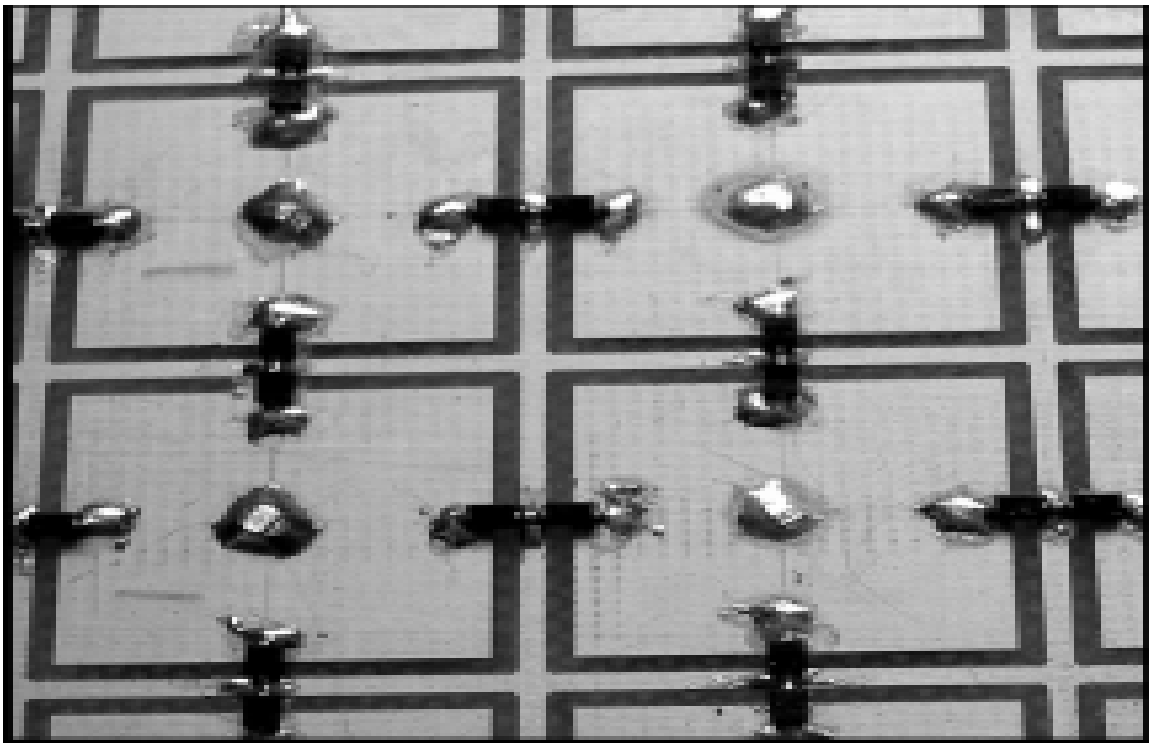

Figure 2-5 Front Close-up View of the switchable FSS Prototype (directly taken from[49]*)*

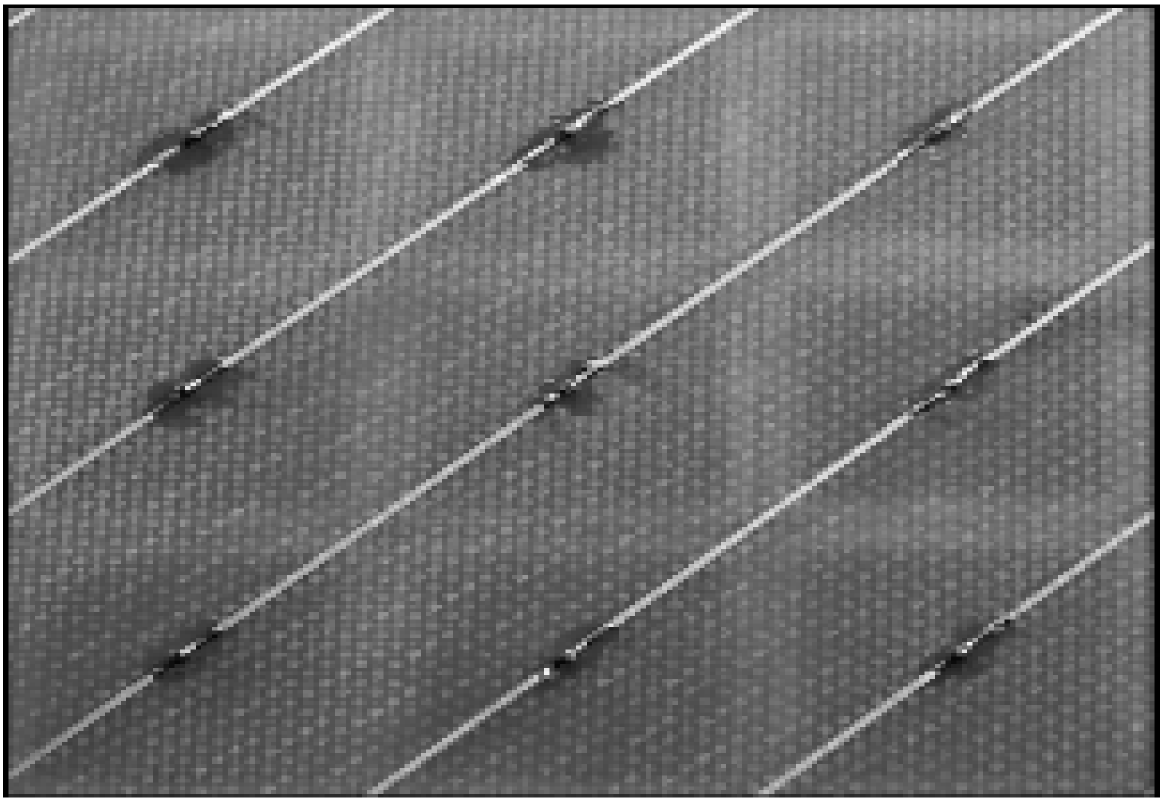

Figure 2-6 Rear Close-up View of the switchable FSS Prototype (directly taken from[49]*)*

2.6 Interference Model

Interference is the major factor that limits wireless systems from applying radio spectrum reuse. The use of channel assignment techniques can reduce interference significantly. However, co-channel interference caused by frequency reuse is becoming the most restraining factor on the overall system capacity in the wireless network. The main objective is to minimize the carrier-to-interference ratio by efficiently using the radio path loss characteristic and hence increasing the radio spectrum reuse efficiency [50].

Consider any two nodes T (for the transmitting node) and R (for the receiving node), where R lies within the transmission radius of T. We denote $\mathcal{N}_T$ and $\mathcal{N}_R$ as a set consisting of neighbours of nodes T and R respectively. We also denote P as the neighbours of transmitting node ($P \in \mathcal{N}_T$) and Q as the neighbours of receiving node ($Q \in \mathcal{N}_R$). A more detailed picture of interference model can be seen in Figure 2.4. For a transmission call made from T → R in channel c to be successful, the following criteria must be satisfied [51]:

1. Nodes T and R must not involve any other transmission/reception in channel c. This criterion ensures that a node cannot simultaneously serve two transmissions in the same channel.
2. Neighbours of transmitting node ($P \in \mathcal{N}_T$) must not receive any other data in channel c. Otherwise the transmission from node T will result in interference in data loss at node P. However, note that a node P can transmit in channel c if this does not violate criterion 3.
3. Neighbours of the receiving nodes ($Q \in \mathcal{N}_R$) must not transmit on channel c, otherwise, the transmission from node Q will result in the loss of data received at node R. However, note that a node Q can receive in channel c if this does not violate criterion 2.

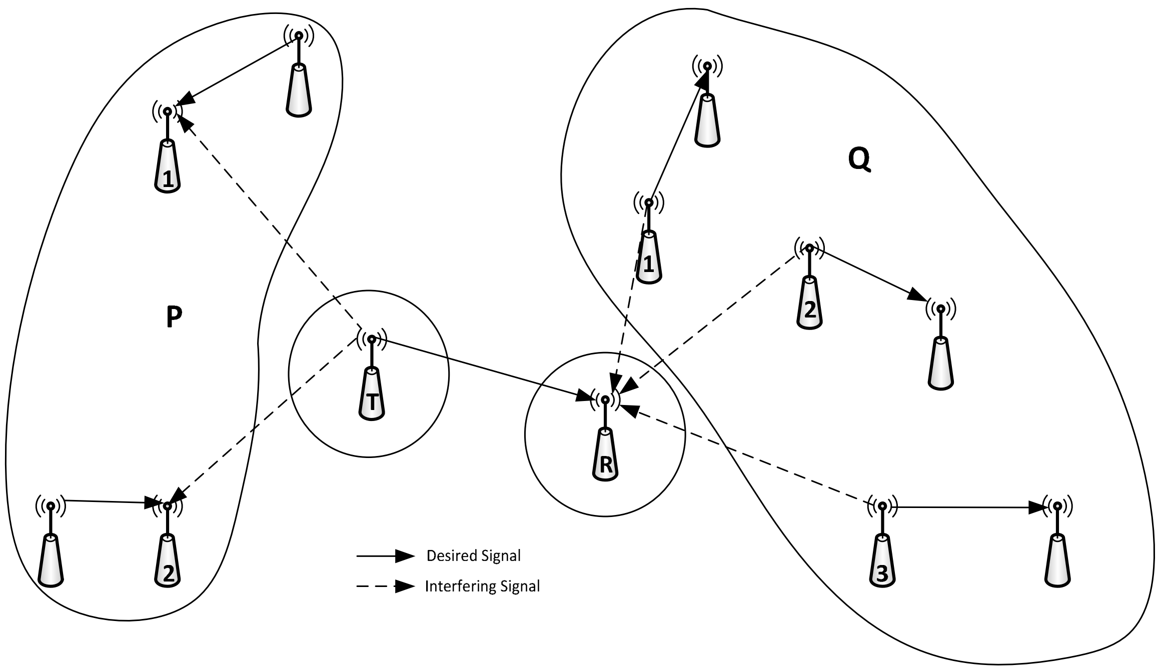

Figure 2-7. Sketch of the Interference Model

Moreover, we have P & Q as a neighbouring station which uses the same channel as the reference channel T → R to communicate with other stations. The average *Signal to Interference plus Noise Ratio* (SINR) at node R is given by:

$$SINR = \frac{P_t d_t^{-\alpha}}{\sum_{Q=i}^{n} P_i d_i^{-\alpha} + N_0}$$

where,

P_t = Transmit power of node T

P_i = Transmit power of node i

d_t = Distance of node T from R

d_i = Distance of node i from R

N_0 = Environmental noise

α = Propagation constant

As we can summarize from the equation above, some of the ideas to minimize SINR are as below:

- Physical separation between node: the shorter the distance, the more interference applied at node R
- Power transmit adjustment between interfering station: the more the power, the more interference applied at node R
- The increment of desired transmit power of P_t

Those basic ideas becoming the major concept for a channel assignment algorithm by separating co-channels and or by adjusting the transmitter power [52].

2.6.1 **Free Space Path Loss**

A very simple path loss model is one which considers a signal propagating in free space. The power radiated by an isotropic antenna is spread uniformly and without loss in all directions surrounding the antenna. The power received, P_r, by the receiving antenna which is separated the transmitting antenna with power transmitted, P_t, by the distance, d, is given by the Friis free space equation [53]:

$$P_r(d) = \frac{P_t G_t G_r \lambda^2}{(4\pi)^2 d^2 L} \tag{2.9}$$

Where G_t and G_r are gains of transmitting and receiving antenna respectively, λ is the wavelength in meters, and L is the system loss factor not related to the propagation model.

The path loss at point r can be defined as "*a measure of the average RF attenuation suffered by a transmitted signal when it arrives at the receiver, after traversing a path of several wavelengths*" [53].

So, it should be the ratio between transmitted power at r_0, $P_t(r_0)$, and received power at r, $P_r(r)$, and is given by [53]:

$$PL(dB) = 10\log\frac{P_t(\mathrm{r}_0)}{P_r(r)} \tag{2.10}$$

In the case of an isotropic antenna, it can be assumed to have a gain equal to unity, by inserting the eq 2.8 into eq.2.10 together with the assumption above:

$$PL(dB) = -10\log\left[\frac{\lambda^2}{(4\pi)^2 d^2}\right] = 20\log\left[\frac{4\pi d}{\lambda}\right] \tag{2.11}$$

In the case of predicting the propagation characteristics between two or more antennas located inside a building, in some cases it is necessary to consider the transmitted signal through Line of Sight (LOS) path to receiver, but in most cases it will be through the Obstructed Line of Sight (OLOS) path

2.7 Indoor Propagation Model

The increasing use of WLANs and personal communication system devices make the indoor propagation model crucial. Typically, a received signal in an indoor environment is mainly attenuated due to propagation reflection, diffusion and transmissions through building material, which can vary as much as 30–40 dB over a fraction of a wavelength [54].

As reported in research from [54, 55] building penetration loss is dependent on many variables including building structure and its geometry, building construction material, and mixture of small obstacle of items of metal, wood, and other objects. Generally, typical indoor obstacles are varying with a very small size of wavelength and normally with propagation distances of not more than 100 meters. In addition, depending upon carrier frequency, other effects caused by, for example, indoor movement of people, may be present. The sum of those effects largely control the way the radio link works in this type of environment.

The ability to accurately predict radio path propagation behaviour is becoming crucial to wireless communication system design. Since practical site measurements are costly, propagation models have been developed as a suitable, low-cost, and convenient alternative, particularly system simulation models. Therefore, it is important to define a suitable path loss prediction model, in order to provide design guidelines for a system simulation which better reflects a real system.

Generally, path loss prediction models can be divided into three categories [53, 56, 57]:

- Empirical Models, which are normally in the form of a set of empirical equations derived from extensive field measurements. These tend to be simple and accurate for the same characteristic environments. They require less computational effort but are less sensitive to changes in the environment.

- Site-specific Models, which are normally in the form of a set of equations derived from extensive computerized numerical results, where the input parameters are very detailed and accurate. They require a vast amount of data related to the environment, so they produce a large computer overhead.

- Theoretical Models, which are normally derived from ideal conditions, and assume physical parameters of the environment. In some cases in highly complex environments, the analysis becomes too complex, making it difficult to derive an equation based model.

2.7.1 Distance-Dependent Path Loss Model

A distance-dependent path loss model is the model which is based on unique parameters of attenuation and loss prediction taken from a number of experiments in various types of indoor environments in different locations and sites. It assumed that the mean path loss, $\overline{L}$, is an exponential function of distance, d, over a reference distance, d_0, usually equal to 1 meter, with power of mean path loss exponent, n, and given by [57]:

$$\overline{L}(d) \in \left(\frac{d}{d_0}\right)^n \tag{2.12}$$

So, the absolute mean path loss is given by [58], [59]:

$$\overline{L}(d) = L(d_0) + 10n\log\left(\frac{d}{d_0}\right) \quad [dB] \tag{2.13}$$

The reference path loss due to free space propagation is given by:

$$L(d_0) = 20\log\left(\frac{4\pi d_0}{\lambda}\right) \quad [dB] \tag{2.14}$$

The total path loss within a building may also need to include the influence of slow fading characteristics within the indoor link and is given by [59]:

$$L(d) = L(d_0) + 10n\log\left(\frac{d}{d_0}\right) + X_\sigma \quad [dB] \tag{2.15}$$

Where, the mean path loss exponent n depends on the surroundings and building type, and varies in the range of 2 to 10. The X_σ is a zero mean log-normally distributed random variable with a standard deviation of σ in dB.

This model does not provide an actual detailed prediction model, e.g. characterization of the path loss between floors, because it only gives estimation through many experiments and over many different scenarios. Most of the measurements have been made at 900 and 1800 MHz.

2.7.2 **Multi-Wall-Model (MWM)**

The Multi-Wall-Model (MWM) takes into account an individual transmission loss of each of the walls penetrated by the direct path between the transmitter and the receiver [60], [61]. This model is based on measurement, and it is found that the total floor loss is a non-linear function of the number of penetrated floors given by an empirical factor, *b,* so MWM is given by [60]:

$$L = L_{FS} + L_c + \sum_{j=1}^{I} k_{wj} L_{wj} + k_f^{\frac{k_f+2}{k_f+1}-b} L_f \tag{2.16}$$

where,

L_{FS} = Free space loss between transmitter and receiver

L_c = Constant Loss, wall losses from measurement which normally close to uniform

k_{wj} = number of penetrated walls of type *j*

L_{wj} = Loss of wall type *j*

k_f = number of penetrated wall of type *j*

L_f = Loss between adjacent floor

b = empirical parameter for non-linear characteristic of floor

j = number of wall type

The difference between wall types in the third term of equation 2.8 above is clearly given by Table 2.1 below:

Table 2-1. Wall Types for the Multi-Wall-Model [60]

Wall Material	Thickness	k = 1	k = 2
Concrete	10 cm	L_{w11} = 16 dB	L_{w12} = 14 dB
Concrete	20 cm	L_{w21} = 29 dB	L_{w22} = 24 dB

Chapter 3. Performance Evaluation Methodologies

Contents

3.1 *Introduction*

Most research in engineering has to face building up a complex system before it can analyse at least one influencing factor related to the system itself. Developing a model with simulation is one of the most convenient alternatives because it is low cost, very flexible and allows for implementation of the system configuration variations. Moreover, quick results can be obtained with the help of high level programming software and powerful computer speed.

This chapter gives a brief introduction to the simulation techniques and the simulation tools that have been used to evaluate the performance of a system scenario. The parameters used to evaluate the performance are also described and, finally, simulation validation will be presented.

3.2 Simulation Technique

Monte-Carlo simulation has been used in this work to solve a complex system scenario that can divide a specific system into many single equations. Monte-Carlo simulation utilizes a large number of random numbers of statistical values which represent an adequate combination of system parameters to be tested to determine the statistical behaviour without the need to test every combination of events related to the system performance evaluation. The larger number of trials the better the expected result to be produced from the system simulation.

This research will consider many wireless indoor user pairs that are uniformly placed in random locations within the indoor communication environment. As shown in Fig. 3.1, all wireless indoor user pairs consist of a transmitter (T_x) and a receiver (R_x) which have transceiver functionality. The location of T_x and R_x can be in the same room or intra-room (yellow solid line) or separated between different room or inter-room (blue and red dashed line) in the same indoor building.

Let us consider one single transmitter activated by starting to transmit signal to its destination receiver. Prior to activation and joining the system, the receiver needs to check the level of interference caused by another transmitter or transmitting signal in the same spectrum, then Signal to Noise Ratio (SNR). If it is above the required threshold, it means this pair is receiving into the system and continues to occupy one available channel and Signal to Interference Noise Ratio (SINR). If it is above the required threshold, it means this pair is not being disturbed by any existing pairs in the channel and continues its process to transmit the signal to its destination. The process will follow the same rule as explained previously for any wireless indoor users trying to transmit within the building. More detail about SNR and SINR will explained later in this Chapter.

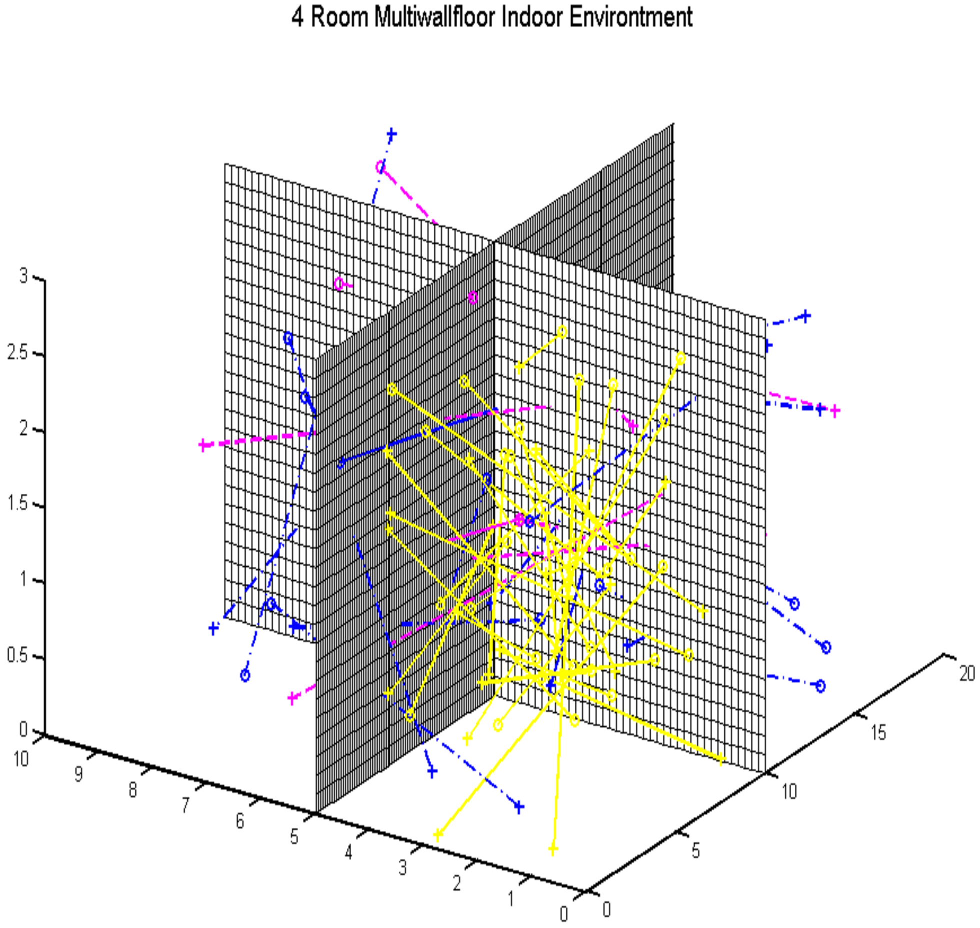

Figure 3-1. The System Scenario for Indoor Communication Environment

The rooms are considered side by side to each other with the size of each room at 10 m x 5 m x 3 m (l x w x h). The simulation algorithm is illustrated in Fig. 3.2. In general, the algorithm is divided into 2 stages:

1. Transmission stage, this is the stage where all the steps are directly related to the pair Tx and Rx setting up the transmission from spectrum selection, spectrum sensing and SINR measuring.

2. FSS stage, the stage where the wall takes action to protect the specific spectrum in relation to the need of a particular user.

The subsection of 1 in the simulation algorithm for the channel selection process will be explained in detail in Chapter 4.

