國 立 交 通 大 學

電信工程研究所

碩 士 論 文

分時全雙工之正交分頻多用戶系統於非對稱服務環境下之跨時槽干擾分析

Cross-Slot Interference Analysis for TDD-OFDMA Systems with Asymmetric Services

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研 究 生：李偉齊　　　　Student：Wei-Chi Li

指導教授： 王蒞君　　　　Advisor：Li-Chun Wang

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摘要

在本篇論文中，我們在支援非對稱服務的環境裡，探討了部分頻率重覆使用 (Fractional Frequency Reuse, FFR) 機制在分時雙工且正交分頻多工存取 (Time Division Duplex-Orthogonal Frequency Division Multiple Access, TDD-OFDMA) 系統中所能獲得的好處。並討論如何應用部分頻率重覆使用機制來降低相鄰細胞間的同頻干擾 (Inter-Cell Interference) 並維持頻譜使用率 (Spectrum Efficiency)。然而，我們提出了一套分析的方式來分析跨時槽範圍 (Cross Time Slot Region, CTS Region) 與設計部分頻率重覆使用機制參數之間的關係。這套分析的方是主要是應用排隊理論原理 (Queuing Theorem) 並且考慮通訊傳輸系統中的每一位使用者 (Mobile Station, MS) 使用情形，來進一步計算出發生跨時槽範圍的機率。如此一來，能透過這套分析的方法來幫助我們在支援非對稱的環境中，適當地設計部分頻率重覆使用機制所使用的參數。

在無線資源管理 (Radio Resource Management) 的領域裡，一個好的干擾管理機制能夠減少相鄰細胞間同頻干擾的情形並且改善系統效能。舉例來說，在蜂巢式無線通訊系統中使用方向性天線 (Directional Antenna)、多

輸入多輸出天線系統 (Multi-Input and Multi-Output Antenna, MIMO) 和部分頻率重覆使用機制…等等。據我們所瞭解，我們需要在未來的第四代 (Fourth Generation, 4G) 通訊系統中使用更多的頻寬來達到高傳輸率 (Transmission Rate) 的要求。然而，最有效換取更多頻寬的方式就是在每一個基地台 (Base Station, BS) 的覆蓋範圍 (Cell Coverage) 中重覆使用相同的頻譜。雖然，在每一個基地台重覆使用相同的頻率可以立即增加可使用頻譜，但是卻會嚴重影響傳輸訊雜比 (Signal to Interference Plus Noise Ratio, SINR)。然而，較差的訊雜比會影響到系統內使用者的連線品質 (Link Quality) 造就了干擾消除和頻譜使用率之間的難以取捨，也使得如何在重覆使用頻譜的環境下依然可以維持良好的連線品質變成了一個很有趣的議題。

為了維持良好的傳輸品質，我們必須謹慎的區分相鄰細胞間同頻干擾的情況。在無線通訊系統中，主要有兩種雙工的模式可以用來區分上傳 (Uplink) 和下載 (Downlink) 的傳輸，也就是分頻雙工 (Frequency Division Duplex) 和分時雙工 (Time Division Duplex)。在這兩種不同的雙工模式下，會產生不同的相鄰細胞間同頻干擾的情形，尤其是在分時雙工模式並且支援非對稱服務的環境下，更容易產生較強的相鄰細胞間干擾。這種特殊的干擾量主要發生在跨時槽範圍內，也就是細胞間同時執行不同的傳輸模式，而這種干擾量被稱為跨時槽干擾 (Cross-Slot Interference)。跨時槽干擾主要可區分成兩種，分別為基地台對基地台的跨時槽干擾 (BS-to-BS Cross-Slot Interference) 和使用者對使用者的跨時槽干擾 (MS-to-MS Cross-Slot Interference)。其中，基地台對基地台的跨時槽干擾會對系統效能造成很嚴重的影響，特別是對於基地台較遠的使用者而言。

因此，為了改善細胞邊緣使用的傳輸品質，我們使用了部分頻率重覆使用機制來降低相鄰細胞間同頻干擾的情形，特別是在會產生跨時槽干擾

的非對稱服務的環境中。設計部分頻率重覆使用機制中的參數，可以同時獲得提升頻譜使用率和降低相鄰細胞間干擾的好處。在本篇論文中，我們探討了如何配置頻寬給不同區域的使用者、設計細胞內圈的大小和細胞外圈的頻率重覆使用參數 (Frequency Reuse Factor)。此外，我們使用了一套分析的方法來分析跨時槽範圍的大小和設計部分頻率重覆使用機制參數之間的關係。更重要的是，我們可以應用這套分析的方法來找出最適當的參數設定並且隨時更新設定，藉此改善現有系統所需的繁複計算和長時間的模擬。最後，我們建立了一套應用部分頻率重覆使用機制在分時雙工且正交分頻多工存取系統並支援非對稱服務的模擬平台，藉由此平台來找出最適當的部分頻率重覆使用機制參數使系統傳輸量 (System Throughput) 最大並同時維持傳輸可靠度 (Link Reliability)。

Cross-Slot Interference Analysis for TDD-OFDMA Systems with Asymmetric Services

Student: Wei-Chi Li Advisor: Dr. Li-Chun Wang

Institute of Communication Engineering
National Chiao Tung University

Abstract

In this thesis, we investigate the benefits of fractional frequency reuse (FFR) in a time division duplex (TDD) to orthogonal frequency division multiple access (TDD-OFDMA) systems for supporting asymmetric traffics. We consider FFR scheme to discuss how we can use FFR to reduce the effects of inter-cell interference (ICI) and maintain the spectrum efficiency. However, we provide an analytical approach to analyze the relationship between cross time slot (CTS) region and the design factors of FFR scheme. The analytical approach depends on queueing theory and considers each wireless access points to evaluate the probability of generating CTS region. Therefore, the analytical approach can help us to design FFR factors in asymmetric traffic environment with different uplink/downlink requirements.

In the field of radio resource management (RRM), a good interference management scheme can mitigate the effects of inter-cell interference and improve system throughput, such as directional antenna, multi-input and multi-output antenna (MIMO), and FFR scheme while they implement in multi-cellular wireless communication systems. As we know, we need more and more frequency spectrums can be used in fourth generation (4G) wireless communication. The effective approach to increase frequency spectrums is reusing same bandwidth in multi-cellular system that means some cells may reuse same frequency

spectrums in the meanwhile. Although this method can increase frequency spectrums immediately, it will degrade the received signal to interference plus noise ratio (SINR) seriously because of the effects of inter-cell interference comes from neighboring cells. The poor SINR levels will affect link quality while MS arrives in the system. Hence, how to reuse same bandwidth in multi-cellular system and also maintain link quality become an interesting issue in wireless network as the interference mitigation and spectrum efficiency become trade-off on the system performance.

There are two options of division duplex mode may be used to separate uplink and downlink transmission, frequency division duplex (FDD) and time division duplex (TDD). In the different division duplex modes may generate different kinds of inter-cell interference from neighboring cells especially TDD mode. TDD mode with supporting asymmetric services may cause stronger inter-cell interference than symmetric services. The stronger inter-cell interference always occurs in the CTS region that presents observed cell and neighboring cells are executing different transmission mode, uplink or downlink transmission. This kind of inter-cell interference be called cross-slot interference in TDD mode with asymmetric traffics. For uplink transmission, base station (BS) may receive inter-cell interference from neighboring cell's mobile station (MS) because the neighboring MS is transmitting signal to the BS. Hence, the stronger inter-cell interference comes from neighboring BS, called BS-to-BS cross-slot interference. In other words, it will cause MS-to-MS cross-slot interference in downlink transmission while neighboring cell is executing uplink transmission. While the MS-to-MS cross-slot interference causes minimal degradation in downlink, the BS-to-BS cross-slot interference can severely decrease SINR in uplink, especially when the MS executes uplink mode and locates at cell boundary.

Hence, using the FFR scheme can decrease the effects of inter-cell interference including cross-slot interference and non cross-slot interference especially it is surrounded in an asymmetric traffic environment. Different design for FFR scheme will get advantages on spectrum efficiency and interference mitigation, respectively. We develop FFR scheme that's main solution is considering interference mitigation at cell's outer region. In the thesis, we discuss how to allocate channel bandwidth, design the size of inner region and number of frequency reuse factor in outer region. Furthermore, we use an analytical method to analyze size of CTS and the design factors of FFR scheme in a TDD-OFDMA system with supporting asymmetric services. More importantly, using the analytical method can find optimal design factors of FFR scheme and updates adaptively according to the traffic requirements in practical systems due to the simulation-based adaptation requires huge complexity and processing time. Finally, we build a simulation platform for the FFR based TDD-OFDMA system to simulate different asymmetric traffic environments and find out the optimal FFR factors to maximize system throughput with guaranteeing link reliability.

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Contents

List of Tables

List of Figures

CHAPTER 1

Introduction

1.1 Motivation

In wireless transmission networks, the type of signal context has been changing from the first generation (1G) to fourth generation (4G) system. The voice and messages context are widely used in 1G and 2G wireless networks due to the multi-media applications are not popular in the past. However, voice and messages always need symmetric requirements of uplink and downlink bandwidth. There are two division duplex modes to allocate spectrums for uplink and downlink transmission, frequency division duplex (FDD) and time division duplex (TDD). Then, the FDD is suitable to support this kind of symmetric traffics and usually used in traditional wireless communications system since it is easy to implement and suitable to transmit data required smaller bandwidth likes voice data.

Recently, multimedia services become more important because there are more various wireless applications being generated, such as web browsers, real-time streaming and interactive games. This kind of applications always needs various uplink and downlink bandwidth requirements that be called asymmetric traffics. The size of bandwidth for uplink and downlink transmission always be determined cautiously in the world's standard organization. Therefore, the FDD can't share bandwidth with other transmission modes. If we still use the FDD mode to separate uplink and downlink transmission, it sometimes will waste unused system bandwidth. However, the TDD mode is suitable to be used in wireless communications for providing asymmetric services because TDD mode can allocate different numbers of time slot to each transmission mode dynamically.

1.2 Problem and Solution

Both TDD and FDD are proposed for the next-generation wireless systems, such as IEEE 802.16m-WiMAX [1] and 3GPP Long-Term Evolution (LTE) [2]. Although TDD mode is more suitable to provide asymmetric services than FDD, there is an important issue need to notice - cross-slot interference which is caused by different uplink and downlink bandwidth requirements in different cells using same spectrums. Hence, the TDD mode always be constricted for supporting same uplink and downlink ratios in current multi-cellular systems, such as IEEE 802.16e Mobile WiMAX [3] due to avoid cross-slot interference.

The major effect of cross-slot interference is caused by observed cell is transmitting uplink signal, but neighboring cell is executing downlink transmission. This kind of cross-slot interference is called BS-to-BS cross-slot interference. On the other hand, the MS-to-MS cross-slot interference will be generated by observed cell is downlink and neighboring cell is uplink. However, the MS-to-MS cross-slot interference doesn't degrade SINR seriously. Each cross-slot interference always causes in the cross time slot (CTS) region within a frame just likes Fig. 1.1. Cell A, cell B and cell C have different bandwidth requirements of uplink and downlink transmission. If each cell's base station (BS) can adjust their uplink and downlink requirements, the CTS region will be generated in the intermediate zone within a frame. For uplink transmission, the strong BS-to-BS cross-slot interference will degrade SINR and may make received uplink signal can't be demodulated. Hence, if system supports asymmetric traffics adaptively in each cell, system performance will be restrained due to this kinds of inter-cell interference. However, if we want to provide multimedia services with asymmetric services in next generation wireless communication systems, the problems of cross-slot interference must be solved or avoided.

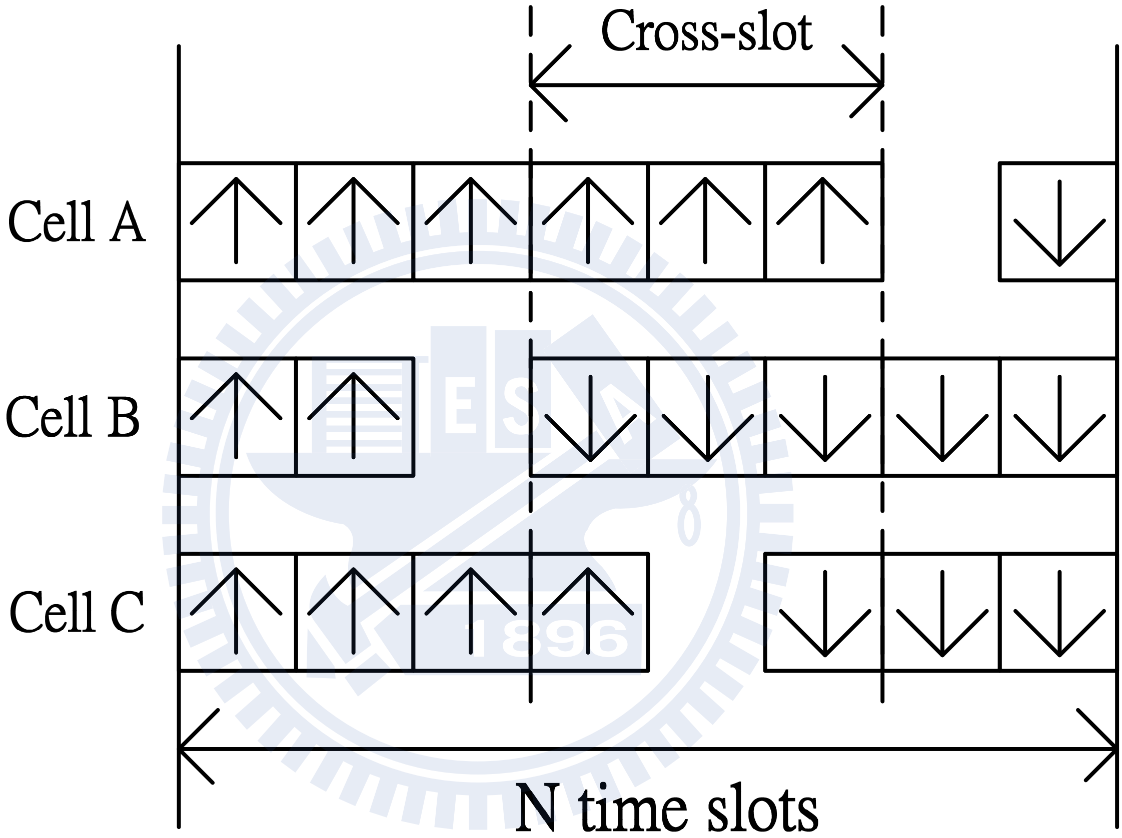

Figure 1.1: Three cells (A,B,C) which support asymmetric traffic that causes cross-slot interference.

Recently, many researches want to overcome the cross-slot interference issues are briefly summarized as follows. [4] avoided strong cross-slot interference by employing antenna beamforming in each cell. In [5], the tri-sector cellular architecture was considered since taking shape of the virtual cells. Then, it fixed the same uplink over downlink time slot ratio (switching point) in time slot allocations to avoid the direct strong cross-slot interference from three adjacent sectors. Another approaches [6], [7], [8] considered the MS location information to make properly scheduling to avoid the MS locating at the cell boundary and transmitting in cross time slot region since this method can also increase the system performance, such as throughput and bit error rate (BER). There are more research just likes [9], [10], [11], [12], [13] also discuss the issues of cross-slot interference. We will investigate this kinds of literature about effect of cross-slot interference in Chapter 3.

There are many researches use time slot allocation strategy to avoid and reduce the effects of cross-slot interference. They always avoid the effects of cross-slot interference in time domain. Not many researches have investigated the effects of cross-slot interference issue in frequency domain. However, the future wireless system-OFDMA has more serious inter-cell interference. If system can support asymmetric traffics, the SINR will be degrade seriously due to the cross-slot interference. Hence, we want to solve this kind of problems by implementing FFR scheme in TDD-OFDMA system when supporting various asymmetric traffics in a multi-cellular system. We investigate the impact of cross-slot interference in the FFR-based system, such as [14], [15], [16], [17], [18], [19]. FFR scheme is an approach which uses spectrums to exchange less inter-cell interference. The asymmetric traffic environments also have serious inter-cell interference than the symmetric traffic environment because of cross-slot interference. The FFR has two important factors which are inner region size and outer region reuse factor can be designed for improving system performance. System always use smaller frequency reuse factor in inner region that is near BS and larger frequency reuse factor in outer region that has longer distance between BS and MS. Hence, each cell can reuse more spectrums because the inner region is always useing same frequency bands and maintains higher link quality for MS transmits signal at outer region due to avoid neighboring cell's inter-cell interference. However, when MS transmit signal in the cross time slot region, system may reduce size of inner region or use larger outer region reuse factor to maintain higher link quality. Hence, we must design the appropriate FFR factors, such as inner region size, frequency reuse factor of each region and resource assignment to maximize spectrum efficiency with guaranteeing link reliability in different random asymmetric traffic environments.

1.3 Thesis Outline

The research in this thesis investigates the effects of inter-cell interference in a FFR based on TDD-OFDMA environment. We develop an analytical approach to evaluate the effects of inter-cell interference on the design of FFR factors. Furthermore, we provide some simulation results to clarify advantages of using FFR in a multi-cellular system with supporting asymmetric services.

The remaining chapters of this work are organized as following. Chapter 2 reviews some background of 802.16m WiMAX standard. Chapter 3 discuss literature surveys about the effects of cross-slot interference, fractional frequency reuse and problem formulation. Chapter 4 analyzes the outage performance for FFR based on TDD-OFDMA systems with asymmetric traffics in a two-cell environment and investigates the size of cross time slot region to effect the system performance. Chapter 5 discusses advantages of FFR schemes in TDD-OFDMA multi-cellular environment. Chapter 6 provides some concluding remarks and suggestions for future research.

CHAPTER 2

Background of 802.16m WiMAX System

2.1 Orthogonal Frequency Division Multiple Access (OFDMA)

OFDMA is a multicarrier modulation technique that has found wide adoption in a widespread variety of high-data-rate communication systems, including WiMAX and LTE standard in fourth generation cellular system. Several advantages of OFDMA can improve transmission performance, such as orthogonal frequency division multiplexing (OFDM) modulation technique, frequency diversity and multi-user diversity...etd.

In wireless transmission environments, multi-path delay interference is a serious problem. The orthogonality of OFDM subcarriers may be lost when the signal passes through a time-dispersive radio channel due to inter-OFDM symbol interference. However, a cyclic extension of the OFDM signal can be performed to avoid this interference. Using the cyclic prefix (CP) method is getting the last part of the OFDM signal is added in the beginning of the OFDM signal. The addition of the CP makes the transmitted OFDM signal periodic and helps in avoiding inter-OFDM symbols.