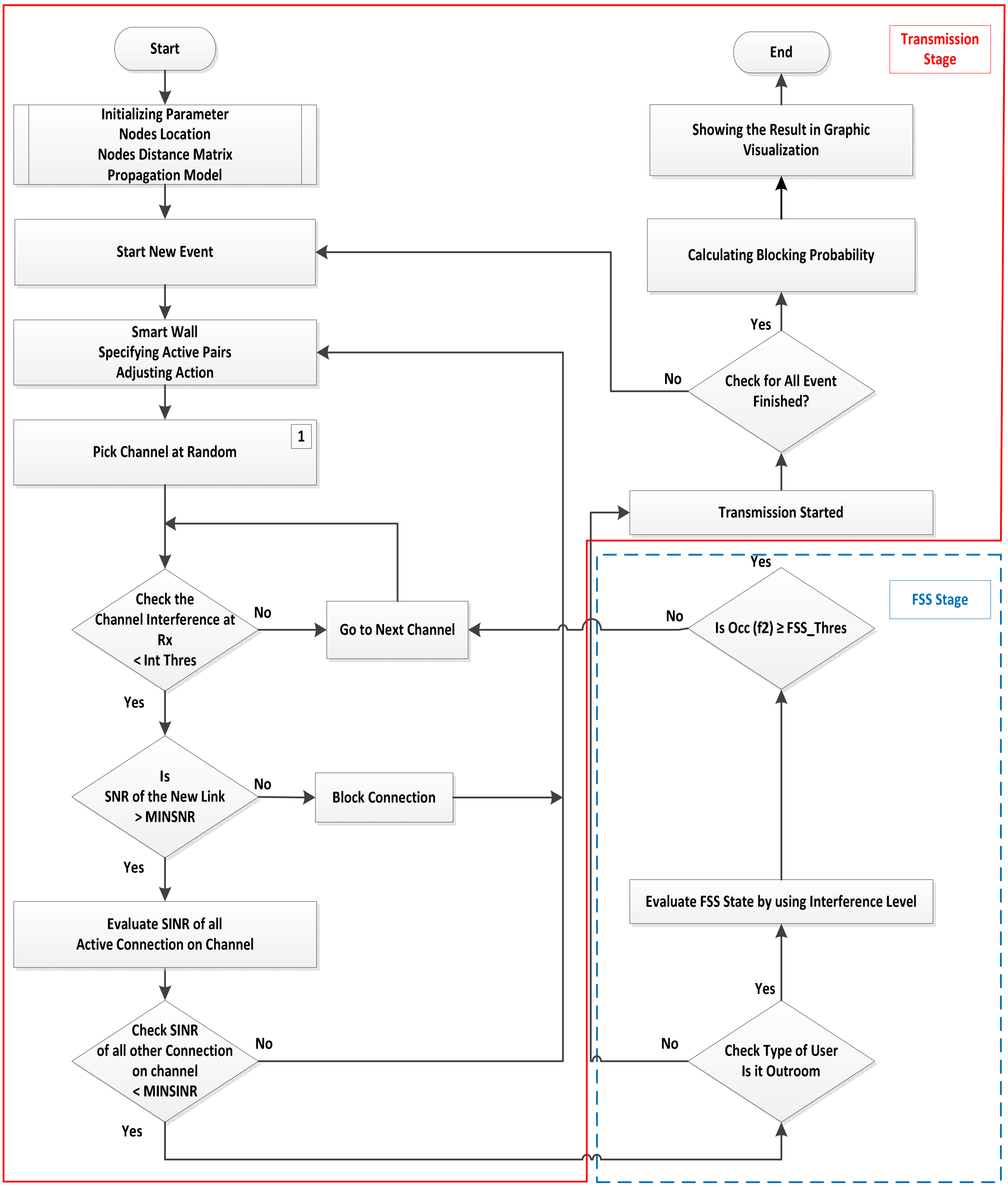

Figure 3-2. The Simulation Algorithm

3.3 Modelling Tools

3.3.1 Simulation Tools

Research in the communication engineering area needs to perform complex simulation tasks as it requires programming tools which can have huge flexibility to suit the requirements of the research. Currently MATLAB is widely used as a simulation tool. It offers high accuracy and stability with its own unique characteristics related to the needs of the research work. As such, MATLAB is used as a main programming tool in this research. MATLAB (or MATrix LABoratory) is a programming language for analytical and numerical computation. Technically, MATLAB combines the process of calculation, visualisation, and high level programming into one built in environment. All problems and solutions in MATLAB can be expressed in a widely used mathematical notation.

In relation to this research work, the use of MATLAB as a simulation tool makes it possible to visualize all system models into matrix algebra, compute the relating data numerically and display the results in many different kinds of graphical display in a two or three dimensional plot.

Moreover, MATLAB has its own built in functions to cover all mathematical calculation in the form of matrix based linear algebra, it also contains many professional toolboxes which have additional functions built for many system modelling applications, especially in area of Communication System and Digital Signal Processing (DSP). The advantages previously explained make MATLAB the first choice for the main programming tool in this research. The disadvantage of MATLAB is that the simulation runs much slower when compared with other programming language such as C, Java or OPNET, but now the execution time of the codes is far less important, as the rapid growth of computing power makes it possible to cut considerable time of simulation and make it a time cost effective approach to simulation.

3.3.2 **Analytical Tools**

For any given system, a defined Markov model consists of a list of the possible states of that system, the possible transition paths between those states, and the rate parameters of those transitions. In communication system analysis the transitions usually consist of an arrivals and departures rate. Graphically, the Markov model is represented as a 'bubble', with arrows denoting the transition paths between states, as depicted in Figure 3.3 below for a single process of '*birth and death process*'. The symbol λ denotes the arrival rate parameter of transition from state 0 to state 1 and, vice versa, the symbol μ denotes the departure rate leaving from state 1 to state 0. This process has the general solution as follows [62, 63]:

$$P_o(t) = \frac{\mu}{\lambda+\mu} + \left(P_o(0) - \frac{\mu}{\lambda+\mu}\right) e^{-(\lambda+\mu)^t} \quad (3.1)$$

$$P_1(t) = \frac{\lambda}{\lambda+\mu} + \left(P_1(0) - \frac{\lambda}{\lambda+\mu}\right) e^{-(\lambda+\mu)^t} \quad (3.2)$$

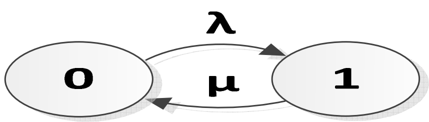

Figure 3-3. Markov Model Representations

Equations (3.1) and (3.2) comprise the transient solution, describing a system as a function of time. In most applications, the interest centres not on the values of these probabilities at a specific point in time, but rather on their long-run values. That is why we need to define the behaviour of the system for large values of *t*, after it has been in operation for a long period of time by letting $t \rightarrow \infty$ in both equations above and we obtain [64]:

$$P_o = \lim_{t\to\infty} P_o(t) = \frac{\mu}{\lambda+\mu} \quad (3.3)$$

and

$P_1 = \lim_{t\to\infty} P_1(t) = \frac{\lambda}{\lambda+\mu}$ (3.4)

The system is then said to be in statistical equilibrium when the state probabilities are independent of the initial conditions and sum to unity and following the conservation-of flow as below

$P_0 + P_1 = 1$ (3.5)

Furthermore, if a system with a multidimensional birth-and-death process is defined as a single-server system with two sources, assume that source *i* generates call at a constant rate γ_i when idle and rate 0 otherwise, and has exponential service time with mean μ_i^{-1}. With *Blocked Customers Delayed* (BCD) queuing assumed and letting $S_i = 0$ if source *i* is idle, $S_i = 1$ if source *i* is being served, and $S_i = 2$ if source *i* is waiting for service.

Finally, let $P\{S_1 = j_1, S_2 = j_2\} = P(j_1, j_2)$ $(j_1, j_2 = 0,1,2)$ be the statistical-equilibrium state distribution. The detailed system is shown in Figure 3.3. The rate of the system leaving each state compares to the rate at which the system entering that state as follows

$$(\lambda_1 + \lambda_2)P(0,0) = \mu_i P(1,0) + \mu_2 P(0,1)$$
$$(\lambda_2 + \mu_1)P(1,0) = \lambda_1 P(0,0) + \mu_2 P(2,1)$$
$$(\lambda_1 + \mu_2)P(0,1) = \lambda_2 P(0,0) + \mu_1 P(1,2)$$
$$\mu_1 P(1,2) = \lambda_1 P(0,1)$$
$$\mu_2 P(2,1) = \lambda_2 P(1,0)$$

By observing the equation above, it can be seen that the term on the left-hand side is identical to the sum of the terms on the right hand side, some of the redundant equations can be ignored and the above equation can be put together into one with the normalization equation.

$P(0,0) + P(1,0) + P(0,1) + P(1,2) = 1$ (3.6)

In which uniquely determines the unknown probabilities.

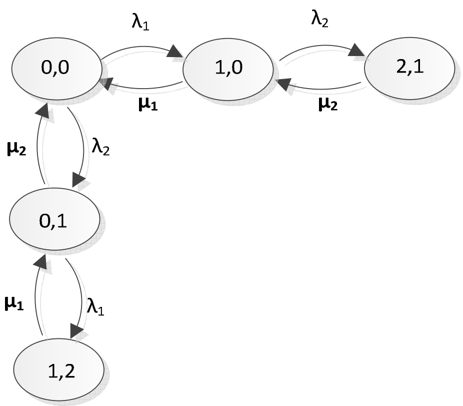

Figure 3-4. Markov Multidimensional Model Example

3.4 Performance Parameters

Considerable effort has been made in selecting suitable performance parameters to evaluate the system performance in this work. Signal to Interference and Noise Ratio (SINR) is used to measure the link quality of each user in the system. Blocking probability and dropping probability are used to evaluate the system capacity.

3.4.1 Signal to Interference and Noise Ratio

In radio communication, especially for signals that are transmitted over line of sight (LOS), we should specify the transmitted power and the SINR required for achieving a given level of performance. Firstly, it is assumed that the transmitting antenna radiates isotropically in free space at the power level of P_t. If the receiving antenna is separated by the distance of d, the received power of the antenna (for uniformity of symbols, we can denote this received power, P_r as the signal power of active transmitter, P_s), can be expressed as [53]:

$$P_s = \frac{P_t G_t G_r \lambda^2}{(4\pi d)^2} \tag{3.7}$$

where,

G_t = Gain of the transmitter

G_r = Gain of the receiver

λ = wavelength of the transmitted signal

The effect of the thermal noise that arises at the receiver is also computed, by using the equation as given below:

$$N_0 = kT_0 B \tag{3.8}$$

where,

k = Boltzmann constant (1.38 x 10^{-23} J/K)

T_0 = Noise temperature in Kelvin

B = Signal bandwidth

Then, the measured ratio of the signal compared to the background noise in the same bandwidth, is

$$SNR = \frac{S}{N_0} = \frac{P_{signal}}{P_{noise}} = \frac{P_s}{P_n} \tag{3.9}$$

This parameter can be used as a performance threshold during the set up phase, when an active transmitter sends a request to set up the transmission, assuming no interference is present in the channel.

In relation to the shared spectrum in use between two or more different transmitters, it needs to consider the co-channel interference which is the interference caused by the other transmitters near the receiver location. Let us assume n interfering transmitters are surrounding the destination receiver, as illustrated in Fig. 3.3. In this illustration, Tx_1 is the active transmitter, which shared the same spectrum with Tx_2 and Tx_3. The modulation used by both Tx_1 and Rx_1 has to have an adequate SINR threshold requirement in order to cope with the interference caused by both transmitter Tx_2 and Tx_3. This interference power can be denoted by P_i, and calculated by:

$$\sum P_i = P_{s2} + P_{s3} + ... + P_{sn} = \sum_{n=1}^{N} P_{sn} - P_{s1} \tag{3.10}$$

In the equation above, it is assumed that the signal power of active transmitter P_s is the main signal path in one particular shared spectrum, denoted as P_{s1}.

The performance evaluation can be calculated by taking into account the influence of interference by using the parameter called Signal to Interference plus Noise Ratio (SINR), and is defined as:

$$SINR = \frac{S}{N_0 + I} = \frac{P_s}{P_n + \sum P_i} \tag{3.11}$$

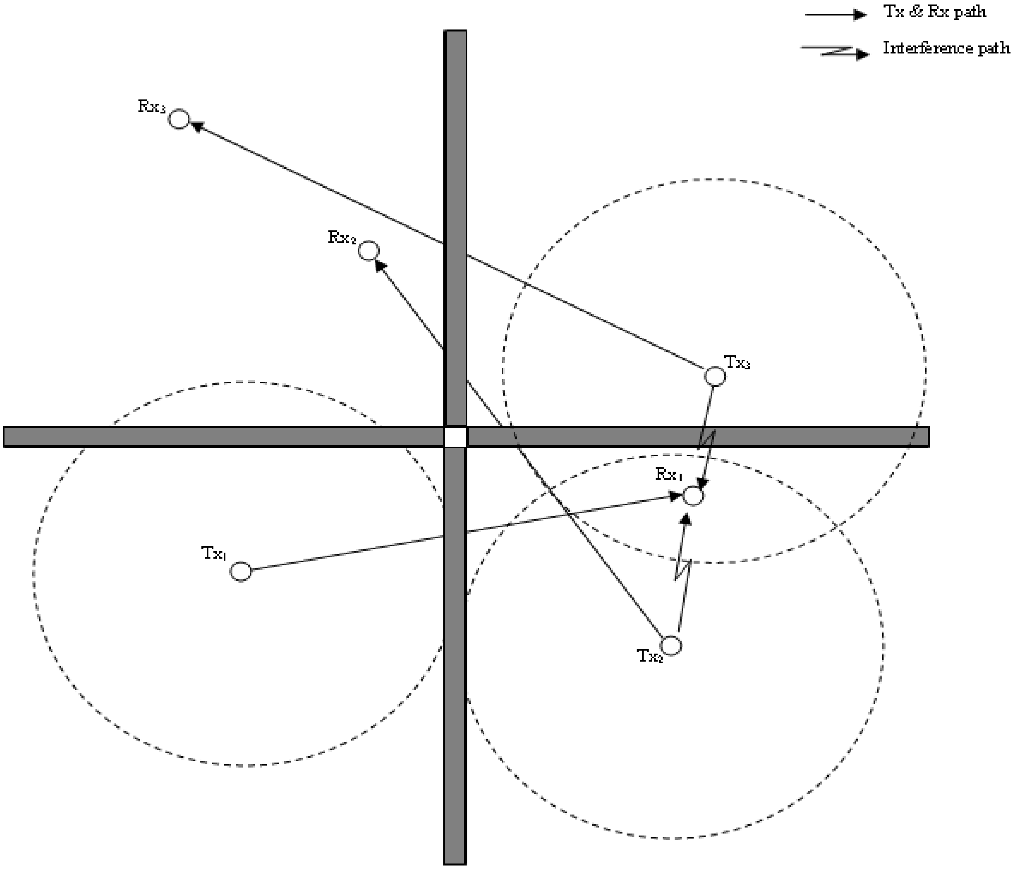

Figure 3-5. Interference Model Used in Simulation

3.4.2 Blocking Probability and Dropping Probability

Blocking probability has been used to measure the probability of a transmission request being rejected during a set up phase. The blocking probability at traffic load *t* is defined as [64]:

$$B(t) = \frac{Number\ \ of\ \ call\ \ blocked\ \ at\ \ load\ \ t}{Total\ \ calls\ \ at\ \ load\ \ t} \tag{3.12}$$

The blocking probability is an important parameter to determine the capacity of the wireless communication system. By using different types of simulation scenarios system performance can be evaluated by comparing the blocking probability of each scenario.

Dropping Probability is the other performance parameter used in relation to the capacity of the wireless communication system. Dropping probability at a particular level will show the performance of a connection that fails when the transmission is in progress and can be indicated as the congestion level over the traffic in use. The dropping probability at traffic load t is defined as [64]:

$$D(t) = \frac{Number\ of\ call\ dropped\ at\ load\ t}{Total\ number\ of\ accepted\ calls\ at\ load\ t} \tag{3.13}$$

3.4.3 **Set Theory**

Furthermore, there is a need to define all users in the model as a group of test users. A specific group of users is part of node distributions in the system model, and can be a set of interested users to look after when we need to determine a statistical result.

Let C be the set of all user pairs randomly scattering in a 2 storey building with *n* rooms, so

$C_{intraroom}$ = is the set of all user pairs located in one room
$C_{interroom}$ = is the set of all user pairs which separated by wall or floor

In addition to the set C, it also defined U to be the set of all user pairs randomly scattering in all coverage area in each *n* particular rooms. The set of all this users can be denoted by:

U_{ij} is the set of all user pairs randomly scattering in all coverage area in each 4 particular rooms

where, i = 1 to n
j = 1 to n

$$U_{ij}\begin{cases} i = j & define\ as\ intra-room\ user \\ else & define\ as\ inter-room\ user \end{cases}$$

For the reason of simple and consistent description for the entirety of this thesis, we define intra-room user as Inroom user and inter-room user as Outroom user.

The sample of set of Inroom user:

U_{11} is the set of pairs in room 1;

U_{11} = {u∈ $C_{intraroom}$: u Inroom pairs} (3.14)

These Inroom pairs have *n* set of pairs for each room from room 1 to *n* rooms.

The sample of set of Outroom user:

U_{12} & U_{21} are the set of pairs across room 1 and room 2 and vice versa

U_{12} & U_{21} = {u∈ $C_{interroom}$: u Outroom pairs} (3.15)

These Outroom pairs have a set of pairs and divided it into:

- 2*n* sets of user pairs which are separated by 1 wall
- *n* sets of user pairs which are separated by 2 walls

In addition to set U, there is a need to define the set of pairs which requires a connection and access to the channel. The set of all these users can be denoted by:

A_{k0} is the set of pairs which requiring connection and randomly scattering in all coverage area in entire building.

$$A_{k0} = \{u \in U_{ij} : u\ is\ requiring\ service\} \quad (3.16)$$

where, k = number of all user pairs

The subscript '0' here refers to the initial stage, which stated earlier above.

Then, it moved to the stage 1 (with the subscript '1'), and all this users can be denoted by:

A_{k1} is the set of pairs which has Interference above or equal to minimum threshold

$$A_{k1} = \{u \in U_{ij} : u(Int\_Thres) \geq -110\} \quad (3.17)$$

where, k = number of all user pairs

Int_Thres = minimum threshold of interference >= -110 dBm

In stage 2 (with the subscript '2'), all these users can be denoted by:

A_{k2} is the set of pairs which has SINR above or equal to minimum threshold

$$A_{k2} = \{u \in U_{ij} : u(SINR) \geq 5\} \quad (3.18)$$

where, k = number of all user pairs

MINSINR = minimum threshold of SINR = 5 dB

The interference threshold is set to -110 dBm, which is more than 10 times greater than the noise floor, so the differentiation between the signal and noise can be observed.

3.4.4 Cumulative Distribution Function (CDF)

The Cumulative Distribution function (CDF) is a mathematical tool used to explain the statistical behaviour of the large amount of data resulting from application of the Monte Carlo simulation. The cumulative distribution function for a random variable at x gives the probability that the random variable X is less than or equal to that number x.

The CDF of x is defined as:

$$CDF = F(x) = \int_{-\infty}^{x} f(t)\partial t \quad (3.19)$$

Where *F(x)* is the probability density function of x, in this thesis, the measuring the system performance can be obtained by looking to the CDF of blocking probability less than required performance, in this case, it could be by capping number to BP equal or less than 5%. The CDF of this result will clearly show the statistical behaviour of the system performance in general.

3.5 Simulation Validation with Analysis

In order to validate the accuracy of the corresponding simulation result of FSS on-off, the results have been compared with theoretical analysis with the assumption of the environment with no frequency reuse taking place. It does mean that any channel can only take one user at a time.

3.5.1 The Engset Distribution

With another assumption that a small number of users are apparent in the indoor environment the Engset distribution should give a better approximation for comparison with the simulation result. In the Engset distribution, we consider the arrival origin from a finite population of sources, say with a total number of customers c who are accessing the maximum of m servers, with the number of costumers being bigger than the number of server. In the model, β is the arrival rate of one customer, the service times are exponential with parameter μ, and there are no waiting places.

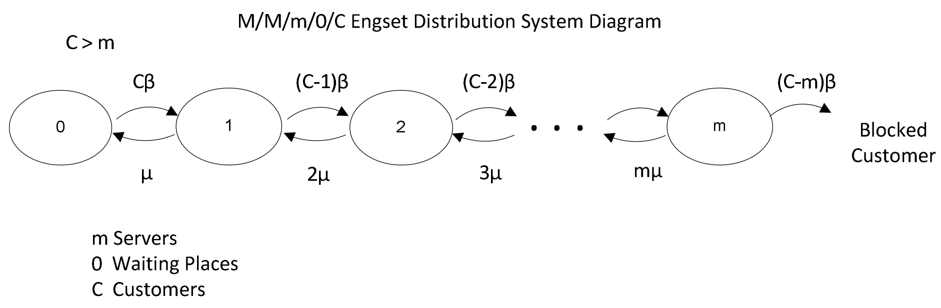

Figure 3-6. Engset Distribution System Diagram

The Engset distribution can be expressed as

$$p_m(m, C) = \frac{\binom{C}{m}\left(\frac{\beta}{\mu}\right)^m}{\sum_{i=0}^{m}\binom{C}{i}\left(\frac{\beta}{\mu}\right)^i} \qquad (3.20)$$

where p_m is the probability that m channels are occupied. If we consider the blocked call, the probability should be when m channels are occupied and there is a new call arrival, and it can be expressed by the equation below [49]

$$p_b(m, C) = \frac{\binom{C-1}{m}\left(\frac{\beta}{\mu}\right)^m}{\sum_{i=0}^{m}\binom{C-1}{i}\left(\frac{\beta}{\mu}\right)^i} \qquad (3.21)$$

3.5.2 **Validation Analysis**

As described previously, this simulation has two sets of group users which are working independently. We simulate the model for FSS indoor wireless communication with the proportion of Inroom:Outroom from [0:60 8:52 16:44 24:36 30:30 36:24 44:16 8:52 60:0]. Using the algorithm from the previous section, we evaluate the blocking probability for each user proportion with two conditions applied, one when FSS is continually off and one when FSS threshold is set for 80%. The Engset distribution equation is used as a comparison, again with each proportion of user and the same two conditions as in our simulation. In general, Figure 3.5 shows a steady concurrence line between the Engset formula and the simulation for the Indoor user. The 80% FSS threshold is not greatly influencing the performance of the Indoor user as it maintains 20 fixed channels for the whole simulation.

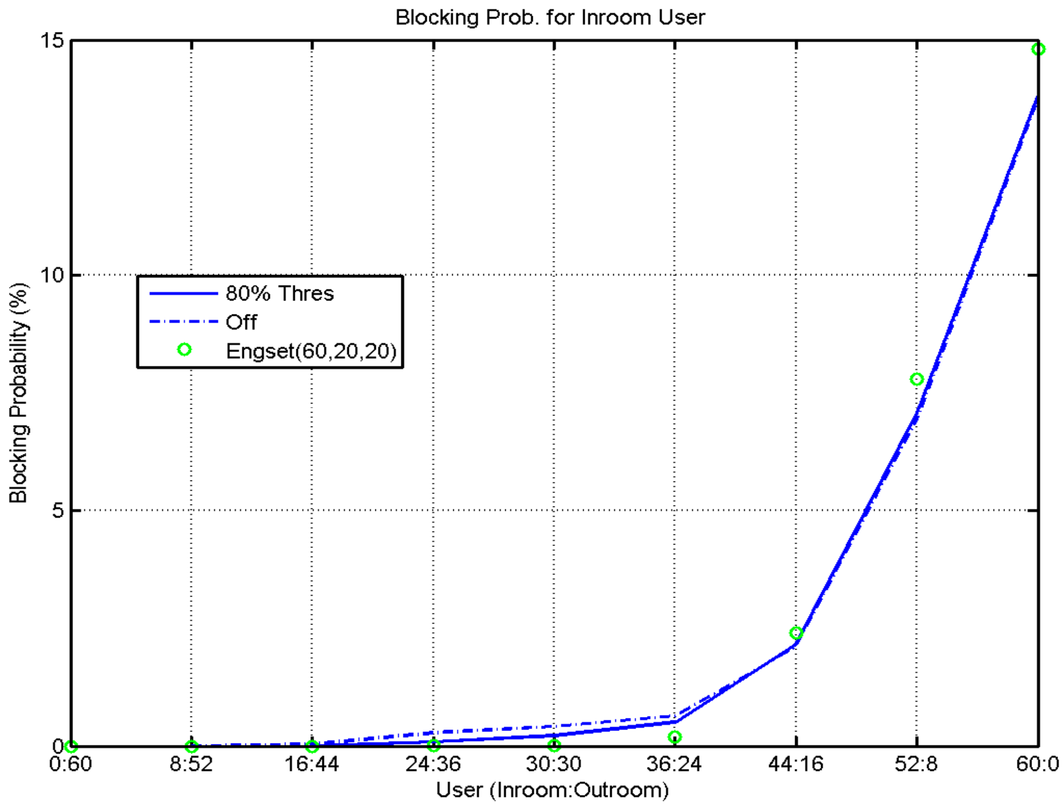

Figure 3-7. Comparison of the FSS simulation with the Engset formula for Inroom Users

The same happens with the result for the Outroom user as shown in Figure 3.5. The dashed line represents the result for FSS system fully off, which means both sets of users have the same set of 20 channels to choose for the whole time, and also have a good agreement with the '*' whom represent the Engset for the 20 channels. The solid line represents the result of the Outroom user if an 80% FSS threshold is set, which means the Outroom user will only have the total of 18 channels to choose from for the whole time, it follows the same concurrence line with Engset formula for 18 users in the 'o'.