In a frequency-selective channel, different modulations symbols can be transmitted by using OFDM technique which can be affected by different channel fading. We can consider the channel fading gain and group subchannels with higher channel gain to each mobile station (MS). Thus, OFDMA can achieve frequency diversity in variety channel fading environment. The OFDMA system will allocate subchannels to each MS due to

Table 2.1: OFDMA scalability parameter in WiMAX system

Parameter	Value						
System bandwidth (MHz)	1.25	5	10	20	3.5	7	8.75
Samplink factor	28/25				8/7		
Sampling frequency (F_s,MHz)	1.4	5.6	11.2	22.4	4	8	10
Sample time ($1/F_s$,nsec)	714.3	178.6	89.3	44.6	250	125	100
FFT size (N_{FFT})	128	512	1024	2048	512	1024	1024
Subcarrier frequency spacing (Δf,kHz)	10.9375				7.8125		9.7656
Useful symbol time (T_b=1/Δf,μs)	91.4				128		102.4
Guard time (T_g=T_b/8,μs)	11.4				16		12.5
OFDMA symbol time (T_s=T_b+T_g,μs)	102.8				144		115.2

the available subcarriers may divided into several groups of subcarriers which are called subchannels. If we suitable arrange these subchannels, the multiuser diversity can improving the transmission quality by different subcarrier and subchannel permutation. However, subchannels form the minimum frequency resource-unit allocated by base station for uplink and downlink scheme. Therefore, different subchannels may be allocated to different users as a multiple-access mechanism in uplink and downlink.

2.1.1 OFDMA Scalable Parameter

The architecture is based on a scalable subchannelization structure with variable Fast Fourier Transform (FFT) sizes according to the system bandwidth. However, coherence time, Doppler shift and coherence bandwidth of the channel are considered in a scalable structure where the FFT sizes scale with bandwidth to keep the subcarrier spacing fixed. The Table 2.1.1 shows the scalability range proposed in IEEE 802.16m WiMAX standard.

2.1.2 Subchannelizaion of the OFDMA System

In an OFDMA system, subchannels may be constituted using either subcarriers pseudo-randomly distributed across the frequency spectrum or contiguous subcarriers. Subchannels are formed by using distributed subcarriers provide more frequency diversity, which is particularly useful for mobile applications. In WiMAX system, the pseudo-randomly distributed scheme is called partial usage of full usage of subcarriers (FUSC) and subcarriers (PUSC).

The subchannelization scheme based on contiguous subcarriers in WiMAX standard is called band adaptive modulation and coding (Band AMC). Although this scheme must lost frequency diversity, Band AMC allows system designers to exploit multiuser diversity that is allocating subchannels to users based on their frequency response or considering the co-channel interference from neighboring cell. In general, multiuser diversity can provide significant gains in system capacity by different allocation scheme.

Full Usage Subcarrier (FUSC) and Partial Usage Subcarrier (PUSC)

In the downlink transmission, the data subcarriers can be used to create the various subchannels by FUSC and PUSC permutation that are called DL-FUSC and DL-PUSC respectively. However, uplink case only support PUSC permutation method called UL-PUSC. They are formed subcarrier as a subchannel by each pseudorandom permutation approach. In the case of DL-FUSC, each subchannel is made up of 48 data subcarriers, which are distributed evenly throughout the en tire frequency band. The DL-PUSC is similar to FUSC except that the subcarriers are first divided onto six groups. Permutation of subcarriers formed subchannels is performed independently within each group. Thus, each group can be separated from each others and still keep the frequency diversity. In the UL-PUSC the subcarriers are first divided into various tiles consist of four subcarriers over three OFDM symbols. The tiles are renumbered and using a pseudorandom numbering sequency, and divided into six groups. Each subchannel is created using six tiles from a single group.

Band Adaptive Modulation and Coding (AMC)

According to use the Band AMC permutation mode, each subchannels is constituted by adjacent subcarriers. Although frequency diversity is lost, implement of multiuser diversity is easier. The system can adaptive allocate subchannels to each user with the highest SINR/capacity or choice subchannels with less co-channel interference since the multiuser diversity provides improvement in link reliability, system capacity and throughput. In the WiMAX system, we can use Band AMC permutation. Nine adjacent subcarriers and one pilot subcarrier are used to form a bin. A Band AMC subchannel consists of six contiguous bins. Thus, a Band AMC subchannel can consist of one bin over six consecutive symbols, two consecutive bins over three consecutive symbols, or three consecutive bins over two consecutive symbols. Hence, the size of subchannel is dependent on the subcarrier permutation mode. For instance, each subchannel is 8, 16, or 24 sybcarriers by six, three, or two OFDM symbols.

2.2 Frame Structure in the WiMAX System

In the OFDMA system, base station (BS) can allocate different subchannels to arrival users for uplink and downlink within a frame duration. Fig. 2.1 illustrates one sample OFDMA frame structure for a time division duplex (TDD) implementation in WiMAX system. The frame is divided into downlink and uplink sub-frames separated by transmit/receive and receive/transmit transition gaps (TTG and RTG) to prevent downlink and uplink transmission collisions. Each frame starts with a preamble followed by frame control header (FCH), the DL-MAP, and a UL-MAP, respectively. The preamble is used for synchronization and the FCH provides the frame configuration information such as MAP message, coding scheme, and usable subchannels...etd. However, system always uses the DL-MAP and UP-MAP to

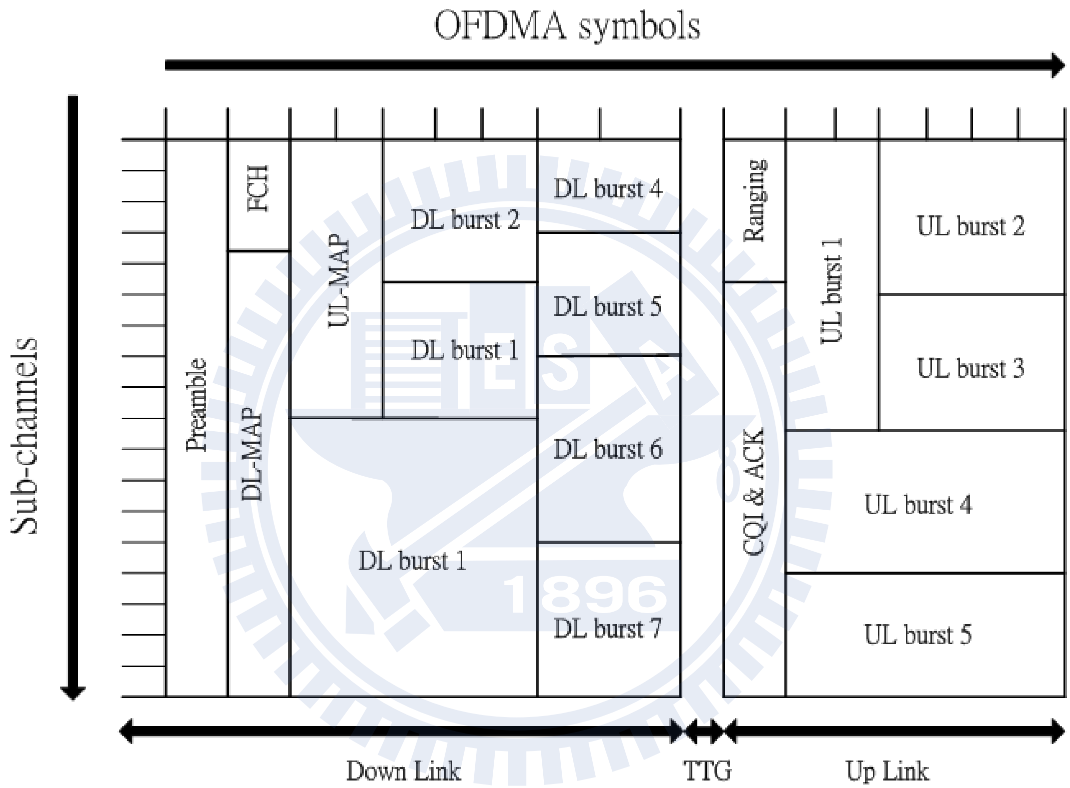

Figure 2.1: A sample TDD-OFDMA frame structure.

allocate subchannels for different users need to implement uplink and downlink. The uplink Ranging contains the mobile station (MS) information such as power adjustment and bandwidth request. The uplink CQICH and ACK is allocated for the MS feedback channel state information and downlink HARQ acknowledge.

Both frequency division duplexing (FDD) and time division duplexing (TDD) are allowed in the WiMAX system. No matter the former or the latter have some advantages respectively forth to used in the frame of wireless transmission system. Fig. 2.2 shows characteristic of FDD and TDD mode on the spectrum usage over timing allocation.

2.2.1 Frequency Division Duplexing (FDD) Mode

In the case of FDD mode, the uplink and downlink subframes are transmitted simultaneously in different carrier frequencies and the size of two subframes always are symmetric due to the type of traditional wireless transmission are almost voice and text message. Two kinds of data need symmetric traffic of uplink and downlink transmission since the FDD mode is easier to implement. Thus, the standard organization always assign two groups of spectrum to support uplink and downlink requirement respectively. However, the FDD always waste spectrum as paired spectrum for uplink and downlink in current transmission requirement due to more applications need various uplink/downlink ratio, such as web browser, interactive game or real-time streaming. The spectrum can't share to each other transmit mode. If MS needs more downlink transmission requirement, the uplink spectrum will waste for the idle transmission state. Nevertheless, the FDD mode need to transmit and receive signal simultaneously. Therefore, the transceiver is difficult to design and has a lot of cost. The fix size of FDD mode for uplink/downlink is not suitable used in the future.

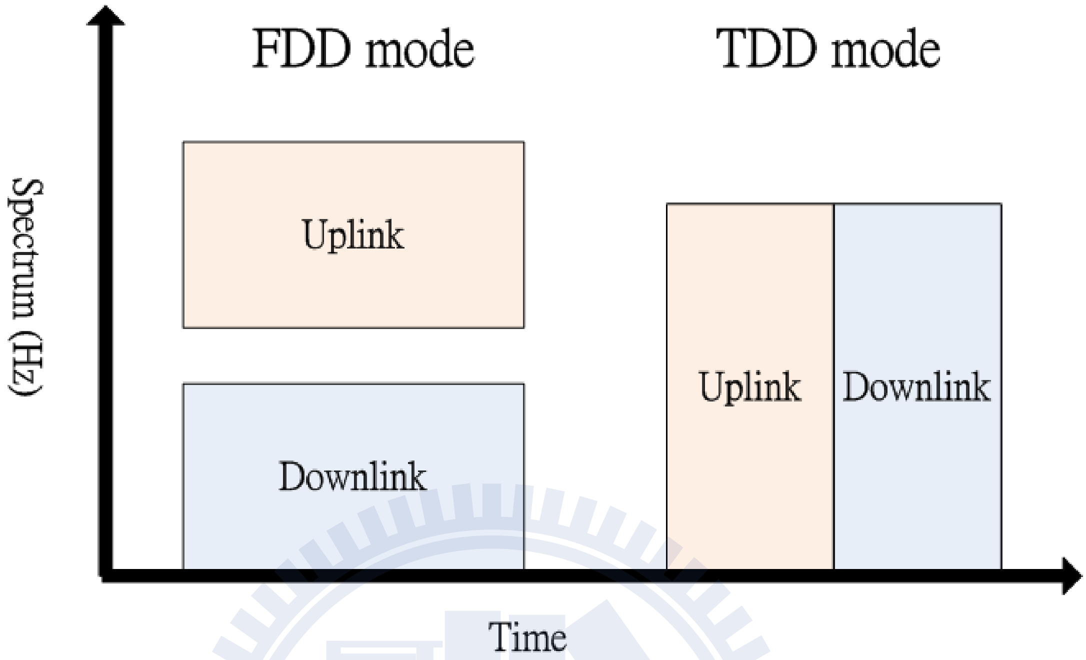

Figure 2.2: Characteristic comparison of FDD and TDD mode on usage of frequency bandwidth and time slots.

2.2.2 Time Division Duplexing (TDD) Mode

Most WiMAX system operators force to deploy TDD mode to transmit uplink and downlink signal respectively as the flexible sharing of bandwidth. Comparison of TDD and FDD mode, TDD mode has more advantages as considering spectrum usage ratio and transceiver cost. The TDD mode uses the time to separate uplink and downlink within a frame duration. System can allocate spectrum dynamically on the instant and TDD mode has a reciprocal channel that can be exploited for spatial processing and has a simpler transceiver design. However, there are some disadvantages need to notice while using TDD mode such as the need for synchronization across multiple base station and existence of strong cross-slot interference that will affect system performance.

2.3 Frequency Reuse Scheme

A good interference management (IM) scheme that can mitigate inter-cell interference. Frequency reuse is a conventional approach to reduce the effects of the inter-cell interference. However, the generic frequency reuse approach faces the trade-off between spectral efficiency and inter-cell interference mitigation. The former is affected by reuse factor is small and the latter can be achieved by big reuse factor. Hence, the FFR scheme [20] is introduced in this chapter.

FFR is an approach to limit the inter-cell interference. How to use it to get the best performance is an interesting issue. For example, the IEEE 802.16m WiMAX supports frequency reuse factor of one which means that all cells operate at only one frequency band to maximize spectrum efficiency. Nevertheless, the strong inter-cell interference is a main issue. Traditional frequency reuse technique can improve the inter-cell interference, but it will lower spectrum utilization. The concept of FFR is based on the idea of applying a reuse factor of one in the zone near the BS, and a higher reuse factor in the zone near the cell boundary. The FFR technique can reduce the inter-cell interference from neighbor cells for the MS near cell boundary and take care of spectrum utilization.

2.3.1 Traditional Frequency Reuse Scheme

The simplest frequency reuse scheme is a frequency reuse factor-n system. About the traditional frequency reuse scheme is shown as in Fig. 2.3. Total bandwidth can be used in the system will be divide into several partitions (n>1) and assign these partitions to neighboring cells that be shaped as a cluster. In a cluster, the neighboring cell will be assigned different bands to avoid inter-cell interference. For instance, Fig. 2.3 is tradition frequency reuse scheme of n=3, there are not inter-cell interference in each cluster. And each cell will be surrounded by six immediate neighboring cells which use orthogonal bands and each bandwidth equal to one-third of the total bandwidth. The traditional

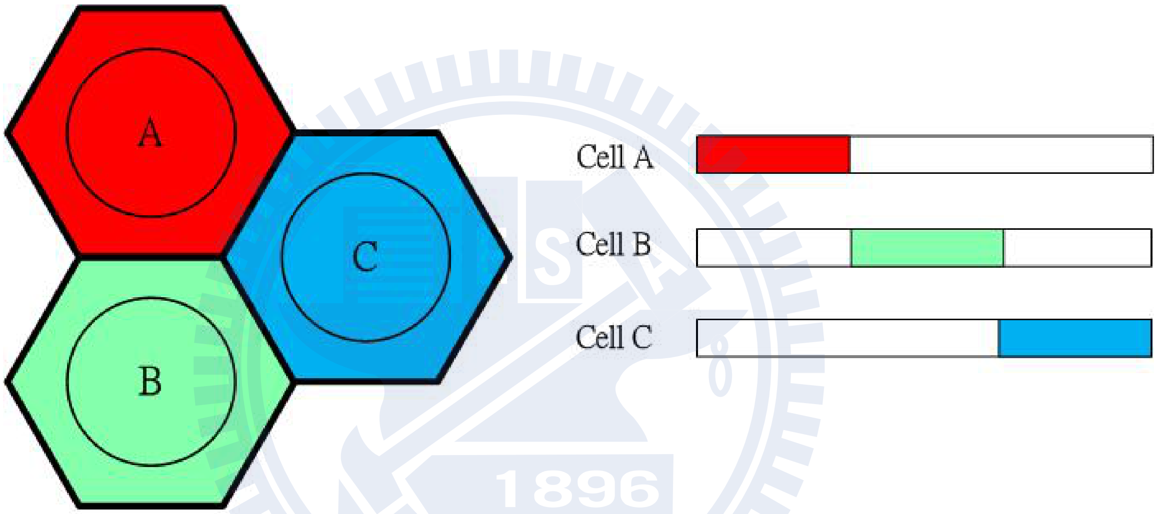

Figure 2.3: The architecture of traditional frequency reuse scheme and demonstrates the scenario of spectrum usage ratio.

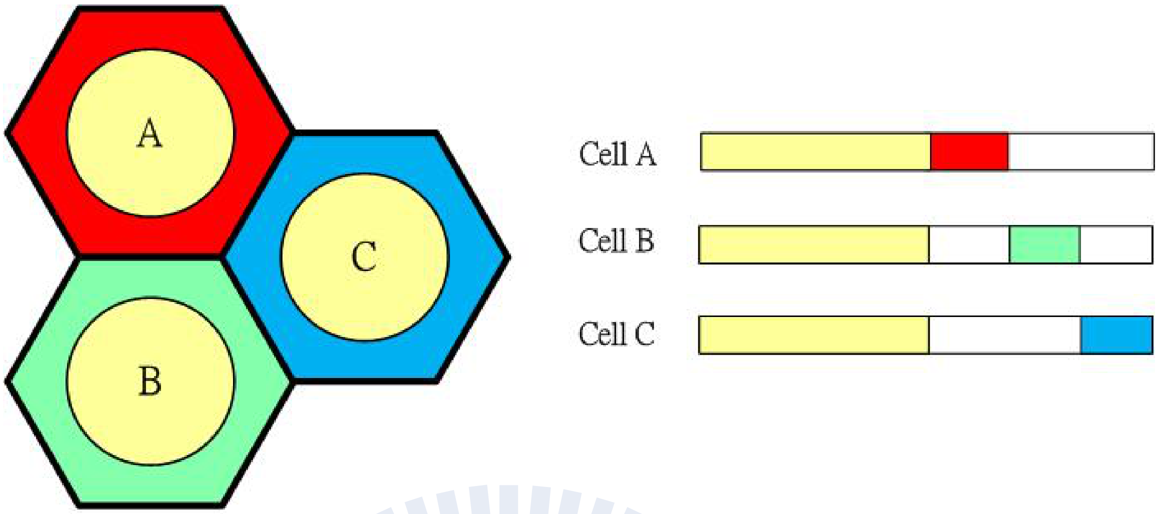

Figure 2.4: The architecture of fraction frequency reuse scheme by considering interference mitigation at outer region and outer region reuse factor equals to three.

frequency reuse scheme can trade the spectral efficiency for the benefits of completing cancellation of stronger inter-cell interference from first-tier cells. As we know, the larger n will receive lower inter-cell interference at receiver, but also degrades spectral efficiency in each cells. Hence, use the tradition frequency reuse scheme in the cellular systems is not the best interference management scheme in the view of system performance.