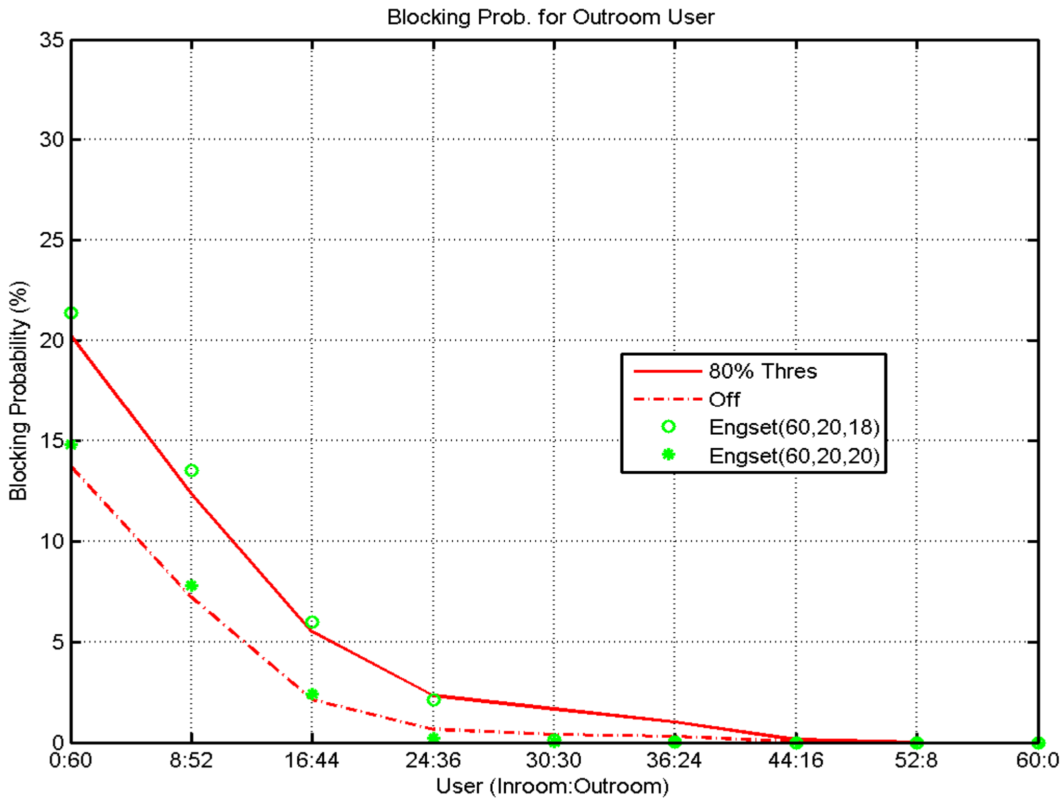

Figure 3-8. Comparison of the FSS simulation with the Engset formula for Outroom Users

A more complex scenario and its analysis with the influence of FSS will be discussed later in this thesis.

3.5.3 **Finding the Right Channel Proportion**

The first thing we need to consider is finding the correct channel proportion. We have 3 active spectrums with 30 channels altogether. The ultimate goal is to find the best channel proportion with all blocking probability (BP) for both users at less than 5% (5% operational area). Another consideration is to give priority to the Inroom user as the *Priority Users* of spectrum f2. We need to decrease the blocking probability of the Outroom user to below 5%, taking into account a minimum deterioration of blocking probability of the Inroom user. In this work, we consider use of 3 different scenarios to look in detail for a good channel proportion. In addition, all simulation is conducted using a default 20 Erlangs *Offered Traffic* (OT), the summary result of all 3 scenarios is shown in Fig. 3.7.

Scenario 1 with Number of Channel f1 constant; in this set up we left the number of channel in f1 constant in 10 channels, but f2 and f3 will vary from 2 – 18 channels. The channel proportion is come as the matrix [10:2:18 10:4:16 10:6:14 10:8:12 10:10:10 10:12:8 10:6:14 10:4:16 10:18:2]. The operational area range from just below channel proportion 10:4:16 to below channel proportion 10:10:10.

Scenario 2 with Number of Channel f2 constant; in this set up we left the number of channel in f2 constant in 10 channels, but f1 and f3 will vary from 2 – 18 channels. The channel proportion is come as the matrix [2:10:18 4:10:16 6:10:14 8:10:12 10:10:10 12:10:8 14:10:6 16:10:4 18:10:2]. The operational area range from just below channel proportion 4:10:16 to below channel proportion 10:10:10.

Scenario 3 with Number of Channel f1 and f3 equally split; in this set up we equally split the number channel in f1 and f3 from 6 – 14 channels each side and the rest of number of channel left in f2. The channel proportion is come as the matrix [14:2:14 13:4:13 12:6:12 11:8:11 10:10:10 9:12:9 8:14:8 7:16:7 6:18:6]. The operational area range from just below channel proportion 13:4:13 to below channel proportion 10:10:10.

As we conclude from the Figure. 3.7, generally, the best option for channel proportion is with the scenario CP f1f3 equally split, and especially the 12:6:12 because it gives a good BP Range between Inroom and Outroom. We need this BP Range as our ‘improvement zone’ to develop a more detail scenario in the future. The CP 11:8:11 also allows greater BP range, but compared with 12:6:12, the BP Outroom is much higher and closer to the maximum affordable performance of 5%. 12:8:12 also provides a balanced number of channels between spectrum f1 and f3.

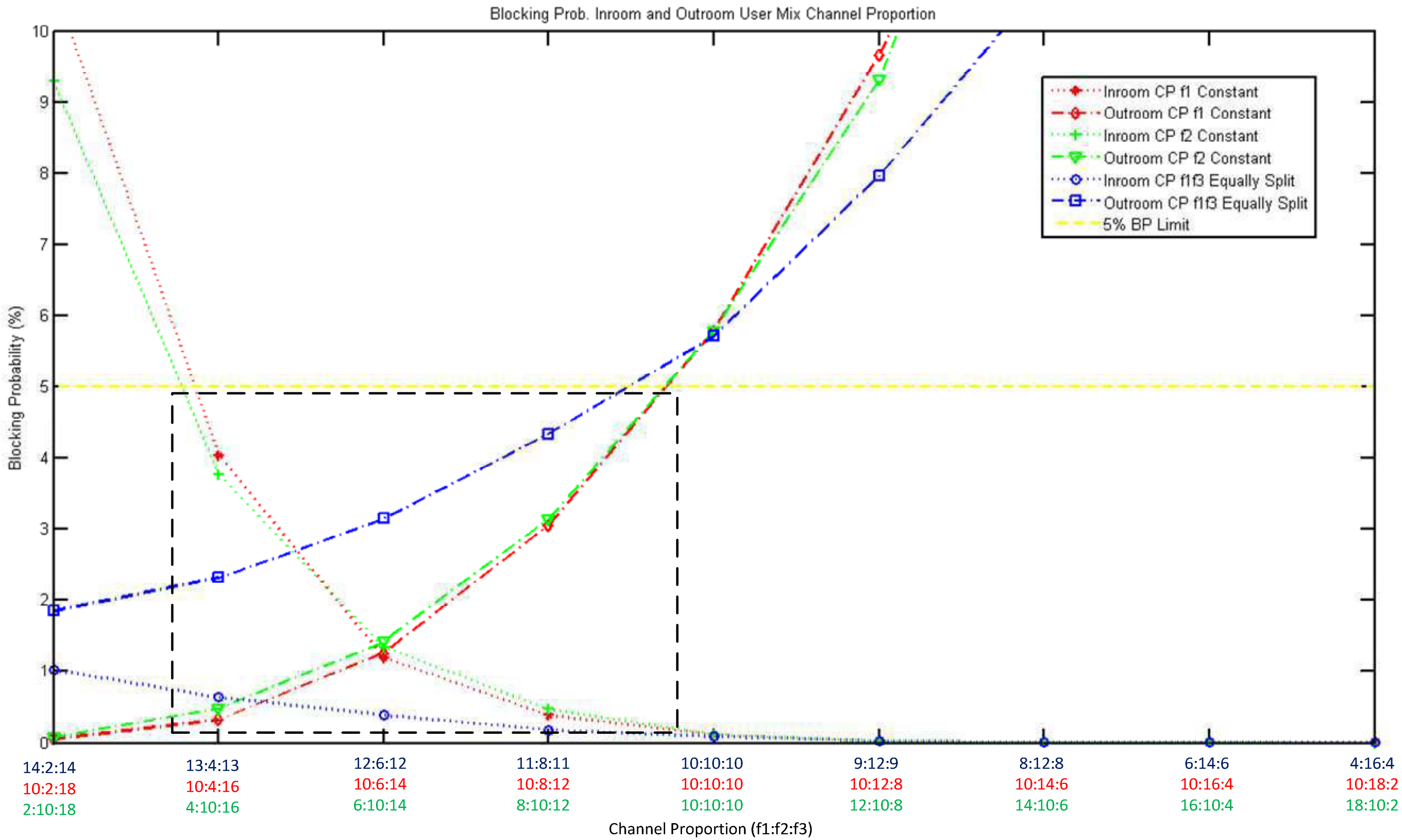

Figure 3-9. Blocking Probability (BP) of Inroom and Outroom User with Varieties Channel Proportion

3.6 Conclusion

In this chapter, firstly introduced the concept of Monte-Carlo simulation of the wireless indoor environment in building with 4 side by side rooms with the size of 10 m x 5 m x 3 m. The simulation itself consists of two distinct stages, the first one is transmission stage, the stage to simulate the set up of wireless communication of each user in the indoor environment and the second one is FSS stage, the stage to simulate the set up of smart wall characteristic changes to follow any adjustment from the interference characteristics of the indoor wireless communication system.

This chapter discussed some of the parameters used in measuring the performance of the wireless communication system starting from the signal to noise ratio (SNR), signal to interference plus noise ratio (SINR), blocking probability, dropping probability, set theory, and cumulative distribution function.

The characteristics of the traffic in the indoor wireless communication system was discussed, which is based on a finite number of sources from a finite user population. It was explained how this could be modelled using an Engset distribution, as a way of validating our simulation in a basic scenario. The direct comparison showed a good match between the two.

We have also determined the most suitable Channel Proportion (CP) by using the comparison between 3 different scenarios. We have chosen the CP 12:6:12, because of its better BP range, as the default for further simulation in the future.

Chapter 4. Performance Analysis in Spectrum Sharing using a Markov Model

Contents

4.1 Introduction

In general, this thesis will discuss 3 different prearrangement spectrum models, which are One Available Spectrum (1AS), Two Available Spectrum (2AS) and Three Available Spectrum (3AS). In the last two models, both Inroom and Outroom users have their own default working spectrum. In addition, for both the 2AS and 3AS model, they have to have their channel proportion arranged to follow a general uniformity with what we have in 1AS spectrum structure.

Both types of users are coexisting and sharing the same spectrum resource. It affects the utilization level for both users to influence each other. This is the area where some interesting interaction can be useful to explore, i.e. interaction between Inroom and Outroom users in the same spectrum can actually degrade the performance of Inroom users as a *Priority User* of the spectrum. In this case, the FSS based restriction mechanism takes its place to provide an appropriate step to increase the performance of the Outroom users without significantly reducing the performance of the Inroom users.

The remainder of this chapter is organized as follows. In section 4.2, the coexistence scenario for two user groups with One Available Spectrum (1AS) and an analytical model to describe the system behaviour are presented. On the basis of an analytical model, FSS restriction mechanisms are considered in section 4.3. The restriction mechanisms are used to protect the performance of *Priority Users*, in this case Inroom users, while maintaining overall resource utilization performances. Finally section 4.4 provides conclusions related to the general outcome of this chapter.

4.2 Coexistence Model for Shared Spectrum with No Restriction

In this section, the system behaviour of the coexistence scenario is analysed. For the easier discussion to define stage-transition diagram, a Poisson arrival process for both Inroom and Outroom users are assumed. It can be seen as shown in Figure 4.1 that arrival flows for both Inroom and Outroom groups arriving in Spectrum *f1*, and are denoted by λ_{in} and λ_{out} respectively. The users are served in a first-come-first-served fashion. The basic scenario is also modelled so that there are no restrictions in place for both users to access the spectrum. We have also assumed that the service times are exponentially distributed with mean service time μ^{-1} and so the departure flow rate is dependent on the number of users using spectrum, j_1 and j_2, for Inroom and Outroom users respectively. A user will be blocked when they cannot find an empty channel in the system.

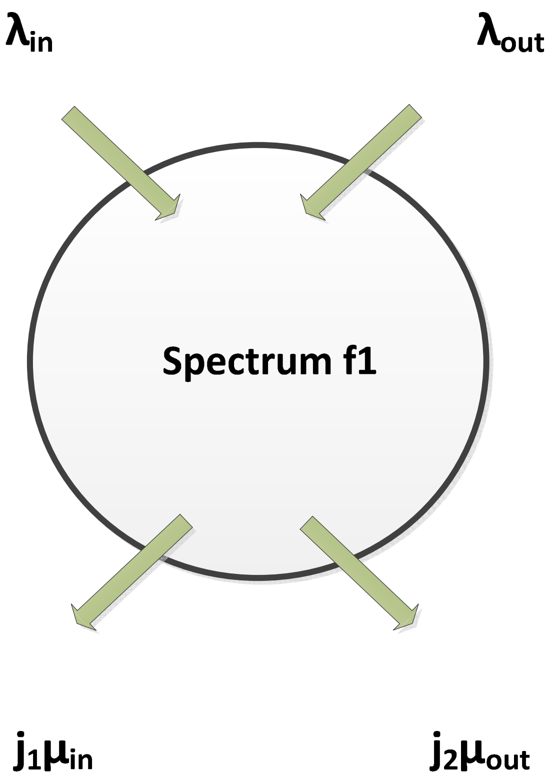

Figure 4-1. Markov Multidimensional Model Example

Figure 4.2 shows a state-transition-rate diagram to define the behaviour of two user groups with One Available Spectrum (1AS) system. Each node in the diagram represents a user active state in the system. The first digit in the node denotes the number of Inroom users on spectrum f1, while the second digit in the node denotes the number of Outroom users on spectrum f1.

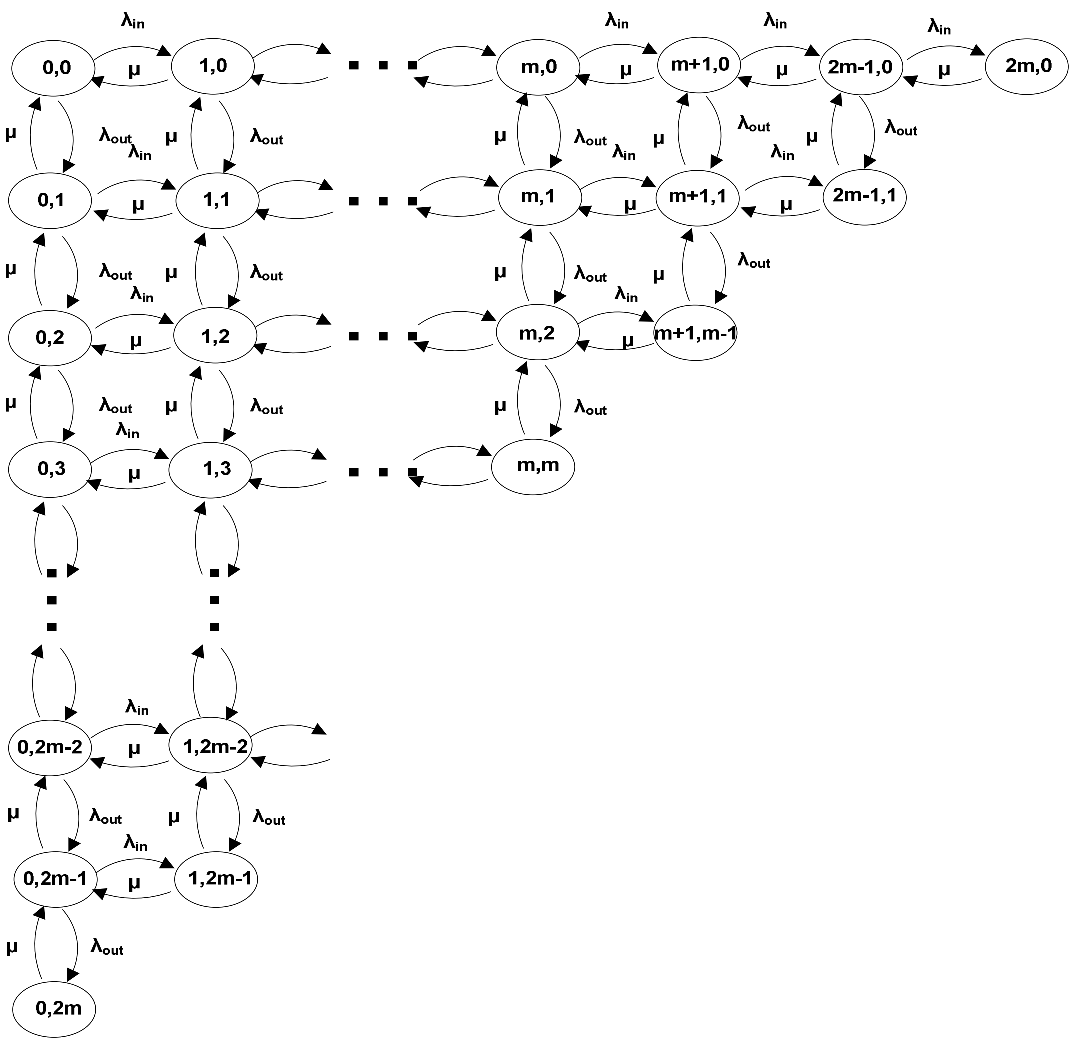

Figure 4-2. *State-transition-rate Diagram for No Restriction Model*

Notations in use are explained as follows:

λ_{in} Arrival rate of Inroom users to access spectrum f1

λ_{out} Arrival rate of Outroom users to access spectrum f1

2m Number of channels in spectrum f1

μ Departure rate per user

It is assumed that the departure rate per user is always constant. It also assumed that a normalized departure rate per user of 1 with respect to the arrival rate. The user allocation process is assumed to follow a birth-death process as explained in [64], which means the allocation process applies only when there is a transition to neighbouring states, i.e. the number of users will increase or decrease by one at a time on the f1 system due to the arrival or departure of users from both the Inroom and the Outroom groups.

In addition, referring to the Figure 4.2, the horizontal direction represents the arrival and departure process in spectrum f1 for Inroom users, while transition in the vertical direction represents the arrival and departure process in spectrum f1 for Outroom users. In the horizontal direction, the arrival rate of Inroom users equals λ_{in} , and the same happens in the vertical direction where the arrival rate of Outroom users equals λ_{out}. Both users will have the constant arrival rate until all the channels in spectrum f1 are fully occupied and follow the condition $j_1 + j_2 \leq 2m$. This condition suggest a logical consequence where half lower-diagonal of the *(2m, 2m)* state-transition-rate diagram becomes unobtainable.

4.2.1 **Markov Equilibrium Analysis**

The analysis of state-transition-rate equilibrium can be reviewed by following the condition of a law of *conservation of flow* where the transition rate into state *(j1,j2)* equals to the transition rate out of state (j_1,j_2) following the equation below [50]:

$$(\lambda_j + \mu_j)P_j = \lambda_{j-1}P_{j-1} + \mu_{j+1}P_{j+1} \qquad (j=0,1,\ldots) \tag{4.1}$$

Where $\{\lambda_j\}$ and $\{\mu_j\}$ are the rates of transition upward and downward respectively, and $\lambda_{-1} = \mu_0 = 0$. More precisely, it is assumed that systems that have the Markov property have to have equilibrium state distributions that satisfy the law of *conservation of flow* when the states are properly defined.

The nodes in Figure 4.2 can be split into three different components in the corners, three components on the edge and one component in the centre. It has 7 different equilibrium equations altogether.

There are 2 conditions that need to be considered to simplify the equilibrium expression

- Unobtainable states at half lower-diagonal of (2m,2m) state-transition-rate diagram, means it has to follow the condition of
  $p((j_1 + j_2) > 2m) = 0$.
- No negative value of number of user states in our system, means
  $p(-1, j_2) = p(j_1, -1) = 0, \;\; 0 \leq j_1, j_2 \leq 2m$.

For state *(0,0)*, we have

$$(\lambda_{in} + \lambda_{out})P(0,0) \; = \; \mu P(0+1,0) + \mu P(0,0+1) \tag{4.2}$$

For state *(2m,0)*,

$$\mu P(2m, 0) = \lambda_{in} P(2m-1,0) \tag{4.3}$$

For state *(0,2m)*,

$$\mu P(0,2m) = \lambda_{out} P(0,2m-1) \tag{4.4}$$

For state $(j_1, 0)$, $\{0 < j_1 < 2m-1\}$,

$$(\lambda_{in} + \lambda_{out} + \mu)P(j_1, 0) \; = \; \lambda_{in} P(j_1 - 1,0) + \lambda_{out} P(j_1, 0-1) + \mu P(j_1 + 1,0) + \mu P(j_1, 0+1) \tag{4.5}$$

$p(j_1, -1) = 0$

For state $(0, j_2)$, $\{0 < j_2 < 2m-1\}$,

$$(\lambda_{in} + \lambda_{out} + \mu)P(0, j_2) \; = \; \lambda_{in} P(0-1, j_2) + \lambda_{out} P(0, j_2 - 1) + \mu P(0+1, j_2) + \mu P(0, j_2 + 1) \tag{4.6}$$

$p(-1, j_2) = 0$

For state (j_1, j_2), $\{ j_1 + j_2 < 2m \;\&\&\; j_1, j_2 > 0\}$,

$$(\lambda_{in} + \lambda_{out} + 2\mu)P(j_1, j_2) = \lambda_{in}P(j_1 - 1, j_2) + \lambda_{out}P(j_1, j_2 - 1) + \mu P(j_1 + 1, j_2) + \mu P(j_1, j_2 + 1) \quad (4.7)$$

For state (j_1, j_2), $\{ j_1 + j_2 = 2m \;\&\&\; j_1, j_2 > 0\}$,

$$2\mu P(j_1, j_2) = \lambda_{in}P(j_1 - 1, j_2) + \lambda_{out}P(j_1, j_2 - 1) \quad (4.8)$$

As a general rule the system always will be in a state, so the state probabilities must also satisfy the normalization equation

$$\sum_{j_1=0}^{2m} \sum_{j_2=0}^{2m} p(j_1, j_2) = 1 \quad (4.9)$$

This model can also be used for Two Available Spectrum (2AS) and Three Available Spectrum (3AS) models to show the state-transition-rate diagram of shared spectrum between Inroom and Outroom with no restrictions in place. The differentiation between those two models and more about restriction will be discussed in the next section of this chapter.