2.3.2 Fractional Frequency Reuse (FFR) Scheme

The fractional frequency reuse scheme is used to increase spectrum efficiency and improve the link quality while MS locate at cell boundary. As Fig. 2.4 shown, each cell divide into two groups, the region of inner and outer. As we realize, if MS arrives to the inner region, they could have good link quality by less propagation lossy than MS locate at outer region. Hence, the MS locates at inner region can tolerate more effects of inter-cell interference from neighboring cells than outer region. On the other hand, the outer region always has larger propagation lossy since if they also receive inter-cell interference from neighboring cells, signal transmission is almost outage that means the received signal can't be demodulated. Therefore, FFR scheme is major solution to improve link quality when MS transmits signal at cell boundary and maintain spectrum efficiency. In the inner region always use frequency reuse factor equals to one or smaller than frequency reuse factor of outer region. However, the frequency reuse factor of outer region is always larger than one for improving the effects of inter-cell interference from neighboring cells. For example, there is a FFR scheme with frequency reuse factor is one at inner region and three at outer region in Fig. 2.4. The total bandwidth will classify four parts to assign in different region for a cluster is combined by cell A, B and C. First part is used in inner region and other parts are assigned to outer region of each cells. In a cluster, the inner region shares the same bandwidth to increase spectrum utilization in a cell and the outer region uses different bandwidth to avoid inter-cell interference.

For the FFR scheme, two important design parameters must be noticed are the size of inner region and the outer region reuse factor. The size of inner region is associated with maintaining spectrum efficiency. The outer region reuse factor will affect spectrum utilization and overall inter-cell interference. Two parameters will affect the system performance in FFR scheme. Hence, system must design this two factors to improve system performance in difference systems.

CHAPTER 3

Effect of Cross-Slot Interference in FFR based TDD-OFDMA Multi-Cellular System

Multimedia services are popularly used in the third generation communication systems. In the future, there are more various applications with different uplink/downlink bandwidth requirements. However, the traditional bandwidth requirements of uplink and downlink transmission are always symmetric by voice and messages. No matter using TDD or FDD mode, system always allocates symmetric traffics in each cell. Thus, inter-cell interference always comes from neighboring cells at different entities between transmitter and receiver. This kinds of inter-cell interference is called non cross-slot interference, such as BS-to-MS and MS-to-BS interference. Oppositely, the inter-cell interference is coming from same entities between transmitter and receiver called cross-slot interference, such as BS-to-BS and MS-to-MS cross-slot interference which doesn't cause in FDD and TDD with fix uplink/downlink ratio among all cells.

Furthermore, more various applications with different uplink/downlink bandwidth requirements are generated. Each cell may support different kinds of uplink/downlink ratio dynamically. Thus, the dynamic TDD mode is popularly researched in the recent years. The key advantage of the dynamic TDD mode is its capability of flexibly adjusting uplink and downlink bandwidth by allocating different numbers of time slot. However, the cross-slot interference may be generated in dynamic TDD mode and it becomes the largest resistance of supporting dynamic TDD mode, because will degrade SINR seriously. If we want to support multimedia service in next generation system, the effects of cross-slot interference must be solved or reduced for guaranteeing link quality.

3.1 Literature Survey

There are several researches to overcome the issue of cross-slot interference on dynamic TDD mode in the recent years. They are briefly introduced as follows.:

3.1.1 Effect of Cross-Slot Interference in Different Wireless System

Interference Analysis and Resource Allocation for TDD-CDMA Systems to Support Asymmetric Services by Using Directional Antennas [5]

This paper explores the advantages of using directional antennas in TDD-CDMA system to support asymmetric traffic services and analyze the interference of the TDD-CDMA system with trisector cellular architecture, where three directional antennas are employed at each base station. The system architecture is shown in Fig.3.1. Each directional antennas can support different uplink and downlink ratios for the sector coverage to implement asymmetric traffic services, but the strong cross-slot interference is frequently generated.

A sample approach to avoid this interference is fixing same uplink and downlink ratio among all cells. The disadvantage of this sample approach is loss the flexibility of assigning uplink and downlink ratio as increasing new call blocking rate in the cell. Thus, the concept of virtual cell is introduced in the paper and virtual cell is composed of three sectors from the three adjacent cells. They can provide an additional degree of freedom for allocating radio resource. Fixing the same uplink and downlink ratio by considering requirement of the virtual cell to avoid the cross-slot interference. This approach can lower the new call blocking likes a dynamic TDD mode and improves the distribution of SINR better than other traditional approaches.

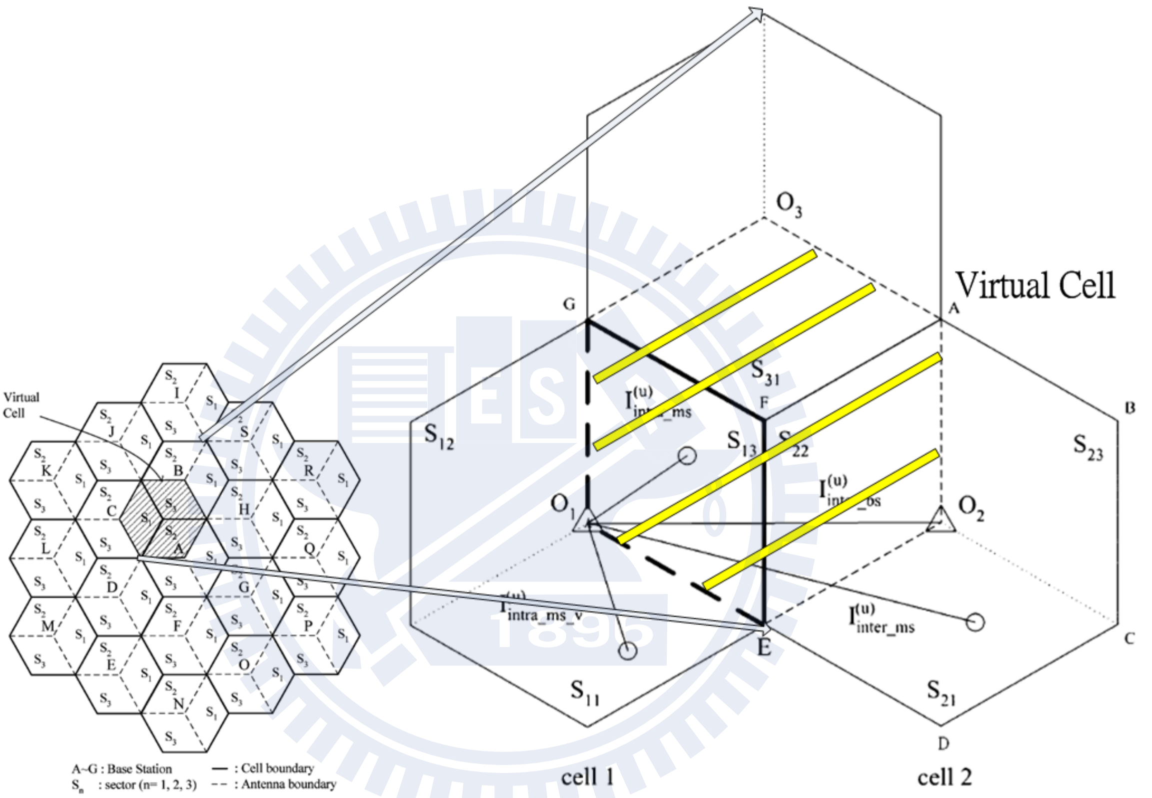

Figure 3.1: The architecture of virtual cell is composed of three sectors from the three adjacent cells.

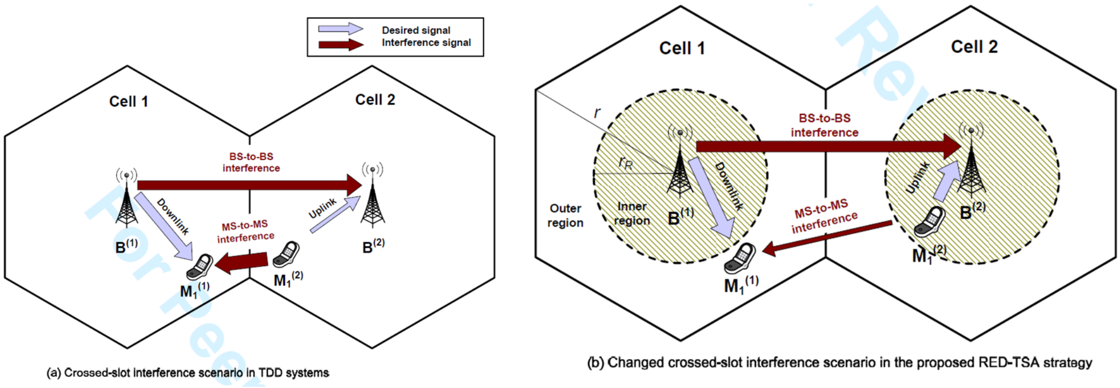

Figure 3.2: The architecture of Red-TSA considers the MS location information to schedule time slots.