4.2.2 **Blocking Probability for Shared Spectrum with No Restriction**

The blocking probability of both Inroom and Outroom users is considered to be identical and equivalent to the sum of the state probabilities along the diagonal edge. These are states reflecting the maximum number of channels in the system.

$$P_{b\_Inroom} = P_{b\_Outroom} = \sum_{j_1=0}^{m} p(j_1, 2m - j_1) + \sum_{j_1=0}^{m} p(2m - j_2, j_2) + p(m, m) \quad (4.10)$$

4.3 Restriction Mechanism as a Tool to Control Coexistence

This research proposes restriction mechanisms that can be categorized into 2 different groups:

- FSS based Restriction Mechanism, which is a restriction applied with the help of an external entity such as FSS walls. FSS will define the factor to activate its filter, i.e. *occupancy level of shared spectrum* or *number of SUs active in shared spectrum*.
- User Spectrum based Restriction Mechanism, which is a restriction applied from user perspective via an internal parameter. Mostly, this restriction is based on the occupancy level of spectrum, i.e. *70% occupancy then search channel in other spectrum*.

4.3.1 FSS based Restriction Mechanism

In the 1AS model, there is only one spectrum available for our two user groups, Inroom and Outroom users. The Outroom, as a Non-Priority User, typically can only use f1 spectrum in an opportunistic way, so it is firstly needed to sense the empty channel before it can occupy any channel in f1. In the case where the *No Restriction* model is in place, there are no such restrictions to cause the Outroom users to stop searching for empty channels in spectrum f1. It can affect the performance of Inroom users in general. On this basis, an FSS based restriction mechanism is needed. It works to protect the performance of Inroom users as the *Priority User* of the spectrum.

FSS as a centralized element can determine the factor to let it activate its filter to block a specific user from using the spectrum by adding up additional interference tuned to a specific frequency. FSS works with the information obtained from the surrounding environment; it could be from interference sensed from a shared spectrum or even with the help of a user beacon to know how many active users are in the spectrum.

4.3.1.1 FSS Restriction based on Maximum Occupancy Threshold

The FSS based restriction mechanism can be applied to manage the spectrum allocation on behalf of the *Priority Users*. With the help of an attached sensor on its surface, the FSS will sense the level of interference in a particular frequency. The Occupancy level is one item of the information that can be gathered from FSS interference sensing activity.

We aim to use a restriction mechanism based on the occupancy level of the shared spectrum. This restriction applies an equal probability of restriction to Outroom users, i.e. in the application of 1AS model, the restriction applies when $Occ\_f1 \leq k$ where k is the threshold of FSS activation.

This scenario is applied with the same coexistence model as previously used in *No Restriction* model. The users will fill up the channel in the shared spectrum on a first-come-first-served basis. The FSS continually observes and gains information on spectrum usage by constantly sensing the interference. In the case where the k threshold value is reached, the FSS then activates its filter and blocks all Outroom users from sensing the f1 spectrum. The effect is that all Outroom users active ($Out\_act\_max \leq k$) in f1 will be dropped (the FSS dropping term is used to differentiate this from dropping caused by other means). The same restriction is not applicable to Inroom users where they still can fill up to channel until it is full. Figure 4.3 shows a state-transition-rate diagram to denote the behaviour of the FSS restriction model.

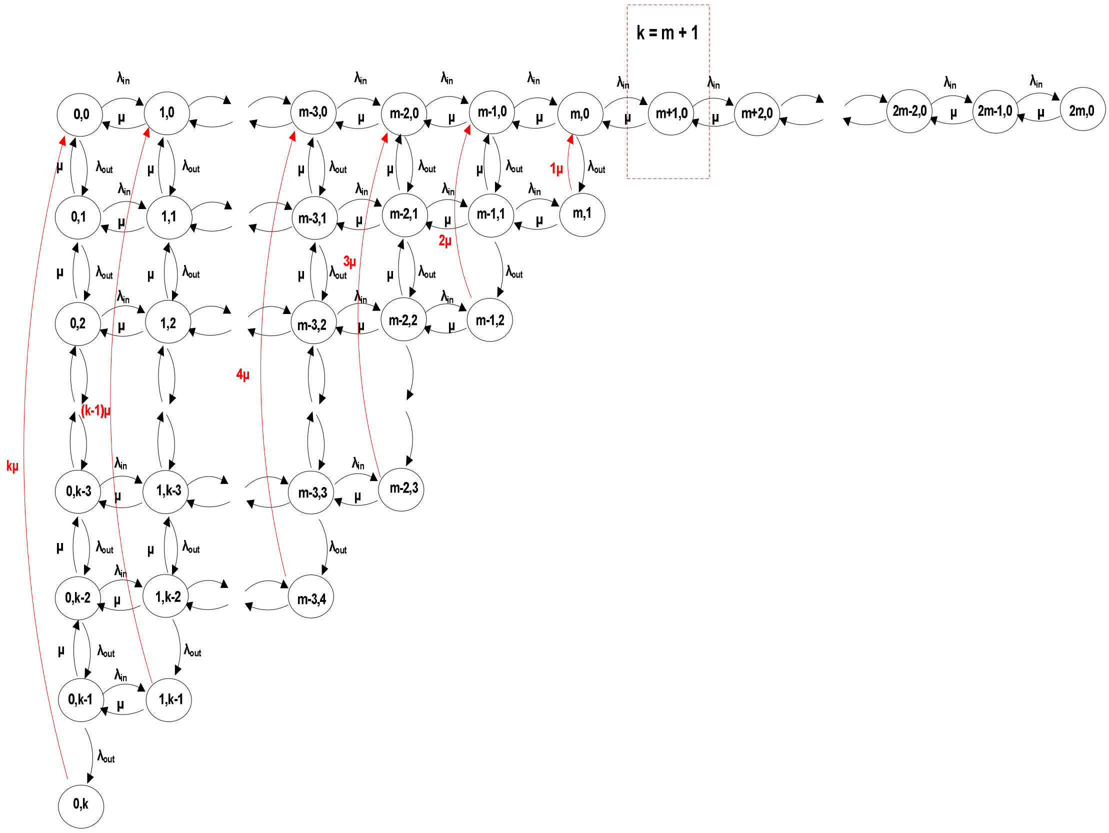

Figure 4-3. State-transition-rate Diagram for FSS based Restriction

Notations in use are explained as follows:

λ_{in}	Arrival rate of Inroom users to access spectrum f1
λ_{out}	Arrival rate of Outroom users to access spectrum f1
2m	Number of channels in spectrum f1
μ	Departure rate per user
k	FSS Threshold

The nodes in Figure 4.3 can be split into three different components in the corners, three components on the edge and one component in the centre. It has 7 different equilibrium equation altogether.

- The Unobtainable states becomes bigger compare to previously in *No Restriction* model and follow the condition of

$$\{p((j_1 + j_2) > k) = 0\} \cap \{p(j_1,0),\quad k+1 \le j_1 \le 2m\}$$

- No negative value of the number of user states is still applicable, means

$p(-1, j_2) = p(j_1, -1) = 0, \; 0 \leq j_1, j_2 \leq 2m.$

The equilibrium expressions are as follows

For state *(0,0)*, as follow

$$(\lambda_{in} + \lambda_{out})P(0,0) = \mu P(0+1,0) + \mu P(0,0+1) + k\mu P(o,k) \quad (4.11)$$

For state *(2m,0)*,

$$\mu P(2m,0) = \lambda_{in} P(2m-1,0) \quad (4.12)$$

For state *(0,k)*,

$$k\mu P(0,k) = \lambda_{out} P(0,k-1) \quad (4.13)$$

For state $(j_1, 0)$, $\{0 < j_1 \leq k-1\}$,

$$(\lambda_{in} + \lambda_{out} + \mu)P(j_1,0) = \lambda_{in} P(j_1 - 1,0) + \lambda_{out} P(j_1, 0-1) + \mu P(j_1 + 1,0) + \mu P(j_1, 0+1) + (k - j_1)\mu P(j_1, k - j_1) \quad (4.14)$$

$p(j_1, -1) = 0$

For state $(j_1, 0)$, $\{k \leq j_1 < 2m\}$,

$$(\lambda_{in} + \mu)P(j_1,0) = \lambda_{in} P(j_1 - 1,0) + \mu P(j_{1+1}, 0) \quad (4.15)$$

For state $(0, j_2)$, $\{0 < j_2 < k-1\}$,

$$(\lambda_{in} + \lambda_{out} + \mu)P(0, j_2) = \lambda_{in}P(0-1, j_2) + \lambda_{out}P(0, j_2 - 1) + \mu P(0+1, j_2) + \mu P(0, j_2 + 1) \quad (4.16)$$

$$p(-1, j_2) = 0$$

For state $(0, j_2), \{j_2 = k-1\}$,

$$(\lambda_{in} + \lambda_{out} + \mu)P(0, j_2) = \lambda_{in}P(0-1, j_2) + \lambda_{out}P(0, j_2 - 1) + \mu P(0+1, j_2) \quad (4.17)$$

$$p(-1, j_2) = 0$$

For state (j_1, j_2), $\{ j_1 + j_2 < k - 1 \ \&\& \ j_1, j_2 > 0\}$,

$$(\lambda_{in} + \lambda_{out} + 2\mu)P(j_1, j_2) = \lambda_{in}P(j_1 - 1, j_2) + \lambda_{out}P(j_1, j_2 - 1) + \mu P(j_1 + 1, j_2) + \mu P(j_1, j_2 + 1) \quad (4.18)$$

For state (j_1, j_2), $\{ j_1 + j_2 = k \ \&\& \ j_1, j_2 > 0\}$,

$$k\mu P(j_1, j_2) = \lambda_{in}P(j_1 - 1, j_2) + \lambda_{out}P(j_1, j_2 - 1) \quad (4.19)$$

For state (j_1, j_2), $\{ j_1 + j_2 = k - 1 \ \&\& \ j_1, j_2 > 0\}$,

$$(\lambda_{in} + \lambda_{out} + 2\mu)P(j_1, j_2) = \lambda_{in}P(j_1 - 1, j_2) + \lambda_{out}P(j_1, j_2 - 1) + \mu P(j_1, j_2 + 1) \quad (4.20)$$

In order to be compliant with the law of *conservation of flow*, the normalization equation in eq. 4.9 is still appropriate.

$$\sum_{j_1=0}^{2m} \sum_{j_2=0}^{2m} p(j_1, j_2) = 1$$

4.3.1.2 Blocking Probability of FSS Restriction based on Maximum Occupancy Threshold

Employing the same approach as that used previously in the *No Restriction* scenario, the blocking probability of Outroom is equivalent to the sum of state probabilities along the diagonal edge.

$$P_{b\_Outroom} = \sum_{j_1=0}^{k} p(j_1, k - j_1) \qquad (4.21)$$

On the other hand, the blocking probability of Inroom is given by the probability of the system to be in state $p(j_1,0)$.

$$P_{b\_Inroom} = p(2m, 0) \qquad (4.22)$$

4.3.2 User Spectrum based Restriction Mechanism

In order to improve the performance of the shared spectrum, especially if we are working toward the 2AS and 3AS models, some conditional restrictions can be imposed, which only affect the *Non-Priority User* of the spectrum. The user spectrum based restriction mechanism is the restriction based on user internal information, i.e. the conditional access can be applied by using the occupancy level of the spectrum at any particular time. It is mostly used by the system to protect the *Priority Users*, in this case Inroom user, from significantly degraded performance if the shared spectrum is being used selfishly by the Outroom users.

The most basic restriction that can be applied is discussed in detail in [50]. They use the constant restriction, which applies an equal probability of restriction to priority user groups. In this way, they can improve the performance of the opposite inferior group. The difference can be made in this case, in which there is a need to restrict the access of *Non-Priority Users* to have high flexibility in the use of a spectrum other than their own. This is the reason why in any case of channel selection of the Outroom user, it is crucial to ensure that the user will use their own spectrum first before going to search for the availability of channel in another spectrum. So in other words, this restriction mechanism is the Outroom user's natural conditional set by the system.

The constant restriction function is specified as follows

$$r(j) = Occ_{thres}, \quad 0 < Occ_{thres} < 1 \tag{4.23}$$

where,

Occ_{thres} = user owned spectrum occupancy based restriction parameter.

The parameter of c_{occ} can be set to any constant value of $0<Occ_{thres}<1$, i.e. $Occ_{thres} = 0.7$, and its restriction imposed to Outroom users as so $r_{out}(j) = Occ_{\ thres}$. It then applied the restriction rule to the Outroom user system by setting the limit of 70% occupancy before it began to search the channel availability on other spectrums. This restriction mechanism is used in the channel selection algorithm of this thesis. Detailed explanation will be given in the next chapter of this thesis.

Figure 4.4 shows a modified state-transition-rate diagram of a shared spectrum, in this case spectrum f1 in 2AS model and spectrum f2 in 3AS model, when restriction is in place. It can be seen that the restriction function *r(j)* is subject to j, the number of occupied channels in the Outroom spectrum prior to the sensing process which affected the arrival rate of λ_{out} to come to the shared spectrum.

The state-transition-rate diagram still has the same equilibrium analysis as the previous *No Restriction* model. It means that it still has the same blocking probability measurement technique for both the Inroom and the Outroom. We only have to incorporate the equation to take into account the restriction mechanism parameter.

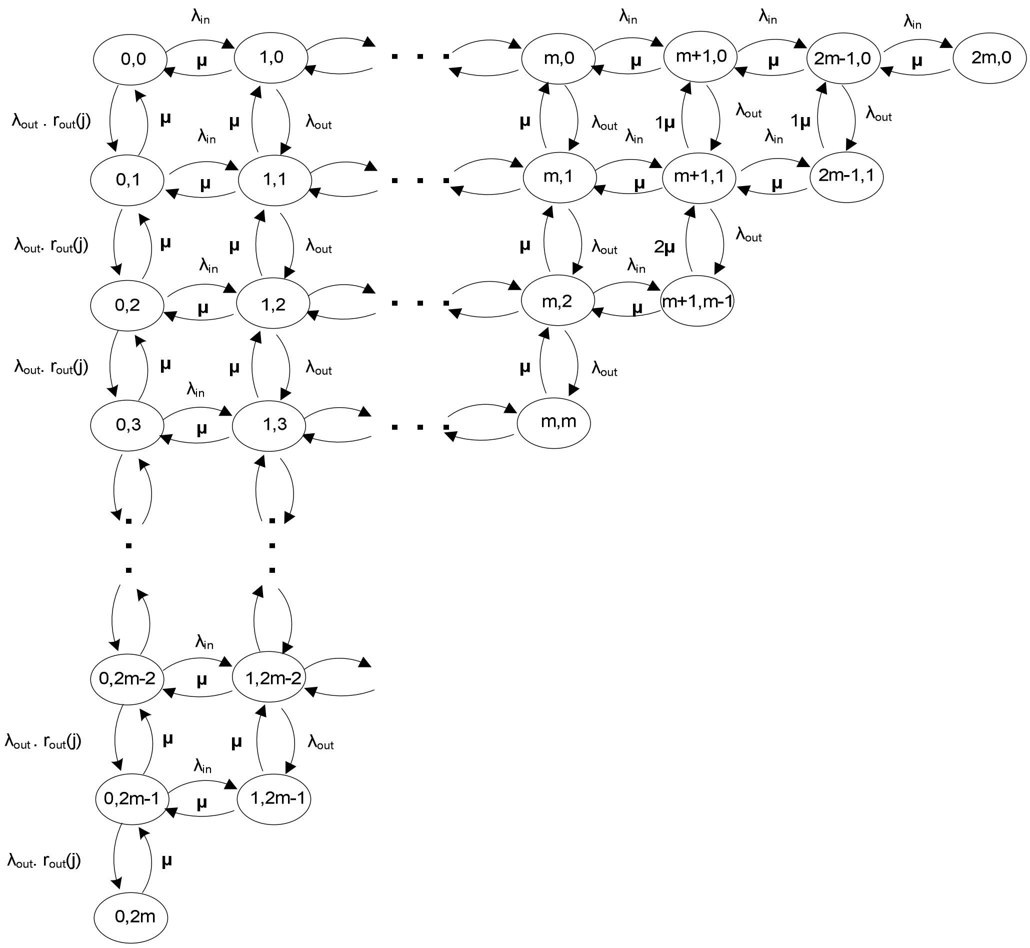

Figure 4-4. State-transition-rate Diagram for Constant Restriction Function Model

The blocking probabilities for both Inroom and Outroom users are equal and still equivalent to the sum of the state probabilities along the diagonal edge and follow the eq. 4.10 as follows

$$P_{b\_Inroom} = P_{b\_Outroom} = \sum_{j_1=0}^{m} p(j_1, 2m - j_1) + \sum_{j_1=0}^{m} p(2m - j_2, j_2) + p(m, m)$$

The same consideration can be applied if the restriction function needs to be imposed on the model which already incorporates the FSS based restriction. This constant restriction mechanism only affects the arrival rate of *Non-Priority Users* to come into the shared spectrum.

4.4 Conclusion

In this chapter, the mathematical analysis of coexistence in spectrum sharing in an indoor wireless environment was introduced. Three spectrum sharing models are defined and all are discussed in detail in relation to the way two user groups, Inroom and Outroom users, use the same spectrum.

The *No Restriction* scenario of shared spectrum coexistence is explained in detail with the help of analysis using the Markov model. A state-transition-rate diagram with its respective equilibrium analysis and blocking probability equation analysis are also presented.

This research continued to introduce the restriction mechanism used to protect the performance of the Inroom user who is the Priority User of the shared spectrum. In addition, the restriction mechanism, which incorporates the use of FSS walls in an external entity of the indoor wireless communication system, was also proposed. The FSS continually observed and gained information from surrounding users and used the information to define the activation of filters in FSS walls. All analytical results of this FSS based model using the Markov model are also presented.

The 1AS model analysis can also be assumed to be the coexistence analysis of the shared spectrum f2. So, it will be used to derive the spectrum sharing analysis for 2AS and 3AS models.

- In the case of the 2AS model, the analysis will begin with the derivation of coexistence analysis of the shared spectrum f2, using the 1AS model, followed by the analysis of the single-dimensional Markov model in spectrum f1.
- In the case of the 3AS model, the analysis will also begin with the derivation of coexistence analysis of the shared spectrum f2, using the 1AS model, followed by the analysis of a single-dimensional Markov model in both spectrums f1 and f3.

Finally, this research proposes the user internal restriction mechanism using a constant restriction function based on user owned spectrum occupancy levels. At this time, this restriction function only imposes on the *Non-Priority Users* of the shared spectrum. This restriction function can be used in the 2AS and 3AS spectrum sharing models, where the Outroom has its own default working spectrum. From the analysis, it can be concluded that this restriction function only affects the arrival rate of *Non-Priority Users* to come into the shared spectrum.

Chapter 5. FSS based Spectrum Sharing in a Smart Indoor Environment

Contents

5.1 Introduction

This chapter introduces FSS based spectrum sharing in a smart indoor environment, which defines the efficient usage of the spectrum and the increased performance of users. Section 5.2 presents the simulation model, which uses the Multi-Wall-Model (MWM) described in chapter 2 as its propagation model. It only considers both the direct Line of Sight (LOS) signal and Obstructed Line of Sight (OLOS) signal. All scenarios presented in this chapter were developed as the basic algorithm which will be expanded further for a more robust and better scenario.

Section 5.3, it desribes in detail about the algorithm inside the FSS based spectrum sharing and is followed by Section 5.4 which gives a mathematical analysis based on the

Markov model when the model is incorporated with the restriction mechanism. The analysis will cover all three models of FSS ON, FSS OFF and FSS Fixed Threshold. The section also derives the blocking probability of all of those models based on the state-transition-rate diagram. Simulation analysis is also shown to provide a good understanding of what happens with those three models. Finally, conclusions are given in section 5.6.

5.2 Simulation Model

The indoor wireless spectrum sharing users are a set of transmitting-receiving user pairs denoted as U, uniformly distributed in the previously described four-room indoor building. The MWM model, which is used as the indoor propagation model, takes into account an individual transmission loss of each of the walls penetrated by the direct path between the transmitter (Tx) and the receiver (Rx).

More specifically, all Inroom users, denoted as U_{in}, are uniformly distributed in room 1 and the rest of Outroom users, denoted as U_{out}, are uniformly distributed in rooms 2, 3 and 4. As shown in Figure 5.1, the model currently has 3 available frequencies where

1. Inroom users use both frequency (f1) 2.45 GHz and frequency (f2) 3 GHz, without any limit at any time.
2. Outroom users work as default in frequency (f3) 5.8 GHz and using frequency (f2) 3 GHz with limitations set depending on the utilization of frequency (f2).

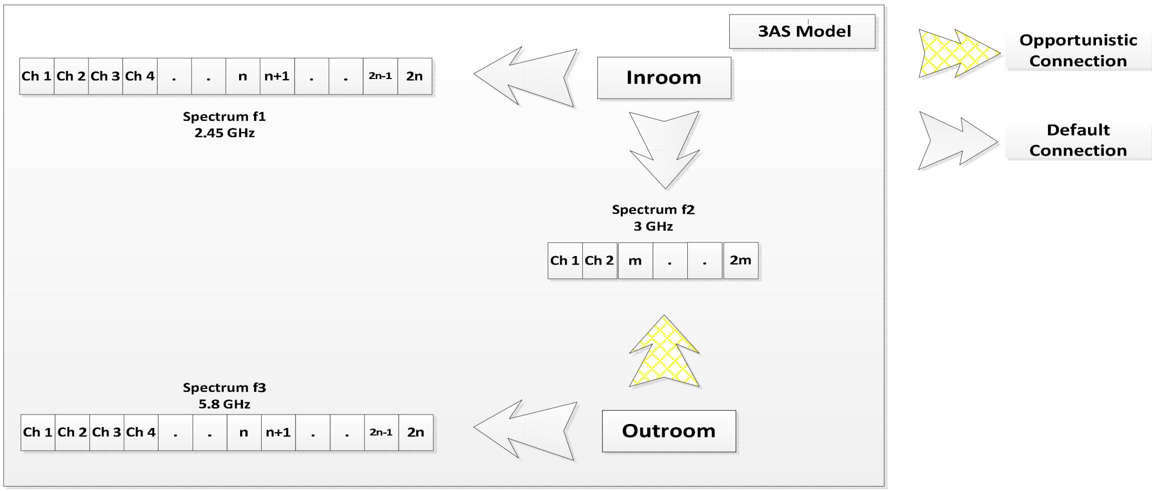

Figure 5-1.Diagram for Frequency Arrangement for 3AS Model

An event-based simulation scenario is used in this work, and at each subsequent time, a random subset of either U_{in} or U_{out} pairs are activated. The summary of system parameters used in this work is shown in table below.

Table 5-1. Simulation Parameter for FSS based Spectrum Sharing

Parameter	Value
Service Area	20 m x 10 m x 3m
Number of Pairs	30 Inroom 30 Outroom
Transmitter Antenna Gain	0 dBi
Interference Threshold	-110 dBm
SINR Threshold	5 dB
Noise Floor	-126 dBm

5.3 FSS based Spectrum Sharing Algorithm

The model is similar as in the previous chapter following two general stages as follows:

- **Transmission Stage:**

  Step 1: Spectrum Selection.

Let C be the set of all user pairs randomly scattering in 2 storey building with *n* rooms, so

C_{inroom} = is the set of all user pairs located in one room
$C_{outroom}$ = is the set of all user pairs which separated by wall

Both U_{in} and U_{out} users start each activation by picking up channel randomly and choose the channel according to each default frequency. The selected channel is denoted as C_{ik} where, i = 1 to 3,

and

Set of channels in frequency (f1) denoted as C_{1k}
Set of channels in frequency (f2) denoted as C_{2k}
Set of channels in frequency (f3) denoted as C_{3k}
C_{1k},C_{2k},C_{3k} ϵ C and C is the available channel set for each frequency.

Step 2: Spectrum Sensing.

Either U_{in} or U_{out} sense interference level on their respective C_{ik} (U_{in} will sense in either C_{1k} or C_{2k}, and U_{out} will sense in either C_{3k} or C_{2k}). If the interference level I of C_{ik} is below the interference threshold (Int_thres), U_i is activated. Otherwise if it falls below the Int_thres, it will be blocked.