Time Slot Allocation Based on Region and Time Partitioning for Dynamic TDD-OFDM Systems [8]

In this paper, the MS location information is being considered to make properly scheduling to avoid the MS is locating at the cell boundary and transmitting in cross time slot region in a TDMA system. The author provide a new time slot allocation (TSA) strategy, region-based decentralized time slot allocation (RED-TSA) strategy which utilizes partial location information of MS. The diagram of RED-TSA is shown in Fig. 3.2 and it can effective to reduce the effects of cross-slot interference than traditional strategies, Fix-TSA and Greedy-TSA. The Fix-TSA which fixes the same ratio of uplink and downlink time slots in all cells to mitigate the cross-slot interference and the Greedy-TSA is just like dynamic TDD mode which each cell can support different uplink and downlink ratios.

The new RED-TSA is a new scheduling approach to reduce the effect of cross-slot interference. Each cell is divided into inner and outer region. According to consider the effect of path loss, the inner region has better link quality than outer region. If Ms transmits or receives signal at inner region will get higher SINR than MS locates at outer region. Hence, the MS locates at inner region can tolerate stronger inter-cell interference and due to this reason which the RED-TSA arranges thesis MS that locates at inner region transmit or receives signal on time slots which near the predefined boundary (likes the switch point introduced in last section). This scheduling method can reduce the effects of cross-slot interference as avoiding received the cross-slot interference when Ms locates at cell boundary.

Furthermore, the author also provides an analytical approach to find out the optimal predefined boundary and analyze system performance by using the Central Limit Theorem and Queueing Theorem. The mathematical analysis can quickly compute the system performance and find out the optimal predefined boundary.

3.1.2 Inter-Cell Interference Reduction of Fractional Frequency Reuse (FFR) Multi-Cellular System

Optimal Fractional Frequency Reuse (FFR) in Multi cellular OFDMA System [14]

The fractional frequency reuse technique is a good interference management that introduced in last chapter. However, the advantages of fractional frequency reuse is introduced in this paper. In addition, the author proposes an optimal analysis (Primal Dual Interior Point Method) [21] to find out the optimal design factors in FFR scheme based OFDMA system in downlink case. This analysis method will compute the optimal numbers of subchannel can be used in each region. The simulation result shows the advantages on FFR scheme that can against the effects of inter-cell interference and improves system throughput by suitable design factors of FFR scheme. Hence, the fractional frequency reuse scheme is suitable to solve the effects of inter-cell interference.

Table 3.1: Comparison between propose work and recent research about effect of cross-slot interference.

	Multiple Access	Division Duplexing	System Service	Main Solution
[4]– [5]	CDMA	Dynamic-TDD	Asymmetric	Directional antenna
[6]– [8]	TDMA	Dynamic-TDD	Asymmetric	Location-TSA
[9]– [11]	CDMA/OFDM	Dynamic-TDD	Asymmetric	Path gain-TSA
[12]	OFDMA	Dynamic-TDD	Asymmetric	RTSO-TSA
[13]	TDMA	Dynamic-TDD	Asymmetric	Power control
[14]– [19]	OFDMA	Fix-TDD	Symmetric	FFR
Propose work	OFDMA	Dynamic-TDD	Asymmetric	FFR

3.2 Problem Formulation

Comparison of thesis research about the effects of inter-cell interference including cross-slot interference. We can find out the effects of cross-slot interference is stronger than general inter-cell interference (non cross-slot interference) especially BS-to-BS cross-slot interference. If asymmetric traffic services want to be implemented in the future, we must reduce or avoid the effects of cross-slot interference in TDD-OFDMA system. Hence, we propose FFR-based TDD-OFDMA system that can effectively reduce the problems of cross-slot interference by dynamically design the factors of FFR scheme at any instantaneous asymmetric traffic requirements among multi-cellular environments. Comparison table is shown in Table. 3.1. Furthermore, performance analysis and simulation result will be introduced in next chapter.

CHAPTER 4

Outage Performance Analysis for Fractional Frequency Reused TDD-OFDMA Systems with Asymmetric Traffics: Two Cell Case

In this chapter, we present an analytical approach to design the inner region size for the fractional frequency reused (FFR) time division duplex (TDD) orthogonal frequency division multiple access (OFDMA) systems when supporting asymmetrical traffic services. In TDD systems, supporting asymmetrical traffics can be achieved by adjusting the ratio of downlink and uplink transmission period. Nevertheless, the inter-cell interference may be deteriorated by the cross-slot interference resulting from the different downlink and uplink ratios among neighboring cells. Although the FFR scheme can overcome the inter-cell interference, impact of the cross-slot interference of TDD systems due to various downlink to uplink traffic ratios in different cells on the inner region size of a FFR-based OFDMA system is an open issue to our best knowledge. Intuitively, the larger the inner region of a FFR system, the higher system capacity will be achieved. Thus, we can provide a systematic method to determine the size of the inner region of FFR-based OFDMA system for different ratios of the downlink to uplink traffic among two neighbor cells.

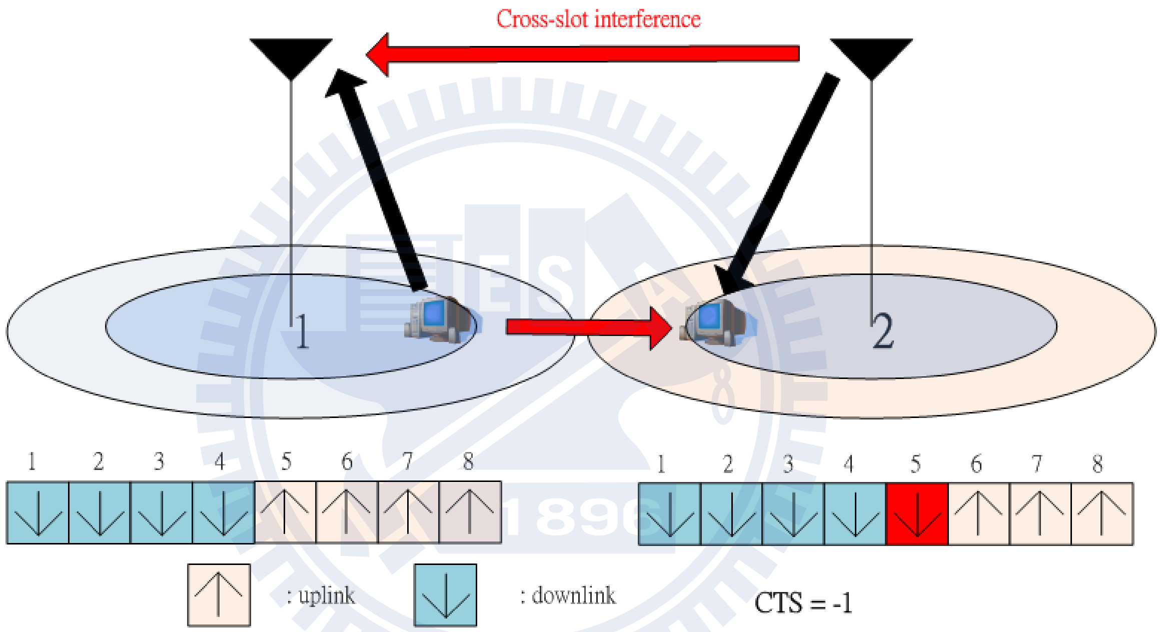

Figure 4.1: The BS-to-BS cross-slot interference appears in slot fifth for cell A.

4.1 System Mode

4.1.1 Two Cellular Scenario

We consider a TDD-OFDMA system with FFR scheme and supports asymmetric services in a two-cell environment just likes Fig. 4.1. Note that the ratios of the downlink traffic to the uplink traffic are different in the two cells. Thus, the strong cross-slot interference occur and can degrade received SINR seriously. Hence, it is crucial to resolve the heavy cross-slot interference issue when employing FFR in the TDD-OFDMA system.

The important design parameters for FFR based TDD-OFDMA system are the inner region radius and the outer region reuse factor. The inner region radius is associated with the numbers of subchannel can be used in each zone. The outer region reuse factor will affect spectrum utilization and the overall inter-cell interference. We will vary the inner radius and outer radius in our analysis to find out the maximum inner radius that can guarantee the success probability in the asymmetric traffic environments.

4.1.2 Resource Assignment Approach

The fairness approach to allocate the numbers of subchannel is proportional to numbers of user in each region. In the TDD frame structure likes Fig. 4.2 which is divided into into two groups according to its uplink/downlink requirements. If we randomly assign resource units to the arriving MS, it will increase the probability of generating cross-slot interference. We must assign resources to MS regularly. The uplink slot assignment begins from the head slot of a frame until the switching point, and downlink slot assignment begins from the end slot of a frame to the switching point. In this way called regular assignment, cross-slot interference can be avoided when cell traffic is low.