Step 3: SINR Measuring

The entire activated U_i user that has already arrived and joined the wireless system needs to maintain their channel quality by measuring the level of Signal-to-Interference-plus-Noise-Ratio (SINR) at their receiver side. It must be above a certain threshold that has been set depending on the modulation technique used in the system. If the SINR of an activated user U_i is greater than the SINR Threshold (U_i(SINR) ≥ SINR_thres), it means that the U_i user has successfully used the spectrum. Otherwise, if SINR of U_i falls below the SINR threshold (U_i(SINR) < SINR_thres), it will be blocked by the channel.

Both Inroom and Outroom users are randomly set to find the channel, for example the Inroom will randomly select the channel in spectrum f1 and f2 and the Outroom users randomly select the channel in spectrum f3 and f2 (restricted access to Outroom users as defined earlier).

- **FSS Stage**

  Step 4: FSS Activation

  This stage is about the Outroom user signal which travels through the wall. The accepted U_j user occupies the channel and starts to send the information to its receiver pair. If the utilization of spectrum f2 is greater than the FSS threshold (*Occ(f2) ≥ FSS_Thres*), then it will activate the FSS and the wall will exhibit more interference on f2, affecting the Outroom users and, in the end, it will block all of the Outroom users from accessing the spectrum f2. Then the blocked Outroom user (FSS Blocked user) will try to reassign its channel and to obtain the channel from its default spectrum f3.

5.4 Restriction Mechanism

5.4.1 Implementation of Restriction Mechanism

The user owned spectrum based restriction mechanism used in this model is the same as specified earlier in eq. 4.21. This function is implemented in the user system as part of the Outroom channel selection algorithm. The restriction mechanism based its process on the level of occupancy in Outroom spectrum f3. This user will keep updating its spectrum utilization under a term defined as $Occ(f3)$ prior to the channel selection process. The value of c_{occ} is set to *0.8Occ_total*. This means that the Outroom user will start sensing both spectrum f2 and f3 as soon as $Occ_{thres} \geq Occ(f3)$ is reached.

The selection of channel process in spectrum f1and f2 follows the algorithm in Figure 5.2 for U_{in} (Inroom), and Figure 5.3 for U_{out} (Outroom) in spectrum f3 and f2.

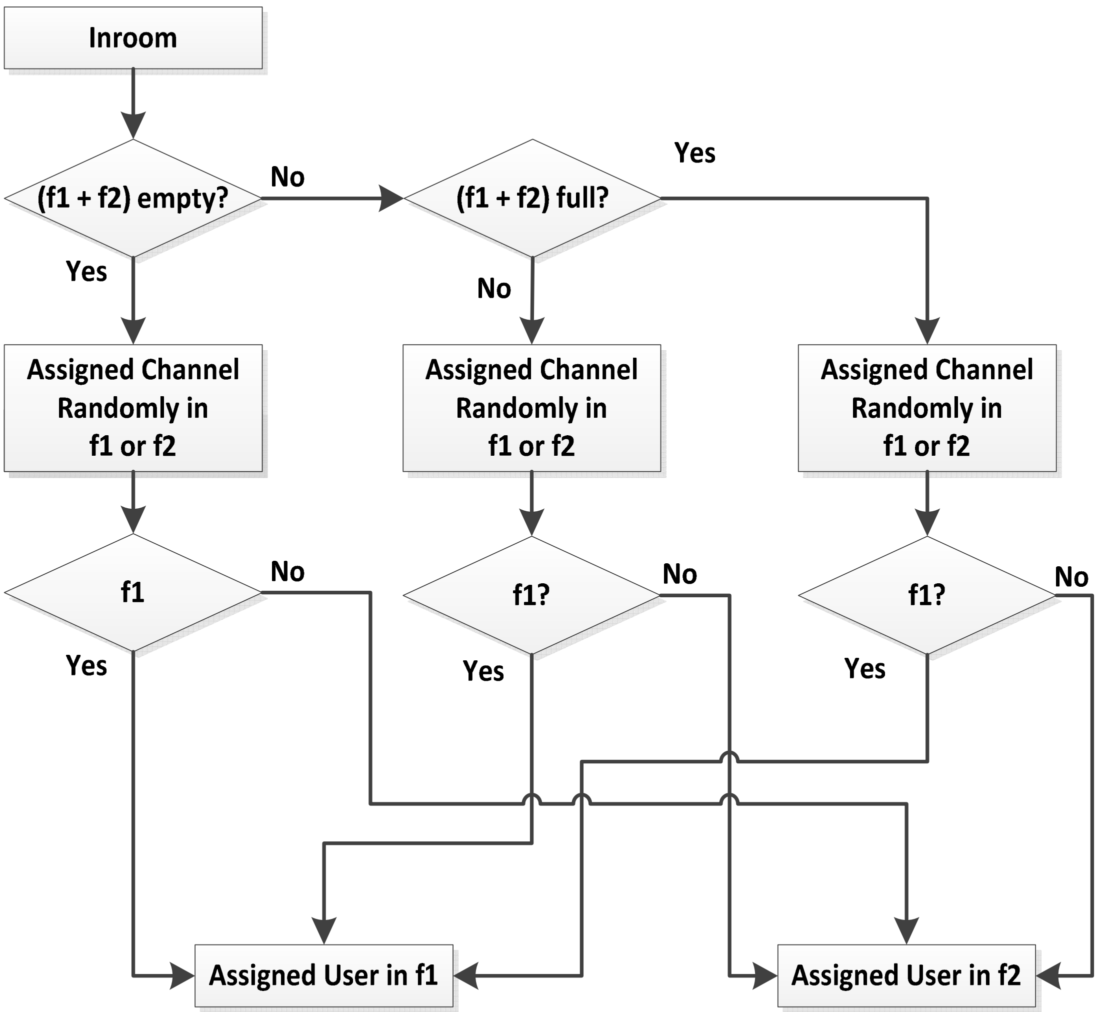

Figure 5-2.Channel Selection Algorithm for Inroom Users

Inroom users will select the channel at random with the selection of empty channels from C_{1k} and C_{2k} without any restriction for the entire time. If all channels in both C_{1k} and C_{2k} are full, it then randomly chooses any channels from C_{1k} and C_{2k} and begins step 3. Otherwise, the Outroom users will pick a channel at random from C_{3k} until they reach $Occ\_C_{3k} \leq Occ\_thres$ then the Outroom users will start to search empty channels at random with a selection of channels from C_{3k} and C_{2k}. If all channels in both C_{3k} and C_{2k} are full, the same will happen to the Outroom users, they then randomly choose any channels from C_{3k} and C_{2k} and begin step 3 above.

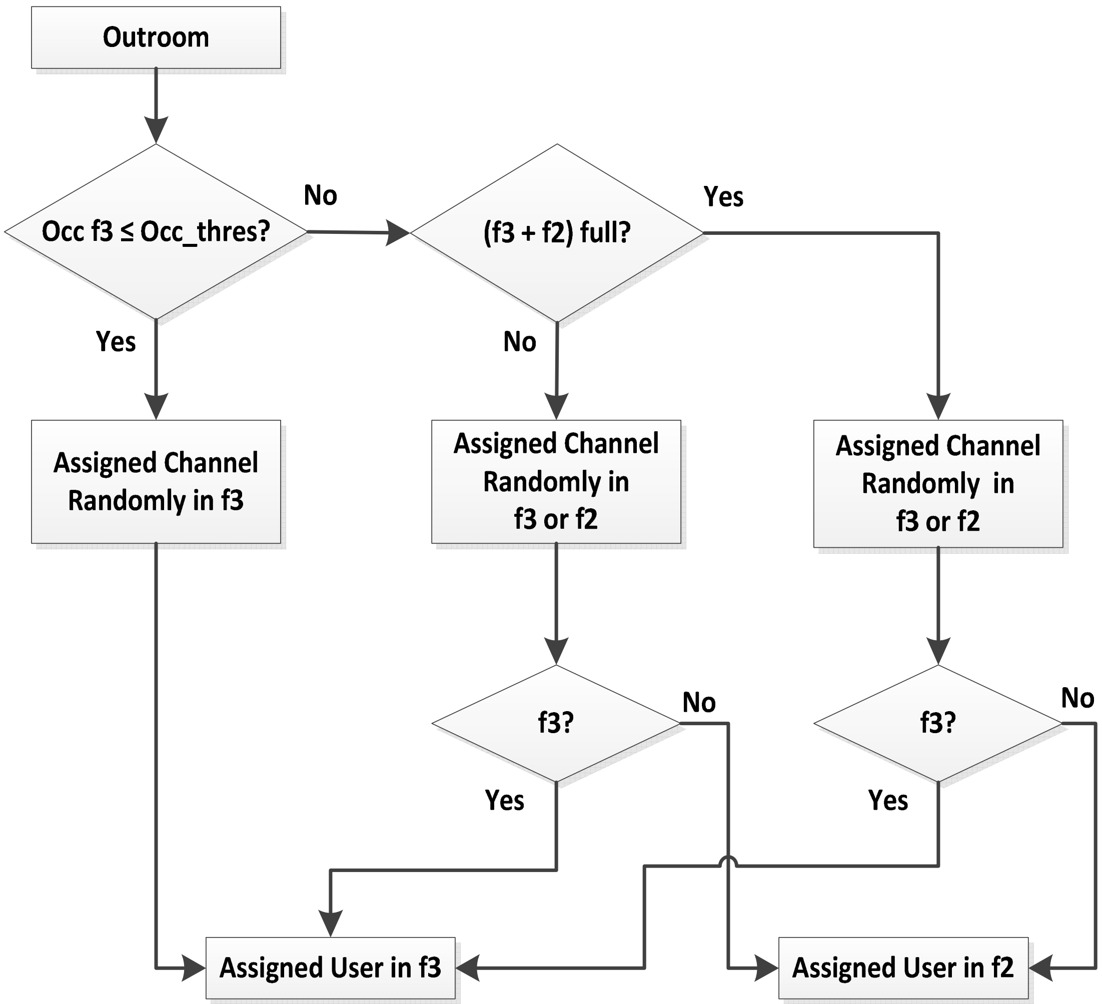

Figure 5-3. Channel Selection Algorithm for Outroom Users

In addition, the model in this chapter also incorporates the FSS based restriction mechanism, which is applied at the FSS stage in FSS algorithm in Figure 3.2. If the scenario of FSS state is applied to this restriction, it will follow the rule as below

- FSS ON, under this state of circumstances the restriction function value is set to zero ($k = 0$); it lets the FSS stay continually in state ON.
- FSS OFF, under this state of circumstances the restriction function value is set to the maximum ($k = 2m$); it lets the FSS stay continually OFF.
- FSS Fixed Threshold, under this state of circumstances the restriction value is set with a fixed value ($k = FSS\_Thres$), the rest of the process will follow FSS activation in step 4 as previously described.

The modified state-transition-rate diagram with the restriction factor for the shared spectrum f2 is shown in Figure 5.3.

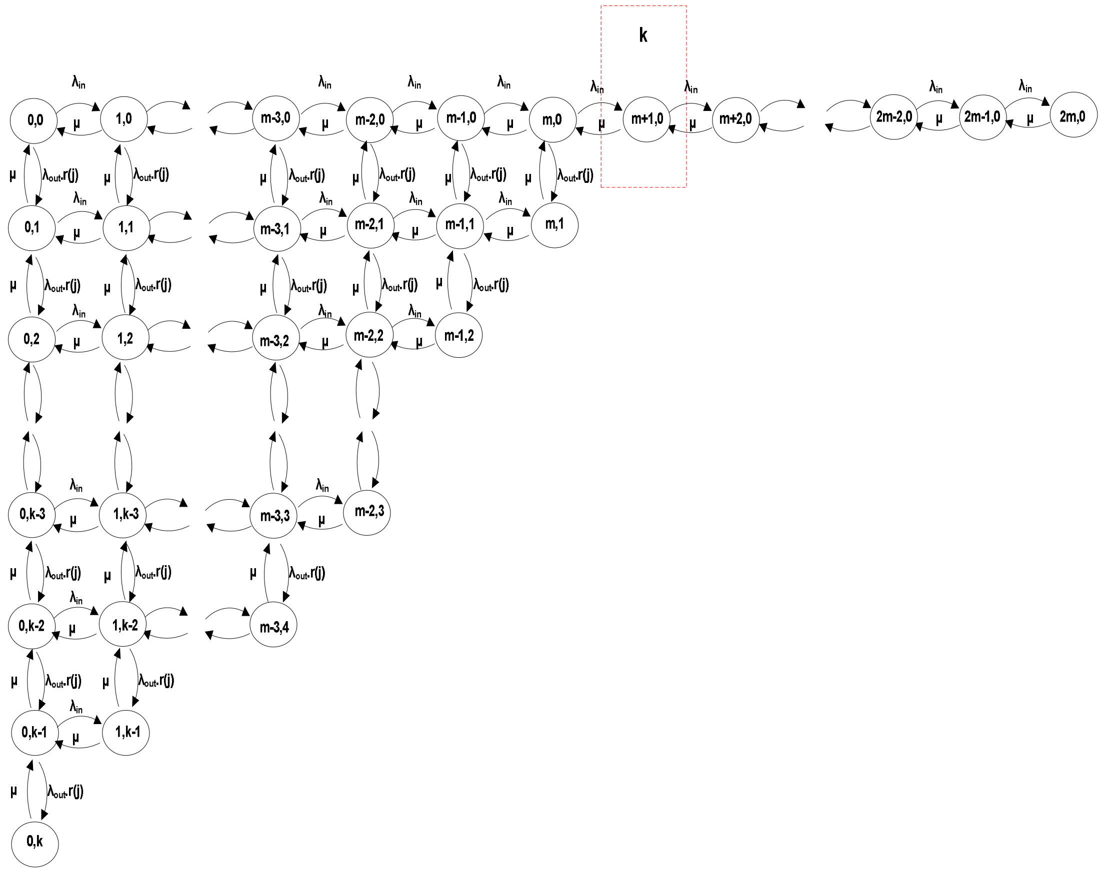

Figure ***5-4. State-transition-rate Diagram for Spectrum f2 with Restriction Mechanism Applied***

5.4.2 **Restriction Mechanism Analysis**

Based on previous discussion in chapter 4, the user spectrum based restriction mechanism will affect the arrival rate of Outroom users to spectrum f2. On the other hand, the FSS based restriction mechanism will affect some states in the state-transition-rate diagram and become unobtainable, i.e. when the FSS state is OFF the usable state area (assuming *2m x 2m* state diagram) follows the condition $\{p((j_1 + j_2) \leq 2m)\}$, and the usable state area reduces to follow the condition $\{p((j_1 + j_2) > k) = 0\} \cap \{p(j_1,0), k+1 \leq j_1 \leq 2m\}$ when FSS state ON. The reduced usable state area depends on the value of *k.* It becomes a single dimensional Markov model when the FSS state is continually ON. This reduced area will affect the way we define the calculation for blocking probability.

It is assumed that all users have a device with the capability of tuning into multi-frequencies, and by the time they have tuned their working frequency to a specific spectrum, they will stay and use that frequency until the end of their connection. If there are active Outroom users left when the FSS is activated in the f2 spectrum, they will remain on the channel until they finish their connection.

- The Unobtainable states still follow the condition of
  $\{p((j_1 + j_2) > k) = 0\} \cap \{p(j_1,0),\ \ k+1 \le j_1 \le 2m\}$.

- The number of user states cannot be negative meaning
  $p(-1, j_2) = p(j_1, -1) = 0,\ \ 0 \le j_1, j_2 \le 2m$.

The equilibrium expressions are as follows

For state *(0,0)*, as follows

$$(\lambda_{in} + \lambda_{out})P(0,0) = \mu P(0+1,0) + \mu P(0,0+1) \quad (5.1)$$

For state *(2m,0)*,

$$\mu P(2m, 0) = \lambda_{in} P(2m-1,0) \quad (5.2)$$

For state *(0,k)*,

$$\mu P(0, k) = \lambda_{out} P(0, k-1) \quad (5.3)$$

For state $(j_1, 0)$, $\{0 < j_1 \le k-1\}$,

$$(\lambda_{in} + \lambda_{out} + \mu)P(j_1, 0) = \lambda_{in} P(j_1 - 1,0) + \lambda_{out} P(j_1, 0-1) + \mu P(j_1 + 1,0) + \mu P(j_1, 0+1) \quad (5.4)$$

$$p(j_1, -1) = 0$$

For state $(j_1, 0)$, $\{k \leq j_1 < 2m\}$,

$$(\lambda_{in} + \mu)P(j_1, 0) = \lambda_{in}P(j_1 - 1{,}0) + \mu P(j_{1+1}, 0) \tag{5.5}$$

For state $(0, j_2), \{0 < j_2 < k\}$,

$$(\lambda_{in} + \lambda_{out} + \mu)P(0, j_2) = \lambda_{in}P(0 - 1, j_2) + \lambda_{out}P(0, j_2 - 1) + \mu P(0 + 1, j_2) + \mu P(0, j_2 + 1) \tag{5.6}$$

$$p(-1, j_2) = 0$$

For state (j_1, j_2), $\{j_1 + j_2 < k \text{ \&\& } j_1, j_2 > 0\}$,

$$(\lambda_{in} + \lambda_{out} + 2\mu)P(j_1, j_2) = \lambda_{in}P(j_1 - 1, j_2) + \lambda_{out}P(j_1, j_2 - 1) + \mu P(j_1 + 1, j_2) + \mu P(j_1, j_2 + 1) \tag{5.7}$$

For state (j_1, j_2), $\{j_1 + j_2 = k \text{ \&\& } j_1, j_2 > 0\}$,

$$\mu P(j_1, j_2) = \lambda_{in}P(j_1 - 1, j_2) + \lambda_{out}P(j_1, j_2 - 1) \tag{5.8}$$

And finally, it should be remembered that the state probabilities must also satisfy the normalization equation in eq. 4.9 as follows

$$\sum_{j_1=0}^{2m} \sum_{j_2=0}^{2m} p(j_1, j_2) = 1$$

5.4.3 **Blocking Probability Analysis**

The analysis of the blocking probability of the system will consist of 3 different models used in this chapter, FSS Continually ON, FSS Continually OFF and FSS Fixed Threshold. The reason behind this is because all three of those models provide different effects to the usable state area of state-transition-rate diagram in shared spectrum f2.

5.4.3.1 FSS Continually ON

The total blocking probability of Inroom users consists of two different parts; the first is the blocking probability of Inroom users in spectrum f1 and the second is the blocking probability of Inroom users in spectrum f2.

$$P_{b\_inroom} = P_{b\_inf1} + P_{b\_inf2} \tag{5.9}$$

$$P_{b\_inf1} = p(2n) \tag{5.10}$$

Where n is the total number of channels in spectrum f1 based on the single-dimensional state-transition-rate diagram in Figure 5.5. P_{b_inf1} will be equal for all three models.

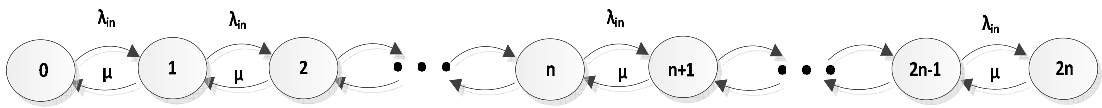

Figure 5-5. State-transition-rate Diagram for Spectrum f1

The blocking probability for Inroom users in shared spectrum f2 is equal to the probability of the system being in the state $p(2m, 0)$ and is equal to P_{b_Inroom} for the 1AS model previously described in eq. 4.20.

$$P_{b\_inf2} = p(2m, 0) \tag{5.11}$$

Therefore the total blocking probability of Inroom users in the system will be

$$P_{b\_inroom} = p(2n) + p(2m, 0) \tag{5.12}$$

The total blocking probability of the Outroom users consists of one part, which is the blocking probability of Outroom users in spectrum f3. Assuming *n* is also the total number of channels in spectrum f3 and is based on the single-dimensional state-transition-rate diagram shown in Figure 5.6, the blocking probability of Outroom users in spectrum f3 can be expressed as

$$P_{b\_outroom} = P_{b\_outf3} = p(2n).r(j) \tag{5.13}$$

P_{b_outf3} or the blocking probability of Outroom in spectrum f3 will be similar for all three models.

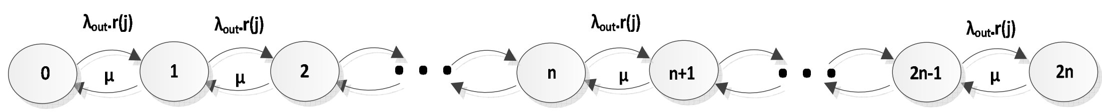

Figure 5-6. State-transition-rate Diagram for Spectrum f3

5.4.3.2 FSS Continually OFF

Similarly, the total blocking probability of Inroom users will follow eq. 5.9. The same effect happens as in the FSS continually ON model, where the blocking probability of Inroom users in spectrum f1 also follows eq. 5.10.

The blocking probability for the Inroom user in shared spectrum f2 is similar to the *No Restriction* model and is equivalent to the sum of the state probabilities along the diagonal edge as shown in Figure 4.2 and follows eq. 4.10.

Therefore the total blocking probability of the Inroom users in the system will be

$$P_{b\_Inroom} = p(2n) + \sum_{j_1=0}^{m} p(j_1, 2m - j_1) + \sum_{j_1=0}^{m} p(2m - j_2, j_2) + p(m, m) \tag{5.14}$$

In the case of the total blocking probability of the Outroom users, they consist of two different parts. The first one is the blocking probability of Inroom users in spectrum f1 and the other is the blocking probability of Inroom users in spectrum f2.

$$P_{b\_outroom} = P_{b\_outf3} + P_{b\_outf2} \quad (5.15)$$

The blocking probability of Outroom users in spectrum f3 will follow the same equation as P_{b_outf3} in eq. 5.13. The blocking probability of Outroom users in spectrum f2 will be similar to that of the Inroom users and follows eq. 4.10.

Therefore, the total blocking probability of Inroom users in the system will be

$$P_{b\_outroom} = p(2n).r(j) + \sum_{j_1=0}^{m} p(j_1, 2m - j_1).r(j) + \sum_{j_1=0}^{m} p(2m - j_2, j_2) + pm,m.r(j) \quad (5.16)$$

5.4.3.3 FSS Fixed Threshold

The total blocking probability of the Inroom users similarly follows eq. 5.9. The same effect happens to the blocking probability of Inroom users in spectrum f1 following eq. 5.10 and in spectrum f2 it following eq. 4.20. In this way, the total blocking probability of Inroom users in the system will be the same as in the FSS continually ON model and follows eq. 5.12.

The blocking probability of the Outroom users in spectrum f3 will follow the same equation as P_{b_outf3} in eq. 5.13 and in spectrum f2 it is still equivalent to the sum of state probabilities along the diagonal edge and is equal with $P_{b\_outroom}$ for the 1AS model as previously described in eq. 4.19.

$$P_{b\_outf2} = \sum_{j_1=0}^{k} p(j_1, k - j_1).r(j) \quad (5.17)$$

Therefore, the total blocking probability of the Outroom users in the system will be

$$P_{b\_outroom} = p(2n).r(j) + \sum_{j_1=0}^{k} p(j_1, k-j_1).r(j) \quad (5.18)$$

5.5 Simulation Result and Analysis

5.5.1 FSS ON and FSS OFF

Before going much further into another complex model, it is important to conduct an in-depth investigation on the system performance of the basic model, in which FSS ON is continually applied and FSS OFF is continually applied in relation to the *Offered Traffic*. It is to show the maximum *Offered Traffic* that can be handled by the system in extreme cases. Figure 5.3 shows detail results as follows

- FSS continually ON (FSS ON) is the condition where the best performance of Inroom users and the worst situation for Outroom users can be expected. The system can accommodate all *Offered Traffic* of Inroom users with the blocking probability from almost zero up to slightly higher than 2% for 25 Erlangs of *Offered Traffic*. On the other hand, the system can only accommodate slightly higher than 16 Erlangs of *Offered Traffic* of Outroom users, where the blocking probability is just slightly less than 5% for 16 Erlangs of *Offered Traffic* and up to a bit less than 24% for 25 Erlangs of *Offered Traffic*.
- FSS continually OFF (FSS OFF) is the reflection of the worst situation of Inroom users and the best performance of Outroom users, where the system can only accommodate slightly higher than 22 Erlangs of *Offered Traffic* Inroom users with the blocking probability increased from almost zero at 16 Erlangs of *Offered Traffic* to slightly higher than 10% at 25 Erlangs of *Offered Traffic*. On the other hand, the system can accommodate more than 24 Erlangs of *Offered Traffic* of Outroom users with the blocking probability increasing from almost zero at 16 Erlangs of *Offered Traffic* to slightly higher than 6% for 25 Erlangs of *Offered Traffic*.

The FSS ON gives maximum flexibility to Inroom users to use both spectrum f1 and f2 and blocks Outroom user from accessing spectrum f2. Consequently, Outroom users can only use their own channels in spectrum f3. This makes the performance of Outroom users poorer with the increase of *Offered Traffic*. Outroom users most probably will lose about one third of their usable channels because they are blocked due to the FSS attenuation.

On the other hand, FSS OFF will enable both users to have equal flexibility for the use of spectrum f2. From the Inroom perspective, they will lose about one sixth of their usable channels through competition with other users sharing the spectrum. For Outroom users, they will obtain more channels with the increased likelihood of at least 25% compared to the FSS ON. In this scenario, it shows the effects of the user spectrum restriction mechanism, by letting the Outroom user access 80% of their own channel before they can access the channel in spectrum f2, this results in better performance for Outroom users in the scenario FSS OFF state.

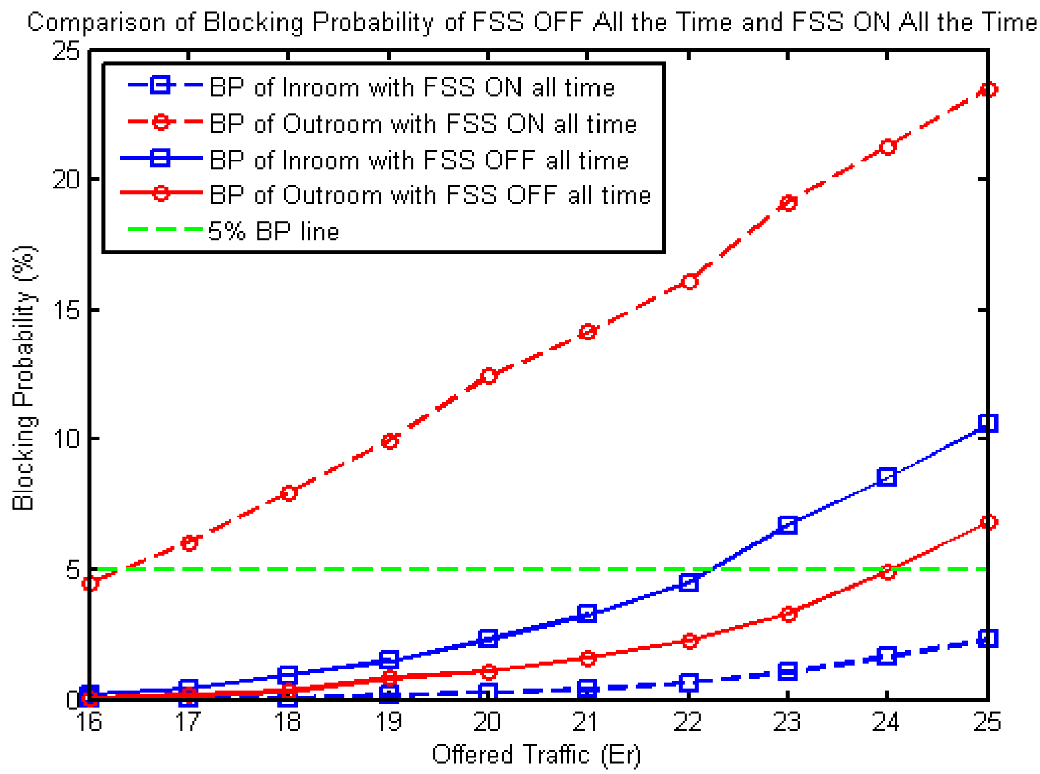

Figure 5-7. Blocking Probability with Different Offered Traffic Load for the FSS ON and FSS OFF All the Time

5.5.2 FSS Fixed Threshold

This method will base its activation trigger on the instantaneous rate of *0.65Occ_maxf2*. When this threshold value is reached in f2, the FSS will instantly exhibit more attenuation to Outroom users and close the access of Outroom users to search the channel in spectrum f2.

By using FSS Fixed Threshold spectrum sharing, the blocking probability of the Outroom users can be significantly reduced. The *Offered Traffic* that can be handled by the system can also increase to up to 21 Erlangs of traffic from only slightly over 16 Erlangs in FSS continually ON state. The blocking probability ranges from 0.4% for 16 Erlangs of *Offered Traffic* and rises with the increase of *Offered Traffic* until 5.73% for 25 Erlangs of *Offered Traffic*. If we look in detail from the Inroom perspective, the Inroom users only experience a small loss in the amount of *Offered Traffic* that can be handled. The blocking probability ranges from 0.1% at 16 Erlangs increasing to 5.7% at 25 Erlangs of *Offered Traffic*.

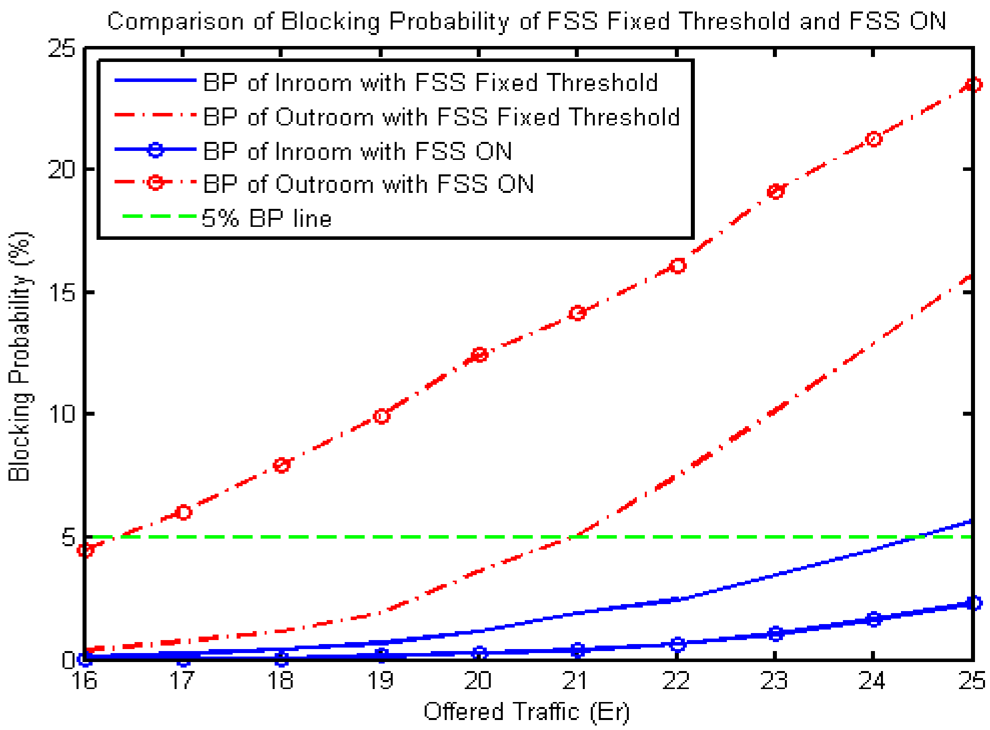

Figure 5-8. Blocking Probability for Different Offered Traffic Levels for FSS Fixed Threshold and FSS ON All the Time

5.6 Conclusion

In this Chapter, we introduced FSS based spectrum sharing in smart indoor environments. Using the instantaneous activation of FSS, we learn the basic performance of the system under three different circumstances which are FSS ON, FSS OFF and Fixed Threshold.

The restriction analysis shows that when we impose FSS based restrictions on all three models, it will provides different outcomes on the usable state area of state-transition-rate diagram in shared spectrum f2. FSS continually ON will turn the multi-dimensional Markov model into a single-dimensional Markov model. FSS continually OFF will form the usable state area defined as $\{p((j_1 + j_2) \leq 2m)\}$. FSS Fixed Threshold will form the usable state area defined as $\{p((j_1 + j_2) > k) = 0\} \cap \{p(j_1,0),\ \ k+1 \leq j_1 \leq 2m\}$ with the (width) area depending on the value of k . This usable state is one of the main factors to define the blocking probability of *Non-Priority Users* in the shared spectrum.

Simulation results show the basic performance range of this FSS based spectrum sharing, where the scenario FSS OFF gives more advantage to Outroom users to gain better performance when compared to Inroom Users. This scenario sets the spectrum f2 to be used for both Inroom and Outroom users with equal opportunity for both users. Alternatively, the scenario FSS ON provides more advantage to the Inroom user to use both spectrum f1 and f2 and forces the Outroom user to only use its own channels in spectrum f3.

With the intention being to keep protecting the performance of the Inroom user, this research attempted the simple scenario by setting the FSS threshold to 65% (Fixed Threshold). The result shows much better performance of Outroom users when compared to the FSS ON situation without decreasing the performance of Inroom users dramatically.

Chapter 6. FSS Spectrum Access in Three Available Spectrum Bands

Contents

6.1 Introduction

In this chapter the thesis proposes the use of a dynamic table to further improve the performance of wireless indoor communication. Firstly, in section 6.2, it discusses how to define the dynamic table based on the summarized performance of previous models and analysis here in section 6.3 shows the performance result of the FSS Dynamic Table when compared with the previous model.

The discussions continue in section 6.4 with how the use of statistical values can minimize the frequency of instantaneous traffic load by using the FSS State Window. The discussion and analysis of some result is then given in section 6.5 and followed by conclusions.

6.2 Defining a Dynamic Table

In order to improve the performance, we introduce a Dynamic Table. This table is summarizes the performance of indoor communication with the variation of *Offered Traffic* from light use of 15 Erlangs to heavy use OT of 25 Erlangs with the 2.5 Erlang increments. With the intention to improve the performance of Outroom users without significantly reducing the performance of Inroom users, we then cap the Inroom user's performance with each offered amount of traffic not to exceed the limit of 5% blocking probability. FSS Instantaneous Threshold value is the extreme threshold obtained from the simulation when the performance reached 5% blocking probability. For example, the value of a maximum threshold of (> 100) means the system with provided mean offered traffic can still maintain its performance below 5% blocking probability for the entire range of threshold set from 0 – 100%. All the results are summarized in Table 6.1 and can be constructed into the equation as follows

$$FSS_{thres} = \begin{cases} 1 & ; \quad OT < 16 \\ 1 & ; \quad 16 \leq OT < 19 \\ 1 & ; \quad 19 \leq OT < 21 \\ 0.76 & ; \quad 21 \leq OT < 24 \\ 0.5 & ; \quad OT \geq 24 \end{cases} \tag{6.1}$$

Table 6-1. The Dynamic Table

Generated Offered Traffic	Mean Offered Traffic	FSS Instantaneous Threshold
$OT_{gen} < 16$	15	>100
$16 \leq OT_{gen} < 19$	17.5	>100
$19 \leq OT_{gen} < 21$	20	>100
$21 \leq OT_{gen} < 24$	22.5	76
$OT_{gen} \geq 24$	25	50

6.3 The Dynamic Table based FSS Spectrum Access

The Dynamic Table based FSS Spectrum Sharing algorithm is illustrated in Figure 6.2. We consider the indoor user as a set of transmitting-receiving pairs of nodes, denoted as U, uniformly distributed inside the building and all the pairs $U_{ij} \in U$ are spatially fixed. As described previously, if $i = j$ then they represent the Inroom user and the Outroom user. Moreover, the process in *Transmission Stage* still follows the three steps as described earlier in chapter 5. However, in the *FSS Stage* process, instead of having a fixed threshold value assigned from the very start of the simulation, it now has the look-up table as a reference to determine the FSS_thres value in relation to equation 6.1 above. The same process then follows as earlier, where we decide to turn the FSS ON or OFF depending on the instantaneous occupancy of spectrum f2. An event based scenario is used in this work, and at each event a random subset of pairs are activated, system parameters used in this work are shown in Table. 5.2.

Table 6-2. Simulation Parameter for FSS Dynamic Table

Parameter	Value
Service Area	20m x 10m x 3m
Number of Pairs	30 Inroom 30 Outroom
Transmitter Antenna Gain	0 dBi
Interference Threshold	-110 dBm
SINR Threshold	5 dB
Noise Floor	-126 dBm

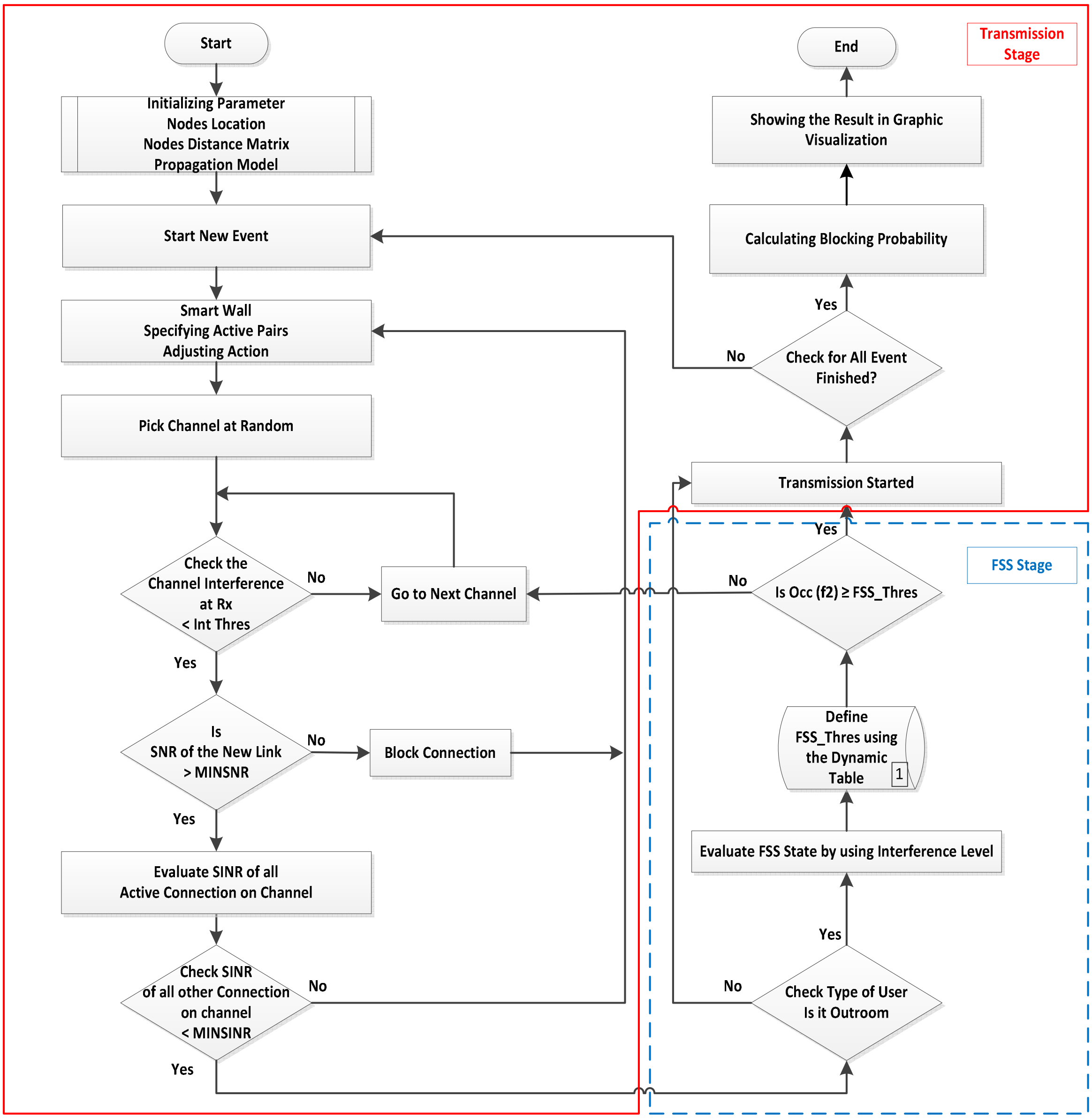

Figure 6-1. The Dynamic Table Simulation Algorithm

The benefit of having this dynamic table in place is that it would set the *FSS_thres* value depending on the instanteneous *Offered Traffic*. So, the FSS activation threshold at time t (*FSS_thres(t)*) when measured *Offered Traffic* is *x* will not be the same as with the FSS activation threshold at time *t+10* (*FSS_thres(t+10)*) when the measured *Offered Traffic* is *y*. It depends on the instanteneous *Offered Traffic* measured at the time the user accesses the shared spectrum f2. The higher the measured *Offered Traffic*, the lower the FSS activation will be set and it will depend on the traffic factor based on eq. 6.1.

If we compare our previous scenario with the one using the FSS Fixed Threshold, this scenario will give much better performance for Outroom users, without significantly reducing the performance for Inroom users. Figure 6.3. shows the snap-shot of FSS state activation with its respective traffic load over the activation 0-500 in iteration 20. We can see a varying traffic load over the timely activation *t*, and its instanteneous changing rate is very fast. This is the reason behind the development of this dynamic table. We cannot use the same fixed activation threshold for the entire activation, instead we use the dynamic table as a look-up table to minimize the instanteneous changing of the traffic load.

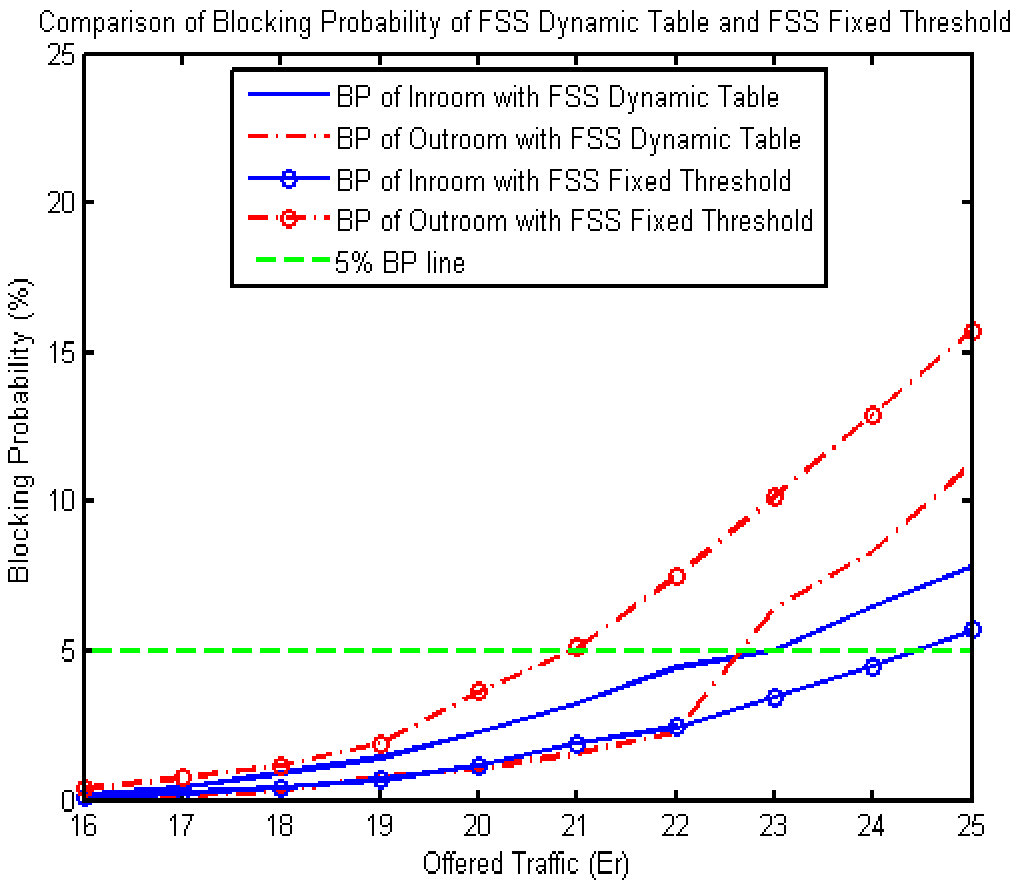

Figure 6-2. Blocking Probability with Different Offered Traffic for FSS Dynamic Table and FSS Fixed Threshold

Figure 6.2 shows the comparison between the FSS Fixed Threshold and the FSS Dynamic Table scenarios with the increasing traffic load from 16 Erlangs to 25 Erlangs. FSS Dynamic Table gives much better performance for Outroom users indicated by the increase in traffic load that can be handled, from 21 Erlangs to slightly higher than 22.5 Erlangs. The blocking probability also gives a much stronger trend where now at up to 22 Erlangs traffic the blocking probability will only reach 2.5% and an increase from the previous scenario of about 19 Erlangs. The FSS Dynamic Table decreased the blocking probability at a maximum traffic load of 25 Erlangs, from 15.7% to 11.2%. The increased performance of the Outroom users does not considerably reduce the performance of Inroom, where they can still handle the maximum 23 Erlangs traffic, even with the increase blocking probability from 3.5% to slightly less than 5%.

6.4 FSS State Window based Spectrum Sharing

The model in the FSS Dynamic Table still uses an instanteneous measurement of traffic load over the time activation. This model still makes the fast flipping states of FSS ON and OFF occurs frequently. As a result, as shown in Figure 6.4, most of the timely activation with the blocking probability Outroom users tend to increase when instanteneous FSS state change occurrs. A stable rate of change in the FSS state tends to give a better performance to Outroom and a much more stable performance to Inroom users.