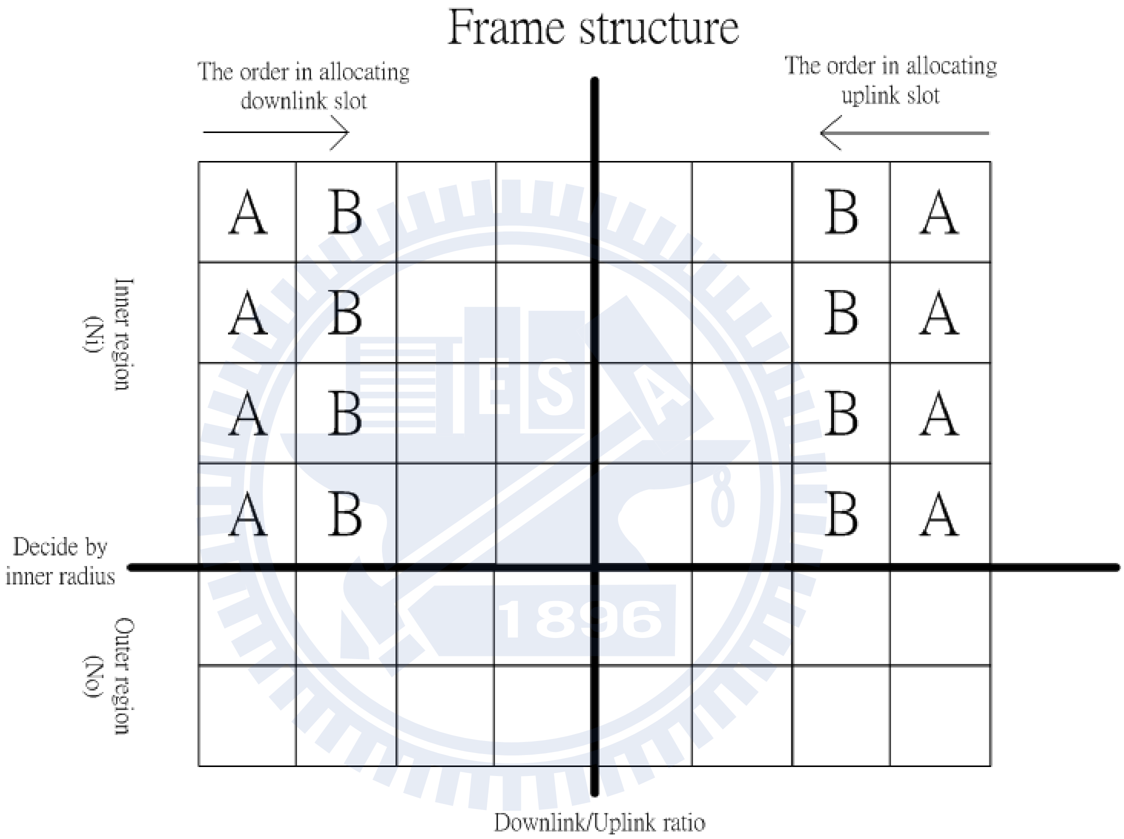

Figure 4.2: The scheme of regular time slot assignment.

4.1.3 Cross Time Slot (CTS) Region of Asymmetric Services

In an asymmetric service systems like Fig. 4.1, each cell has their own downlink/uplink requirements (Δ^{DL}:Δ^{UL}) and will result in the CTS region. In this region, we analyze the effects of cross-slot interference that degrades SINR in the TDD-OFDMA system. Let Δ_1^{DL} be the downlink requirements in cell 1 and Δ_2^{DL} the downlink requirements in cell 2. We define the CTS region as Δ_2^{DL}-Δ_1^{DL} [9]. The positive value of CTS represents cell 2 has more downlink slots than cell 1. Oppositely, the negative value of CTS means cell 2 has more uplink slots than cell 1. Hence, if the CTS is equal to zero, the cell 1 and cell 2 has same downlink and uplink time slots requirement.

4.2 Performance Metrics

4.2.1 Radio Propagation Effects

We consider the following channel effects: path loss, shadowing fading, and multi-path delay fading to analyze success probability for the FFR based TDD-OFDMA two-cells cellular system.

Path Loss

The pathloss decays with the propagation distance r between the transmitter and the receiver is modelled as a common empirical formula approximation [22] that is formulated as following:

$$P_{Loss}(r) = P_0 \left(\frac{d_0}{r}\right)^{\alpha} \quad , \tag{4.1}$$

where α is the pathloss exponent factor and the value of measured pathloss P_0 is considered by reference distance of d_0. However, P_0 is often approximated as $(\frac{4\pi}{\lambda})^2$ when $d_0 = 1$. λ is the wavelength of operating frequency.

Shadowing Fading

Shadowing fading can be modelled as a log-normal random variable $10^{\frac{\xi}{10}}$ in the 802.16m WiMAX system [1]. The variable ξ is distributed as Gaussian random variable with zero mean. Different propagation path will affect levels of the standard deviation because of the different antenna height. In this thesis, the standard deviation on BS-to-BS path is 3 dB and 10 dB on other propagation paths, such as BS-to-MS, MS-to-BS and MS-to-MS link.

Multi-Path Delay Fading

Some buildings locate around the propagation path that will reflect waves which may be received at the receiver. Each of these reflected signals have different paths, amplitude and phases. The Rayleigh distribution [23] is used in this chapter to characterize the multi-path delay fading for analysis success probability on FFR based TDD-OFDMA system. On each subcarrier k, we can formulate the multi-path delay fading h as a Rayleigh distributed random variable with the probability density function (pdf) as following:

$$f_h(h) = 2he^{-h^2} \quad . \tag{4.2}$$

Let $Y = h^2$, the cumulative density function (cdf) of Y can be written as

$$F_Y(y) = 1 - e^{-y} \quad . \tag{4.3}$$

4.2.2 Signal to Interference-and-Noise Ratio (SINR)

According to consider effects of path loss, shadowing fading and multi-path delay fading, we can calculate the total received signal power $P_{r_{i,j,k}}$ at the receiver on k-th subcarrier for the j-th subchannel of transmitter is located in cell i by the following formulation,

$$P_{r_{i,j,k}} = P_t\left(C_{i,j,k}\right) P_{Loss}\left(r_{i,j,k}\right) 10^{\frac{\xi_{i,j,k}}{10}} \left(h_{i,j,k}\right)^2 \quad , \tag{4.4}$$

where $P_t(C_{i,j,k})$ is the transmission power on k-th subcarrier for the j-th subchannel of transmitter is located in cell i. $C_{i,j,k}$ may be $[U, D, X]$ represents that transmission modes on k-th subcarrier for the j-th subchannel of cell i. U, D and X are uplink transmission, downlink transmission and the k-th subcarrier isn't used to transmit signal, respectively. The shadowing fading $10^{\frac{\xi_{i,j,k}}{10}}$ is a log-normal random variable with $\xi_{i,j,k}$ is a Gaussian random variable and the multi-path delay fading is labelled as $h_{i,j,k}$ that represents the channel fading on k-th subcarrier for the j-th subchannel of transmitter is located in cell i.

In a multi-cellular system with I cells, the observed receiver may received co-channel interference comes from other cells. Hence, the total interference on the k-th subchannel can be formulated as,

$$\sum_{i=2}^{I} P_t\left(C_{i,j,k}\right) P_{Loss}\left(r_{i,j,k}\right) 10^{\frac{\xi_{i,j,k}}{10}} \left(h_{i,j,k}\right)^2 \tag{4.5}$$

Then, the SINR on k-th subcarrier for the j-th subchannel of transmitter is located in cell 1 can be written as

$$SINR_{1,j,k} = \frac{P_t\left(C_{1,j,k}\right) P_{Loss}\left(r_{1,j,k}\right) 10^{\frac{\xi_{1,j,k}}{10}} \left(h_{1,j,k}\right)^2}{\sum_{i=2}^{I} P_t\left(C_{i,j,k}\right) P_{Loss}\left(r_{i,j,k}\right) 10^{\frac{\xi_{i,j,k}}{10}} \left(h_{i,j,k}\right)^2 + N_0 W_{sub}} \tag{4.6}$$

where N_0 is the noise power density and W_{sub} is bandwidth size of a subcarrier.

4.2.3 Success Probability of Wireless Transmission

In OFDMA systems, the minimum transmission unit is a subchannel that is grouped by several subcarriers. The lowest level of effective SINR can be demodulated at the receiver is $r_{th} = 0$ that doesn't consider error coding scheme [24]. The success probability of wireless transmission is the probability that effective $SINR_{i,j}$ is higher than the threshold r_{th} just likes following formulation:

$$p_s = P_r\left(SINR_{i,j} > r_{th}\right) \quad , \tag{4.7}$$

where the success probability p_s can represent wireless transmission quality.

4.3 Total Success Probability of Wireless Transmission for the FFR based TDD-OFDMA System

According to the total probability theorem, we can calculate the total success probability for the FFR based TDD-OFDMA system by the following formulation,

$$\begin{aligned} p_s =& A_{in} \cdot \left[P_r\left(C_1 = U\right) \cdot p_s^I\left(C_1 = U\right) + P_r\left(C_1 = D\right) \cdot p_s^I\left(C_1 = D\right) \right] \\ & + A_{out} \cdot \left[P_r\left(C_1 = U\right) \cdot p_s^N\left(C_1 = U\right) + P_r\left(C_1 = D\right) \cdot p_s^N\left(C_1 = D\right) \right] \quad , \end{aligned} \tag{4.8}$$

where A_{in} presents the probability that MSs arrive to the cell 1 and locate at the inner region. Oppositely, A_{out} is the probability that MSs arrive to the outer region in the cell 1. $P_r(C_1 = U)$ and $P_r(C_1 = D)$ are the ratio of uplink and downlink requirement. The success probability in the inner region of the cell 1 transmission mode is given can be represented as

$$\begin{aligned} p_s^I\left(C_1 = U\right) =& P_r\left(C_2 = X | C_1 = U\right) p_s^I\left(C_1 = U, C_2 = X\right) \\ & + P_r\left(C_2 = U | C_1 = U\right) p_s^I\left(C_1 = U, C_2 = U\right) \\ & + P_r\left(C_2 = D | C_1 = U\right) p_s^I\left(C_1 = U, C_2 = D\right) \quad , \end{aligned} \tag{4.9}$$

$$\begin{aligned} p_s^I\left(C_1 = D\right) =& P_r\left(C_2 = X | C_1 = D\right) p_s^I\left(C_1 = D, C_2 = X\right) \\ & + P_r\left(C_2 = U | C_1 = D\right) p_s^I\left(C_1 = D, C_2 = U\right) \\ & + P_r\left(C_2 = D | C_1 = D\right) p_s^I\left(C_1 = D, C_2 = D\right) \quad , \end{aligned} \tag{4.10}$$

In the inner region of the cell 1, receivers may receive inter-cell interference that come from neighboring cells because of frequency reuse scheme. Hence, there are three kinds of success probability may be generated in the inner region. First, the receiver doesn't receive inter-cell interference just like $p_s^I(C_1 = U, C_2 = X)$ and $p_s^I(C_1 = D, C_2 = X)$, because neighboring cells doesn't use same resource units (subchannel). Second, receivers may be suffered the effects of non cross-slot interference, $p_s^I(C_1 = U, C_2 = U)$ and $p_s^I(C_1 = D, C_2 = D)$. In the second situation, the neighboring cells have same transmission mode. The third kind of success probability is the receiver receives strong cross-slot interference that is generated when neighboring cells have different transmission mode. We will calculate each kinds of success probability in the next section.