This is the area where we need to improve the system performance by proposing a system to minimize the instanteneous FSS state changes. The idea is to use a sliding window averaging the traffic load with a specific slot range. The way it works is the FSS State Window will record the measured traffic load every time activation is successful and average the sum of those recorded with a specific value of window size, following the basic equation as shown below

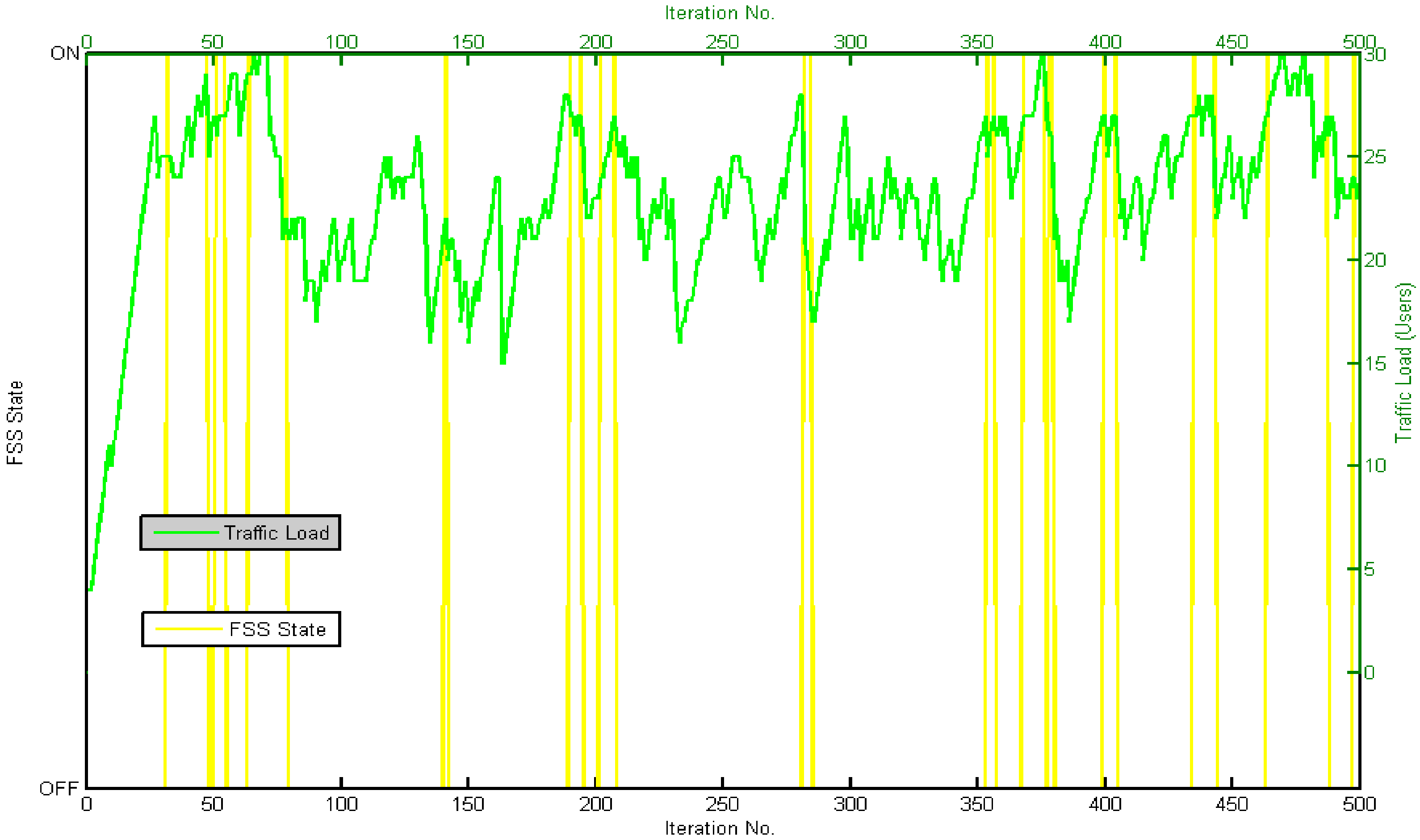

Figure 6-3. Snap-shot of FSS State with Respective Traffic Load

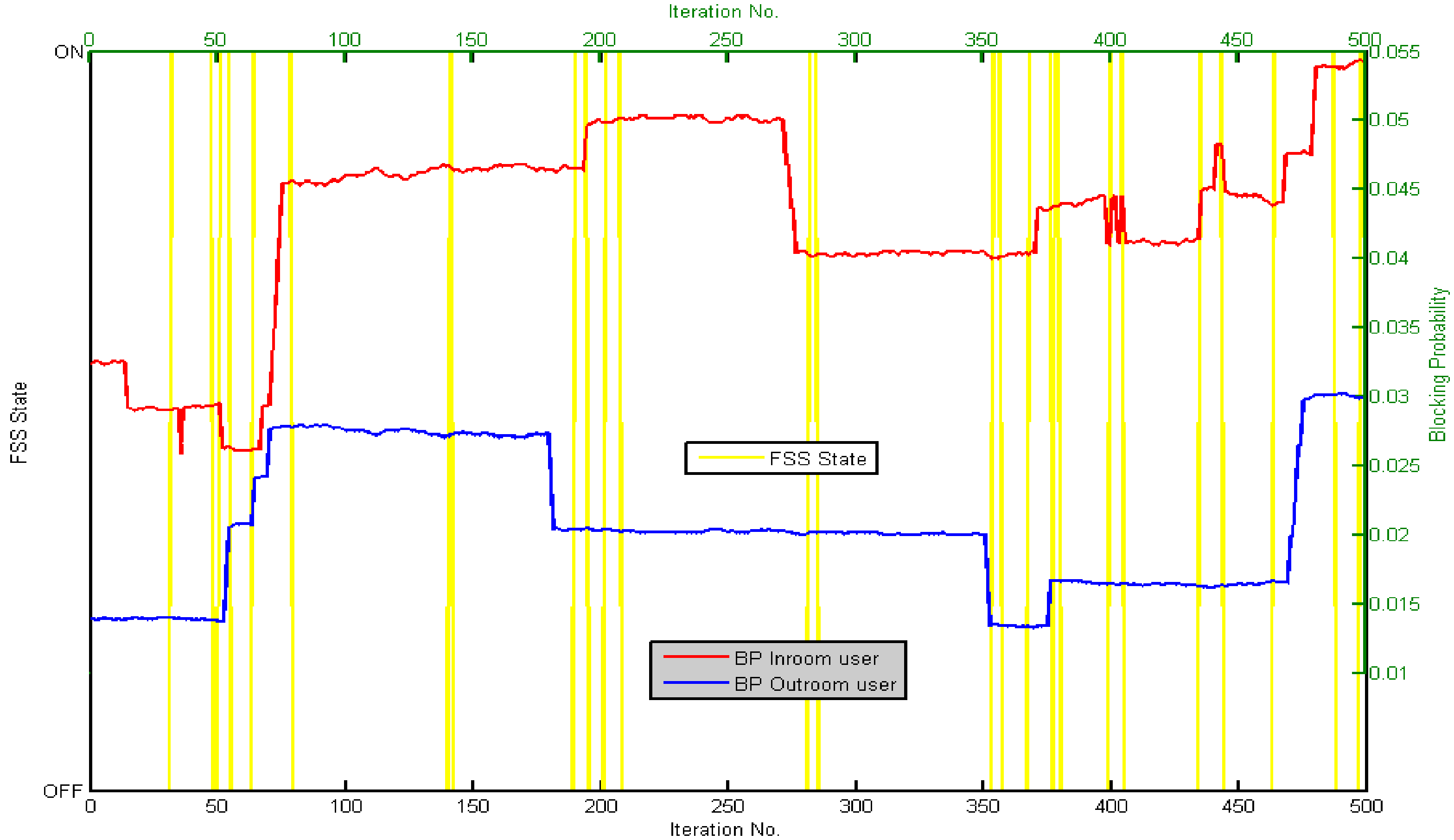

Figure 6-4. Snap-shot of FSS State with Respective Measured Blocking Probability

$$Traffic\_load_{ave} = \frac{\sum_{i=0}^{ws} Traffic\_load(i)}{ws} \tag{6.2}$$

where,

Traffic Load (i) = Instant Traffic at activation *i*

ws = Window size

The sliding window, with a size of *ws*, to record traffic load is used and keeps averaging the measured traffic load over a range of activation *t* to *t*+*ws* and the following equation will modify eq. (6.2) to include the sliding window as follows

$$Traffic\_load_{ave}(t \to t + ws) = \frac{\sum_{i=t}^{t+ws} Traffic\_load(i)}{ws} \tag{6.3}$$

As a result, as shown in Figure 6.5, by using the statistical value resulting from this $Traffic\_load_{ave}$ we can define a more realistic measured traffic to incorporate the dynamic table.

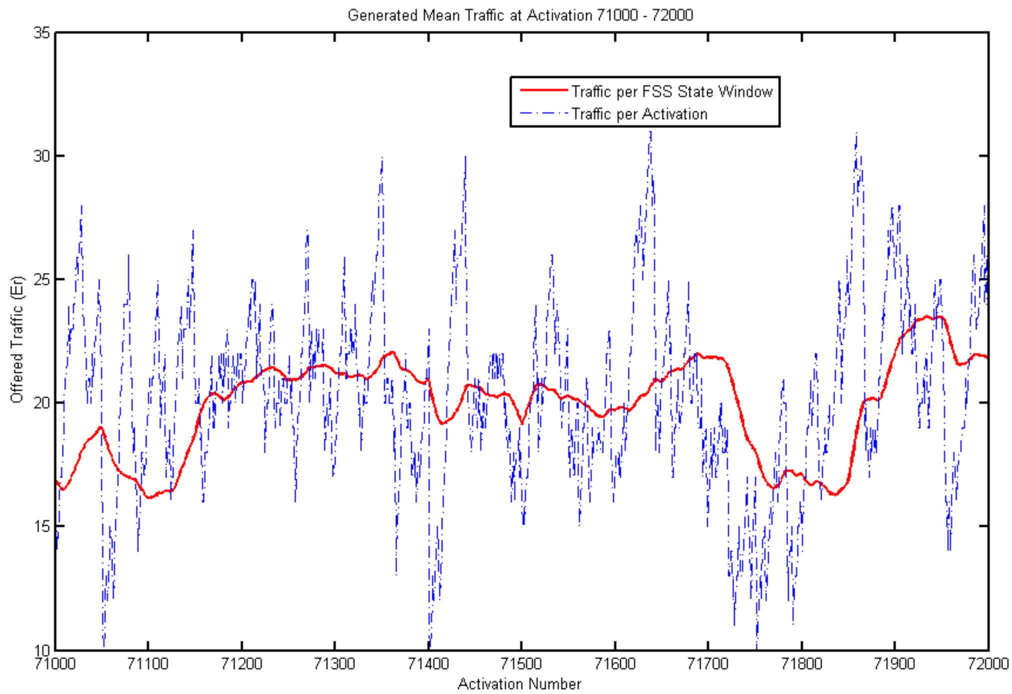

Figure 6-5. Generated Mean Traffic at Activation 71000 – 72000

6.5 Results and Analysis

The performance of all models is simulated by using Monte Carlo simulation modelling techniques (see Chapter 3). It is assumed that user connection arrivals in the coverage area are consistent with a poisson arrival process, and are uniformly distributed throughout the coverage area.

The X axis in both figures is the percentage of the blocking probability obtained from each model. The Y axis is the probability that $P\{x < P_b\}$ where P_b is a given value of percentage blocking probability or is the Cumulative Distribution Function (CDF) of measured blocking probability of every user in each activation.

Figure 6.6 (Inroom plot) and Figure 6.7 (Outroom plot) illustrate the CDF of system blocking probability of some FSS based spectrum access models used previously both for Inroom and Outroom users, from the basic FSS ON, FSS OFF, the dynamic table and the model combining the dynamic table with the FSS sliding window.

As described in earlier chapters, the FSS ON (black solid line) state provides the best performance of Inroom users and the worst performance of Outroom users. This is in line with the result shown in Figure 6.6 for Inroom user where 100% of users have a blocking probability less than or equal to 5% and the result shown in Figure 6.7 for the Outroom users where only 1% of users have blocking probability less than or equal to 5%. On the other hand, the FSS OFF (red dotted line) gives the worst performance of the Inroom users and the best performance of the Outroom users. Figure 6.6 shows only 86.3% of Inroom users have blocking probability less than or equal to 5% and the result in Figure 6.7 shows where 96.9% of Outroom users have blocking probability less than or equal than 5%.

In the case of the FSS model using the dynamic table, here we compare performance in the model without using the FSS state window (blue dash dotted line) with the model using the FSS state window of 25 s (cyan dashed line). Figure 6.7 shows an increased performance of the Outroom user from 80.5% in the model without the FSS state window up to 85.1% if the FSS state window is in place. The increased Outroom user performance does not significantly decrease the performance of Inroom users where it only drops from 93.7% to 92.4%.

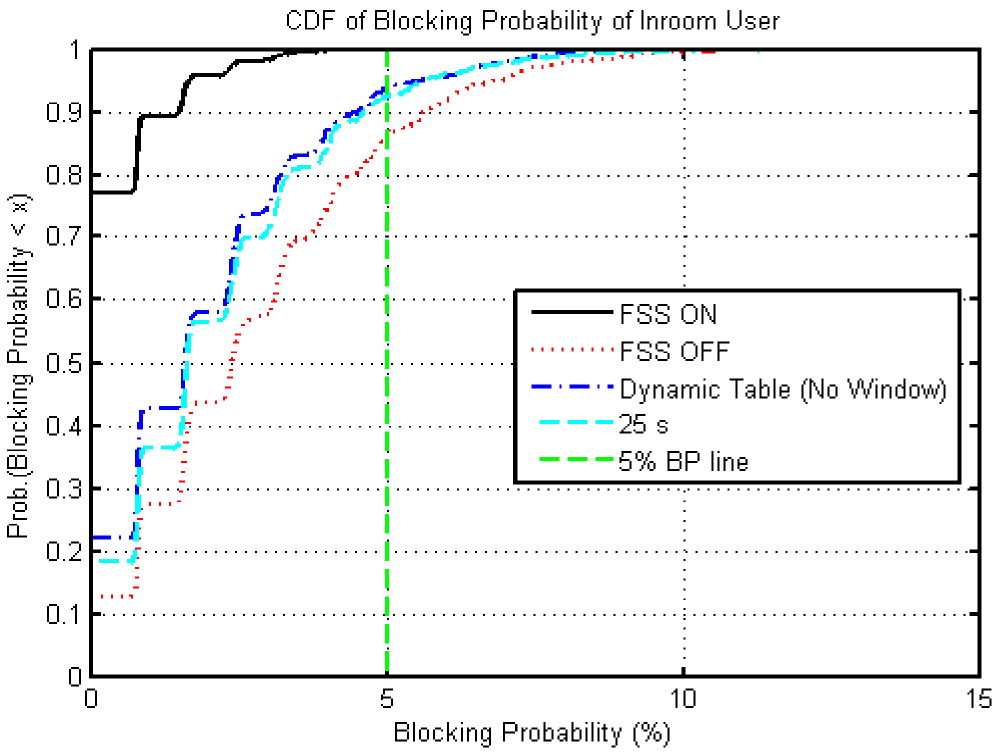

Figure 6-6. Cumulative Distribution Function of System Blocking of Inroom Users Comparing Different Models

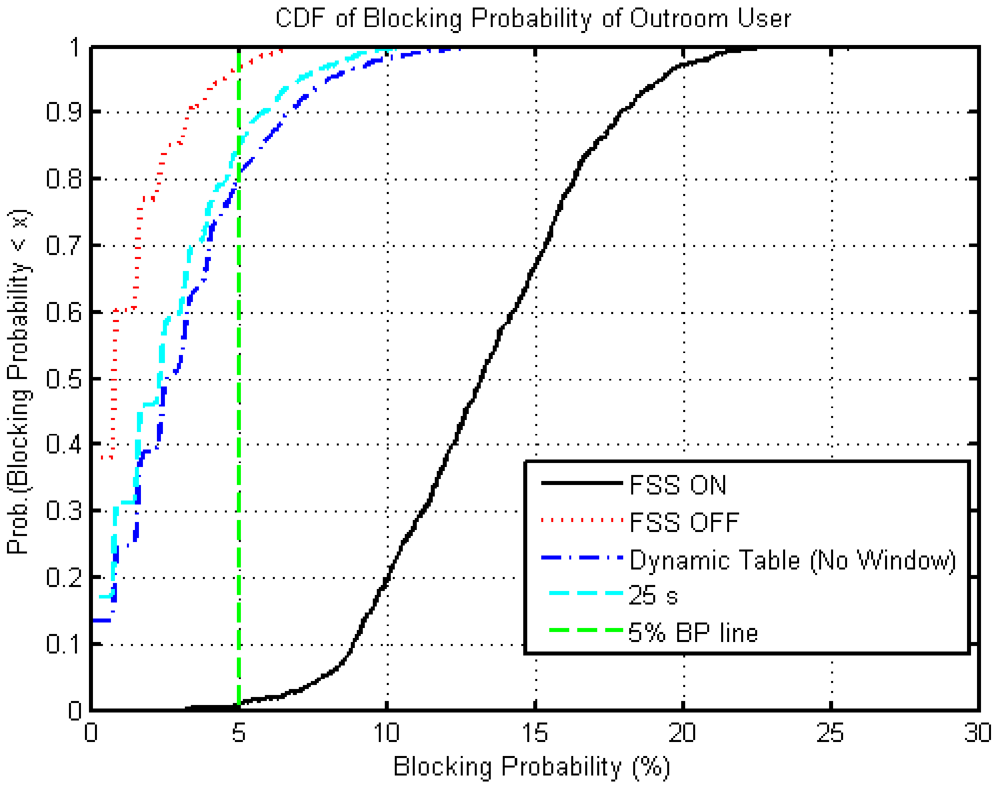

Figure 6-7. Cumulative Distribution Function of System Blocking of Outroom Users Comparing Different Models

In addition, if we examine the detail of the effect of the size of the sliding window, we can see the result as shown in Figure 6.8 (Inroom plot) and Figure 6.9 (Outroom plot), that a longer sliding window tends to allow better performance for Outroom users without significantly decreasing the performance of Inroom users.

We compare this result with the model without using the FSS state window of 25 s (cyan dashed line) and with the model using the FSS state window of 100 s (blue dotted line). It has shown in Figure 6.9 an increased performance of Outroom user from 85.1% in the model without the FSS state window up to 94% if the FSS state window is in place. The increased Outroom user performance does not significantly decrease the performance of Inroom users where it only drops from 92.4% to 88.4%.

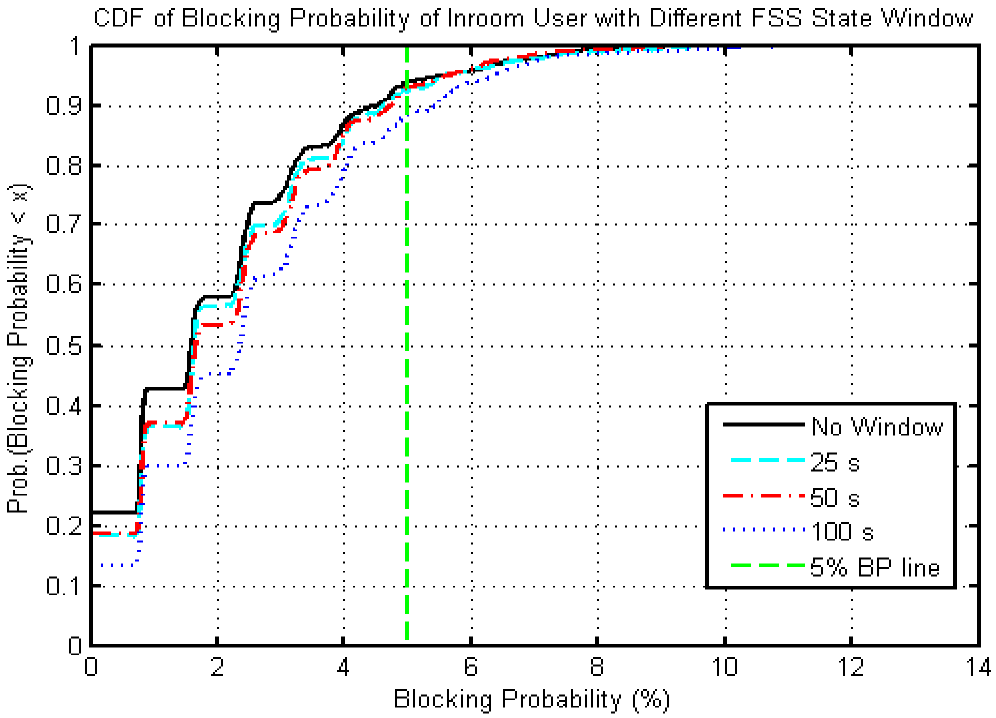

Figure 6-8. CDF of System Blocking of Inroom Users Comparing Different FSS State Window Size

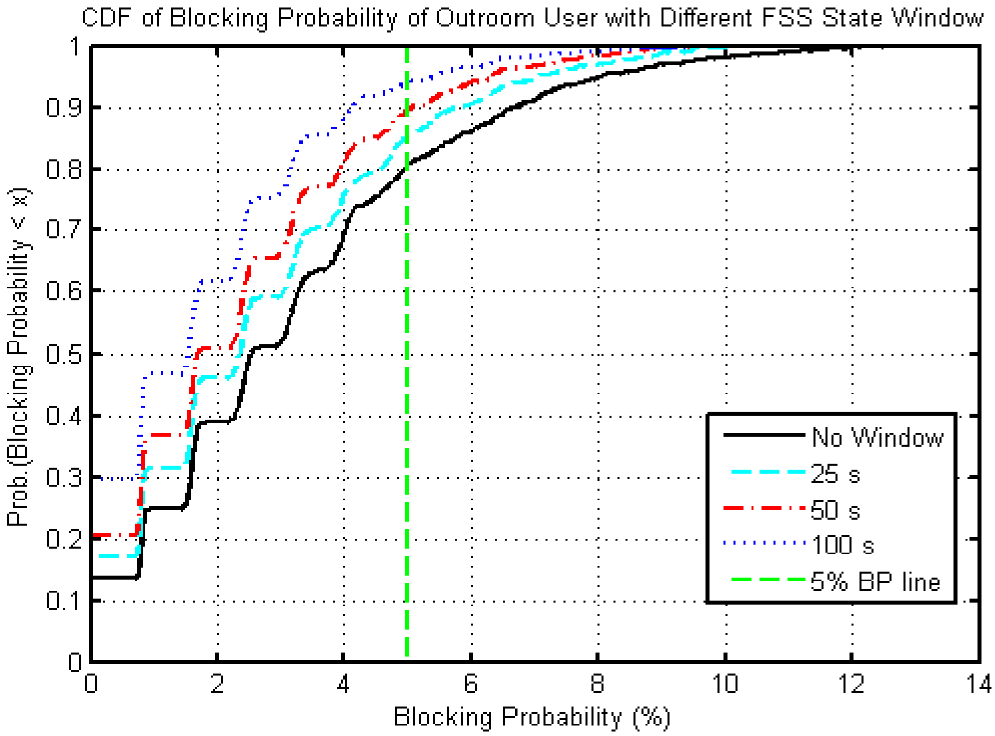

Figure 6-9. CDF of System Blocking of Outroom Users Comparing Different FSS State Window Size

6.6 Conclusion

Based on the techniques developed in the previous chapter, we have defined the dynamic table as a look-up table used by the FSS for its FSS State activation. The performance of this model was then compared with FSS Fixed Threshold.

To further improve the system performance we proposed the use of the FSS State Window. This model used a sliding window averaging the traffic load over a specific time interval based on window size. As a result, we get less variation in the measured traffic load and minimize the frequency of instantaneous changes in traffic. This statistical value was then incorporated in the dynamic table to perform the new improved FSS model. The result shows that a longer sliding window compared with instant measurement provides a better performance for Outroom users without significantly decreasing the performance of Inroom users.

Chapter 7. Further Work

Contents

7.1 *Incorporating Dynamic Channel Assignment to Increase System Performance*

In the context of this thesis, Dynamic Channel Assignment can be categorized as a user spectrum restriction mechanism. In this work, currently it only uses the random channel selection technique and it gives a good balance performance between different user groups. The combined use of dynamic channel assignment will enable a more efficient channel selection process. In turn, it will improve the performance of the system. There are several different parameters that can be considered such as

- The use of interference levels in each test user on channel selection and determining the best channel by selecting the one with the highest SINR.
- Estimated traffic load can also be used as a flexible variable, i.e. if there is more than one assignment of channel, the best channel option will be determined depending on the predetermined peak of traffic change.

7.2 *Dynamic Cooperation between Same Level of Users*

This thesis focuses on the Outroom user to improve their performance by finding opportunities to use the Inroom spectrum, but not vice versa, where Inroom can only use its default spectrum. In the option of Two Available Spectrum (2AS), we can further look into detail on the way in which the system reacts if both users can use each other's spectrum depending on their occupancy level. For example, if the Inroom user can use the Outroom user's spectrum (f3) when they need it and the same preference also occurs on Outroom user as they can use the Inroom spectrum (f1).

The dynamic cooperation between both users, with the use of FSS walls, will give more detailed information on how dynamic spectrum access can be gained for user groups with the same level of flexibility. The two-dimensional Markov analytical model, as previously developed in this thesis, can be used to understand the way in which those different user groups affecting each other's performance.

7.3 *Incorporating Learning into the Activation Process of FSS Walls*

Utilizing distributed coordination between users seems to be a promising alternative to overcome the shortage of radio spectrum resources inside the building. The way it operates is by applying the cognitive learning application to the user radio system. The cognitive radio system can benefit from its learning capability and with their action adjusted accordingly in order to achieve their objective. The knowledge which is obtained from previous information (it could be from a predetermined initial state or even the concept of a pre-play state) is continuously being added, so it then allows users to explore more alternative states to achieve better coexistence performance. In the context of this research, learning-based application can be carried out to incorporate with the FSS system to further improve the FSS state activation process.

7.4 *Multidimensional Markov Model*

This thesis focuses its discussion on the Markov analysis of shared spectrum (f2). It applies the Markov model by using user set as its variable to define equilibrium analysis of the provided state-transition-rate diagram. More than two user groups will require a multi-dimensional approach even though the same method is still applicable.

As a starting point, i.e. for three user group spectrum sharing, the use of the three-dimensional Markov chain model in [66], [67] can be considered. They use the Markov model to analyse the performance of different back-off window algorithms in IEEE 802.11. However, the way they analyse the three-dimensional Markov analysis appears to have similarity with the basic Markov analysis in this research. By applying their model with some modification to suit this research user's interaction case, the complexity of state-transition-rate diagram will be reduced. The equilibrium analysis can be derived to form the equation to reflect performance analysis at every stage of three user groups' spectrum sharing model.

Chapter 8. Summary and Conclusion

Contents

8.1 *Summary and Conclusions of the Work*

This thesis has explored the fundamental issues in applying dynamic shared spectrum in smart indoor environments. A brief summary and conclusion of the entire thesis is presented below. In addition, the main findings of the research and the original contributions are also highlighted in this chapter.

Chapter 1 provides a general introduction to the thesis and elucidates the purpose of this research. Chapter 2 presents a comprehensive literature review focusing on *Dynamic Spectrum Access* (DSA). It also explains types of coexistence or cooperation that a *Non-Priority User* (NPU) can use to access the spectrum in terms of spectrum sharing with *Priority User* (PU) and why *Cognitive Radio* (CR) is an excellent fit to support spectrum sharing between the PU and NPU. In addition, chapter 2 also briefly discusses the concept of the smart building environment together with the use of *Frequency Selective Surfaces* (FSS) to create small ‘communication’ isolated zones with the use of FSS walls.

Chapter 3 describes the research methodology, modelling techniques and validation methods used to evaluate the performance. MATLAB is used as a tool to perform all of the simulation tasks. The Monte Carlo simulation technique has been widely used to verify the statistical behaviour of the random selected event related to the system performance evaluation. Several performance measures and verification methods are introduced for systems performance analysis such as *Blocking Probability* (BP) for each specific set of users inside a building. It provides *Engset Distribution* comparison between theoretical and simulation results for the use of simulation validation and explained how a *Cumulative Distribution Function* (CDF) was a fundamental tool to show any improvement of performance for each scenario used in this research. Then, it continues to find the acceptable parameter for *Channel Proportion* (CP), the proportionate number of channels in relation to each of the three spectrums, and uses that CP parameter of 12:6:12 (f1:f2:f3) to perform all simulation scenarios throughout this thesis.

Chapter 4 gives broad mathematical analysis of spectrum sharing with two users and one available spectrum (1AS) using Markov analysis. An analytical model is developed to understand the behaviour of different user groups, i.e. a group with full flexibility compared to a group with limited flexibility, and study the way in which they influence each other in terms of system performance. The model is extended to incorporate the use of a restriction mechanism in order to control the relative user performance among different groups. Two types of restriction are proposed. The first one is the FSS based restriction mechanism, which uses the information gathered from interference from the surrounding environment and bases its activation restriction on maximum occupancy on the shared spectrum. The other is the user spectrum based restriction mechanism, which uses their local information of level of occupancy and applies it to their action restriction. The analytical approach and restriction mechanism proposed in this chapter are generally applicable to any other types of systems.

Chapter 5 explains the basic modelling scenario for an FSS used in the control of 3 frequency spectrum sharing scenarios in a smart indoor environment. It proposes a definition of the smart environment in this scenario, where the active FSS walls have three capabilities: 1) FSS ON, the condition where the wall will exhibit high isolation through the entire surface of the wall and provide high interference at a specific frequency targeted by the user; 2) FSS OFF, the condition where the wall acts as a standard wall; and 3) Fixed Threshold, the condition where the wall bases its FSS activation on instantaneous occupancy of a specific frequency. This chapter provides a thorough discussion on how restriction mechanism can be implemented by using the analysis with the help of the Markov model. It continues to derive the blocking probability analysis specifically for each of the three FSS models using the state-transition-rate diagram constructed earlier.

In Chapter 6, more explorations using three frequencies similar to the previous chapter were conducted, with different scenarios. One novel approach is presented, using the Dynamic Table. This table is an instantaneous FSS threshold look up table that has been grouped to its respective traffic load. The benefit of having this dynamic table is that it would set the FSS Activation threshold value depending on the instantaneous traffic load and it proved to have a better performance when compared with the previous model.

However, the use of an instantaneous value is proven not to be an ideal option as it causes the FSS state to frequently alter its state (oscillating ON-OFF) when it reaches the threshold value. For this reason, this research introduces another novel approach based on a sliding window (‘FSS State Window’) to determine when to activate the FSS. It is shown that a longer sliding window tends to give a better performance for Outroom users without significantly decreasing the performance of Inroom users.

8.2 *Summary of Original Contributions*

This thesis is focused on investigating the impact of FSS walls on the performance of wireless indoor communication. The original and novel contributions of this thesis are highlighted in this section.

8.2.1 **Concept of Using FSS to Control QoS within a Smart Building Environment**

- Novel restriction mechanisms based on FSS are developed in this thesis to control the relative QoS among different groups of users with different levels of flexibility. This mechanism will restrict the FSS state activation based on a maximum level of occupancy of the shared spectrum. Results show that a balanced blocking probability between different user groups can be achieved by applying this restriction mechanism.

- In addition to the work in [36] where they have shown the achievable coverage control building by using FSS walls, this research is able to add another dimension by simulating the performance of FSS based spectrum access. The novelty of this scheme is the way in which it determines when to activate the FSS using an instantaneous FSS threshold value. Two different strategies have been discussed in this thesis.

8.2.2 Mathematical Analysis of Spectrum Performance using Markov Diagram

An original two-dimensional Markov analytical model is developed to understand the way in which different groups of users, i.e. Priority User or Non-Priority User, affect each other's performance. The two-dimensional Markov model is used to model the coexistence in a shared spectrum. This analytical model distinguishes itself from other models such as [65], [68] by defining its model from the user set and its application to a heterogeneous multi-user indoor communication system with different resource availability.

This thesis also proposed an FSS based restriction mechanism. It is the analysis of imposing the external restriction (FSS Wall) to further improve the spectrum performance. The restriction analysis shows that when we impose FSS based restriction on all three models, FSS continually ON, FSS continually OFF and FSS Fixed Threshold, it will provide different outcomes on the usable state area of state-transition-rate diagrams in shared spectrum f2. FSS continually ON will turn the multi-dimensional Markov model into a single-dimensional Markov model. FSS continually OFF will form the usable state area defined as $\{p((j_1 + j_2) \leq 2m)\}$. FSS Fixed Threshold will form the usable state area defined as $\{p((j_1 + j_2) > k) = 0\} \cap \{p(j_1,0), \quad k+1 \leq j_1 \leq 2m\}$ with the (width) area depending on the value of k . This usable state is one of the main factors to define the blocking probability of *Non-Priority Users* in the shared spectrum.

8.2.3 FSS based Spectrum Sharing Using FSS State Window

Chapter 6 introduces a novel algorithm, the FSS State Window, to determine the activation of the FSS state by using the sliding window. The novelty of this model comes in the way it works by recording the measured traffic load every time activation is successful over the size duration of the sliding window and averages the sum of that recorded information with a specific value of sliding window size. The result is represented by *Cumulative Density Function* (CDF) for a specific user when the blocking probability equals or is less than 5%. It shows that increasing the time duration of the FSS State Window, provides a better Non-Priority User performance without significantly decreasing the performance of the Priority User. To the best of our knowledge, our algorithm is the first to apply this sliding window method to determine the FSS activation.

Glossary of Terms

1AS	: One Available Spectrum
2AS	: Two Available Spectrums
3AS	: Three Available Spectrums
BCD	: Blocked Customers Delayed
BPSK	: Binary Phase Shift Keying
BRTI	: Badan Regulasi Telekomunikasi Indonesia
CDF	: Cumulative Distribution Function
CDMA	: Code Division Multiple Access
CP	: Channel Proportion
CR	: Cognitive Radio
DAI	: Distributed Artificial Intelligence
DCA	: Dynamic Channel Assignment
DSA	: Dynamic Spectrum Access
DSSS	: Direct Sequence Spread Spectrum
EM	: Electro-Magnetic
FCC	: Federal Communications Commission
FDMA	: Frequency Division Multiple Access
FHSS	: Frequency Hopping Spread Spectrum
FSS	: Frequency Selective Surfaces
ISM	: Industrial Scientific and Medical
ITU-R	: International Telecommunication Union – The Radio Communication Sector
LOS	: Line of Sight
MIMO	: Multiple Inputs Multiple Outputs
MWM	: Multi-Wall-Model
NPU	: Non-Priority Users
OFCOM	: The Office of Communications
OFDM	: Orthogonal Frequency Division Multiplexing
OFDMA	: Orthogonal Frequency Division Multiple Access

OLOS	: Obstructed Line of Sight
OSS	: Opportunistic Spectrum Sharing
OT	: Offered Traffic
PU	: Priority Users
QAM	: Quadrature Amplitude Modulation
QoS	: Quality of Service
QPSK	: Quadrature Phase Shift Keying
SDMA	: Spatial Division Multiple Access
SDR	: Software Defined Radio
SINR	: Signal to Interference plus Noise Ratio
SNR	: Signal to Noise Ratio
TDMA	: Time Division Multiple Access
U-NII	: Unlicensed National Information Structure
UWB	: Ultra Wide Band
WLAN	: Wireless Local Area Network

References

[1] J. Chen, "Improving Spectrum Utilization in Heterogeneous Wireless Systems Through Cognitive Radio," The University of York, 2010.

[2] K. Shuaib, M. Boulmalf, F. Sallabi, and A. Lakas, "Co-existence of Zigbee and WLAN, A Performance Study," in *2006 IFIP International Conference on Wireless and Optical Communications Networks*, pp. 1–5.

[3] A. Stranne, F. Floren, O. Edfors, and B.-A. Molin, "Throughput of IEEE 802.11 FHSS networks in the presence of strongly interfering Bluetooth networks," in *The 13th IEEE International Symposium on Personal, Indoor and Mobile Radio Communications*, vol. 2, pp. 161–165.

[4] Z. Alliance, "ZigBee and Wireless Radio Frequency Coexistence," no. June 2007, 2011.

[5] "IEEE Xplore - IEEE Std 802.11-2007 (Revision of IEEE Std 802.11-1999)." [Online]. Available: http://ieeexplore.ieee.org/xpl/mostRecentIssue.jsp?punumber=4248376. [Accessed: 02-Oct-2012].

[6] "The UK Frequency Allocation Chart." [Online]. Available: http://www.roke.co.uk/resources/datasheets/UK-Frequency-Allocations.pdf.

[7] Qinetic, "Cognitive Radio Technology: A Study for OFCOM – Volume 1," 2007.

[8] M. McHenry and D. McCloskey, "New York Spectrum Occupancy Measurements," 2007.

[9] M. MA, T. P, M. D, R. DA, and H. CS, "Chicago spectrum occupancy measurements and analysis and a long-term studies proposal," in *Proc. of the first international workshop on technology and policy for accessing spectrum*, 2006.

[10] FCC, "Report of the spectrum efficiency working group," 2002.

[11] B. M. Sadler and Q. Zhao, "A Survey of Dynamic Spectrum Access," *IEEE Signal Processing Magazine*, vol. 24, no. 3, pp. 79–89, May 2007.

[12] B. M. M., "Understanding Dynamic Spectrum Access : Models , Taxonomy and Challenges," in *Proc. of IEEE DySpan*, 2007.

[13] Q. Zhao and B. M. Sadler, "Signal Processing , Networking , and Regulatory Policy."

[14] P. SM, D. M, L. S, and C. JM, "Opportunistic interference alignment in MIMO interference channels," in *Proc. IEEE International Symposium on Personal, Indoor and Mobile Radio Communications*, 2008, pp. 1–5.

[15] S. Haykin, "Cognitive radio: brain-empowered wireless communications," *IEEE Journal on Selected Areas in Communications*, vol. 23, no. 2, 2005.

[16] S. Tang, G. Mason, and B. L. Mark, "Performance analysis of a wireless network with opportunistic spectrum sharing," in *Proc. IEEE Global Telecomm. Conf.*, 2007.

[17] N. Hoven and A. Sahai, "Power Scaling for Cognitive Radio," in *2005 International Conference on Wireless Networks, Communications and Mobile Computing*, vol. 1, pp. 250–255.

[18] F. Meshkati, H. V. Poor, S. C. Schwartz, and N. B. Mandayam, "An Energy-Efficient Approach to Power Control and Receiver Design in Wireless Data Networks," *IEEE Transactions on Communications*, vol. 53, no. 11, pp. 1885–1894, Nov. 2005.

[19] J. Lehtomaki, "Analysis of energy based signal detection," University of Oulu, Finland., 2005.

[20] R. K. Shakya, S. Agarwal, Y. N. Singh, N. K. Verma, and A. Roy, "DSAT-MAC : Dynamic Slot Allocation based TDMA MAC protocol for Cognitive Radio Networks," in *IEEE WOCN-2012*, 2012.

[21] S. Geirhofer, L. Tong, and B. Sadler, “COGNITIVE RADIOS FOR DYNAMIC SPECTRUM ACCESS - Dynamic Spectrum Access in the Time Domain: Modeling and Exploiting White Space,” *IEEE Communications Magazine*, vol. 45, no. 5, pp. 66–72, May 2007.

[22] M. Hefnawi, “Space division multiplexing access aided cognitive radio networks,” in *2012 26th Biennial Symposium on Communications (QBSC)*, 2012, pp. 10–14.

[23] D. T. Ngo, C. Tellambura, and H. H. Nguyen, “Resource Allocation for OFDM-Based Cognitive Radio Multicast Networks,” in *2009 IEEE Wireless Communications and Networking Conference*, 2009, pp. 1–6.

[24] X. Zhang and H. Su, “Opportunistic Spectrum Sharing Schemes for CDMA-Based Uplink MAC in Cognitive Radio Networks,” *IEEE JOURNAL ON SELECTED AREAS IN COMMUNICATIONS*, vol. 29, no. 4, pp. 716–730, 2011.

[25] A. B. MacKenzie and S. B. Wicker, “Game theory in communications: motivation, explanation, and application to power control,” in *GLOBECOM’01. IEEE Global Telecommunications Conference (Cat. No.01CH37270)*, vol. 2, pp. 821–826.

[26] J. M. Peha and S. Panichpapiboon, “Real- Time Secondary Markets for Spectrum,” *Telecommunication Policy*, pp. 603–18.

[27] “WRC-12 Agenda Item 1.19 - Software-Defined Radio and Cognitive Radio Systems.” [Online]. Available: http://www.itu.int/ITU-R/information/promotion/e-flash/4/article5.html. [Accessed: 26-Sep-2012].

[28] “Notice of Proposed Rule Making and Order, ET Docket No. 03-222,” 2003.

[29] “FCC Spectrum Policy Task Force Report, ET Docket 02-135.”

[30] S. D and P. J, “Performance of unlicensed devices with a spectrum etiquette,” in *Proc. IEEE Global Telecomm. Conf.*, 1997, pp. 414–418.

[31] S. D and P. J, “Etiquette modification for unlicensed spectrum: approach and impact,” in *Proc. IEEE Vehicular Technology Conference*, 1998, pp. 272–276.

[32] J. M. III, “Cognitive Radio An Integrated Agent Architecture for Software Defined Radio,” Royal Institute of Technology (KTH), 2000.

[33] J. Mitola and G. Q. Maguire, “Cognitive radio: making software radios more personal,” *IEEE Personal Communications*, vol. 6, no. 4, pp. 13–18, 1999.

[34] G. M. Youngblood, D. J. Cook, L. B. Holder, and E. O. Heierman, “Automation intelligence for the smart environment,” in *Proceedings of the International Joint Conference on Artificial Intelligence*, 2005.

[35] M. Wigginton and J. Harris, *Intelligent Skins*. Oxford: Butterworth-Heinemann, 2002.

[36] L. Subrt, D. Grace, and P. Pechac, “Controlling the Short-Range Propagation Environment Using Active Frequency Selective Surfaces,” *Radio Engineering*, vol. 19, no. 4, pp. 610–617, 2010.

[37] M. Gustafsonn et all, “Design of Frequency Selective Window for improve Indoor Outdoor Communication,” 2005.

[38] A. Newbold, “Designing buildings for the wireless-age [FSS build-up],” *Communications Engineer*, vol. 2, no. 3, pp. 18–21.

[39] G. H. H. Sung, K. W. Sowerby, and A. G. Williamson, “The impact of frequency selective surfaces applied to standard wall construction materials,” in *IEEE Antennas and Propagation Society Symposium, 2004.*, 2004, vol. 2, pp. 2187–2190 Vol.2.

[40] E. A. Parker and S. B. Savia, “Fields in an FSS screened enclosure,” *IEE Proceedings - Microwaves, Antennas and Propagation*, vol. 151, no. 1, p. 77, Feb. 2004.

[41] F. A. Chaudhry, M. Raspopoulos, and S. Stavrou, “Effect of Frequency Selective Surfaces on radio wave propagation in indoor environments,” pp. 1–5.

[42] M. Raspopoulos, F. A. Chaudhry, and S. Stavrou, “Radio propagation in frequency selective buildings,” *European Transactions On Telecommunications*, vol. 17, pp. 407–413, 2006.

[43] D. C. Kemp, C. Martel, M. Philippakis, M. W. Shelley, R. A. Pearson, and I. Llewellyn, “Enhancing radio coverage inside buildings,” in *2005 IEEE Antennas and Propagation Society International Symposium*, 2005, vol. 1A, pp. 783–786.

[44] G. H. Sung, K. Sowerby, and A. Williamson, “Modeling a Low-Cost Frequency Selective Wall for Wireless-Friendly Indoor Environments,” *Antennas and Wireless Propagation Letters*, vol. 5, no. 1, pp. 311–314, Dec. 2006.

[45] J. Hirai and I. Yokota, “Electro-magnetic shielding glass of frequency selective surfaces,” in *Proceedings of the International Symposium on electromagnetic compatibility*, 1999, pp. 314–316.

[46] G. I. Kiani, A. R. Weily, and K. P. Esselle, “A novel absorb/transmit FSS for secure indoor wireless networks with reduced multipath fading,” *IEEE Microwave and Wireless Components Letters*, vol. 16, no. 6, pp. 378–380, Jun. 2006.

[47] G. I. Kiani, K. L. Ford, K. P. Esselle, A. R. Weily, and C. J. Panagamuwa, “Oblique Incidence Performance of a Novel Frequency Selective Surface Absorber,” *IEEE Transactions on Antennas and Propagation*, vol. 55, no. 10, pp. 2931–2934, Oct. 2007.

[48] “CELANE, Engineering - Macquarie University.” [Online]. Available: http://engineering.mq.edu.au/research/groups/celane/projects/.

[49] G. I. Kiani, K. L. Ford, L. G. Olsson, K. P. Esselle, and C. J. Panagamuwa, “Switchable Frequency Selective Surface for Reconfigurable Electromagnetic Architecture of Buildings,” *IEEE Transactions on Antennas and Propagation*, vol. 58, no. 2, pp. 581–584, Feb. 2010.

[50] S. Sarkar and K. N. Stvarajan, “Channel assignment algorithms satisfying cochannel and adjacent channel reuse constraints in cellular mobile networks,” in *Proceedings. IEEE INFOCOM ’98, the Conference on Computer Communications. Seventeenth Annual Joint Conference of the IEEE Computer and Communications Societies. Gateway to the 21st Century (Cat. No.98CH36169)*, vol. 1, pp. 59–68.

[51] R. . Cooper, *Introduction to Queueing Theory*, 2nd Ed. North-Holland: Elsevier, 1981.

[52] Z. Chen, C.-X. Wang, X. Hong, J. Thompson, S. Vorobyov, and X. Ge, "Interference Modeling for Cognitive Radio Networks with Power or Contention Control," in *2010 IEEE Wireless Communication and Networking Conference*, 2010, pp. 1–6.

[53] J. Proakis, *Digital Communications*, 4th ed. New York: McGrawHill Inc., 2001.

[54] S. S and S. SR, "Review of constitutive parameters of building material," in *12th International Conference on Antennas and Propagation (ICAP)*, 2003, pp. 211–215.

[55] Y. M and S. S, "Investigation of radio transmission losses due to periodic building structures," in *11th European Wireless Conference*, 2005, pp. 737–739.

[56] J. B. Andersen, T. S. Rappaport, and S. Yoshida, "Propagation measurements and models for wireless communications channels," *IEEE Communications Magazine*, vol. 33, no. 1, pp. 42–49, 1995.

[57] S. Saunder and A. Aragon-Zavala, *Antennas and Propagation for Wireless Communication Systems*, 2nd ed. John Wiley & Sons Ltd, 2007.

[58] S. Y. Seidel and T. S. Rappaport, "914 MHz path loss prediction models for indoor wireless communications in multifloored buildings," *IEEE Transactions on Antennas and Propagation*, vol. 40, no. 2, pp. 207–217, 1992.

[59] S. Y. Seidel and T. S. Rappaport, "Site-specific propagation prediction for wireless in-building personal communication system design," *IEEE Transactions on Vehicular Technology*, vol. 43, no. 4, pp. 879–891, 1994.

[60] M. Lott and I. Forkel, "A multi-wall-and-floor model for indoor radio propagation," in *IEEE VTS 53rd Vehicular Technology Conference, Spring 2001. Proceedings (Cat. No.01CH37202)*, vol. 1, pp. 464–468.

[61] COST Action 231, "Digital Mobile Radio Towards Future Generation Systems, Final Report," 1999.

[62] M. Schwartz, *Telecommunication Networks: Protocols, Modeling and Analysis*, 1st Ed. Prentice Hall, 1987.

[63] L. Kleinrock, *Queuing Systems Volume I: Theory*. John Wiley & Sons Ltd, 1975.

[64] D. Grace, “Distributed Dynamic Channel Assignment for the Wireless Environment,” 1999.

[65] L. Yiming, D. Grace, and P. D. Mitchell, “Exploiting HAP Diversity for GoS Improvement for Users with Different HAP Availability,” *IEEE Transactions on Communications*, 2009.

[66] G. Bianchi, “Performance Analysis of the IEEE 802.11 Distributed Coordination Function,” *IEEE on selected areas in communication*, vol. 18, no. 3, p. 535, 2000.

[67] A. Alshanyour and A. Agarwal, “Three-Dimensional Markov Chain Model for Performance Analysis of the IEEE 802.11 Distributed Coordination Function,” in *IEEE Globecom*, 2009.

[68] J.-W. Wang and R. Adriman, “Analysis of Cognitive Radio Networks with Imperfect Sensing and Backup Channels,” in *2013 Seventh International Conference on Innovative Mobile and Internet Services in Ubiquitous Computing*, 2013, pp. 626–631.