4.4 Success Probability in the Flat-Fading Channel

4.4.1 Effective Subchannel Gain in the Flat-Fading Channel

In the flat-fading environment, each subcarriers of a subchannel always have same multipath delay fading that is $h_{i,j,1} = h_{i,j,2} = ... = h_{i,j,M_{sub}}$, where M_{sub} is the number of subcarriers are grouped as a subchannel. Hence, we can formulate received power $P_{r_{i,j}}$ for the j-th subchannel as following:

$$\begin{aligned}
P_{r_{i,j}} &= \sum_{k=1}^{M_{sub}} P_{r_{i,j,k}} \\
&= P_t(C_{i,j}) P_{Loss}(r_{i,j}) 10^{\frac{\xi_{i,j}}{10}} \left(\frac{1}{M_{sub}} \sum_{k=1}^{M_{sub}} (h_{i,j,k})^2 \right) \\
&= P_t(C_{i,j}) P_{Loss}(r_{i,j}) 10^{\frac{\xi_{i,j}}{10}} \left(\frac{1}{M_{sub}} \sum_{k=1}^{M_{sub}} y_{i,j,k} \right) \\
&= P_t(C_{i,j}) P_{Loss}(r_{i,j}) 10^{\frac{\xi_{i,j}}{10}} y_{i,j} \quad , \qquad (4.11)
\end{aligned}$$

where $y_{i,j} = y_{i,j,k}$ and $y_{i,j}$is the effective subchannel gain which is distributed as an Exponential random variable with the pdf and cdf as following:

$$f_Y(y) = e^{-y} \ , \tag{4.12}$$

$$F_Y(y) = 1 - e^{-y} \ . \tag{4.13}$$

However, the effective $SINR_{1,j}$ on the j-th subchannel of transmitter is located in cell 1 under a flat-fading channel can be represented as

$$SINR_{1,j} = \frac{P_t(C_{1,j}) P_{Loss}(r_{1,j}) 10^{\frac{\xi_{1,j}}{10}} y_{1,j}}{\sum_{i=2}^{I} P_t(C_{i,j}) P_{Loss}(r_{i,j}) 10^{\frac{\xi_{i,j}}{10}} y_{i,j} + N_0 W_c} \ , \tag{4.14}$$

where the bandwidth of a subchannel $W_c = M_{sub} W_{sub}$.

4.4.2 Success Probability without Inter-Cell Interference in the Flat-Fading Channel

The success probability without inter-cell interference under conditions of $y_{1,j}$,$r_{1,j}$, $\xi_{1,j}$ are given can be defined as following:

$$\begin{aligned}
& p_s^N(C_{1,j}|y_{1,j}, r_{1,j}, \xi_{1,j}) \\
&= P_r\{SNR_{1,j} > r_{th}\} \\
&= P_r\left\{\frac{P_t(C_{1,j}) P_{Loss}(r_{1,j}) 10^{\frac{\xi_{1,j}}{10}} y_{1,j}}{N_0 W_c} > r_{th}\right\} \\
&= P_r\left\{y_{1,j} > r_{th} \frac{N_0 W_c}{P_t(C_{1,j}) P_{Loss}(r_{1,j}) 10^{\frac{\xi_{1,j}}{10}}}\right\} \\
&= 1 - F_Y\left[r_{th} \frac{N_0 W_c}{P_t(C_{1,j}) P_{Loss}(r_{1,j}) 10^{\frac{\xi_{1,j}}{10}}}\right] \ ,
\end{aligned} \tag{4.15}$$

where r_{th} is the required received-SINR threshold which is chosen in accordance with the selected modulation and coding scheme [24].

For considering the propagation distance $r_{1,j}$ and shadowing effects $\xi_{1,j}$, the success probability without inter-cell interference can be evaluated as:

$$
\begin{aligned}
&p_s^N\left(C_{1,j}\right) \\
&= \iint p_s^N\left(C_{1,j}|y_{1,j}, r_{1,j}, \xi_{1,j}\right) \cdot f_{R_{1,j}}(r_{1,j}) f_\xi(\xi_{1,j}) dr_{1,j} d\xi_{1,j} \\
&= \iint \left\{1 - F_Y\left[r_{th}\frac{N_0 W_c}{P_t(C_{1,j})P_{Loss}(r_{1,j})10^{\frac{\xi_{1,j}}{10}}}\right]\right\} \cdot f_{R_{1,j}}(r_{1,j}) f_\xi(\xi_{1,j}) dr_{1,j} d\xi_{1,j} \\
&= \int_{-\infty}^{\infty}\iint_{S_1}\left[e^{-r_{th}\frac{N_0 W_c}{P_t(C_{1,j})P_{Loss}(r_{1,j})10^{\frac{\xi_{1,j}}{10}}}}\right] \cdot \frac{e^{-\frac{\left(\xi_{1,j}\right)^2}{2\sigma^2}}}{\sqrt{2\pi}\sigma} dx_{1,j} dy_{1,j} d\xi_{1,j} \quad , \qquad (4.16)
\end{aligned}
$$

where S_1 is the set of coordination in the cell 1 and $f_\xi(\xi_1, j) = \frac{e^{-\frac{\left(\xi_{1,j}\right)^2}{2\sigma^2}}}{\sqrt{2\pi}\sigma}$ represents the distribution of the log-normal shadowing.

4.4.3 Success Probability with Inter-Cell Interference in the Flat-Fading Channel

The success probability subjects to the inter-cell interference for the jth subchannel in cell 1 under conditions of $y_{1,j}$,$r_{1,j}$,$\xi_{1,j}$,$y_{2,j}$,$r_{2,j}$ and $\xi_{2,j}$ are given can be defined as follows:

$$
\begin{aligned}
&p_s^I\left(C_{1,j}, C_{2,j}|y_{1,j}, r_{1,j}, \xi_{1,j}, y_{2,j}, r_{2,j}, \xi_{2,j}\right) \\
&= P_r\left\{SINR_{1,j} > r_{th}\right\} \\
&= P_r\left\{\frac{P_t(C_{1,j})P_{Loss}(r_{1,j}) \cdot 10^{\frac{\xi_{1,j}}{10}} y_{1,j}}{P_t(C_{2,j})P_{Loss}(r_{2,j}) \cdot 10^{\frac{\xi_{2,j}}{10}} y_{2,j} + N_0 W_c} > r_{th}\right\}
\end{aligned}
$$

$$= P_r \left\{ y_{1,j} > r_{th} \left(\frac{P_t(C_{2,j})}{P_t(C_{1,j})} \right) \left(\frac{P_{Loss}(r_{2,j})}{P_{Loss}(r_{1,j})} \right) 10^{\frac{\xi_{2,j}-\xi_{1,j}}{10}} y_{2,j} + r_{th} \frac{N_0 W_c}{P_t(C_{1,j}) P_{Loss}(r_{1,j}) \cdot 10^{\frac{\xi_{1,j}}{10}}} \right\}$$

$$= P_r \{ y_{1,j} > \gamma_j y_{2,j} + \beta_j \}$$

$$= 1 - F_Y [\gamma_j y_{2,j} + \beta_j] \quad , \tag{4.17}$$

where

$$\gamma_j = r_{th} \left(\frac{P_t(C_{2,j})}{P_t(C_{1,j})} \right) \left(\frac{P_{Loss}(r_{2,j})}{P_{Loss}(r_{1,j})} \right) 10^{\frac{\xi_{2,j}-\xi_{1,j}}{10}} \quad , \tag{4.18}$$

$$\beta_j = r_{th} \frac{N_0 W_c}{P_t(C_{1,j}) P_{Loss}(r_{1,j}) \cdot 10^{\frac{\xi_{1,j}}{10}}} \quad , \tag{4.19}$$

Then, $r_{2,j}$ and $\xi_{2,j}$ are the propagation distance and shadowing effects between transmitter at cell 2 and receiver at cell 1 for the jth subchannel. γ_j is the ratio of received interference power over received signal power and β_j is the ratio of thermal noise power over received signal power. However, the equation (4.17) can be integrated by considering effects of channel fading $y_{2,j}$,

$$p_s^I (C_{1,j}, C_{2,j} | r_{1,j}, \xi_{1,j}, r_{2,j}, \xi_{2,j})$$

$$= \int_0^\infty p_s^I (C_{1,j}, C_{2,j} | y_{1,j}, r_{1,j}, \xi_{1,j}, y_{2,j}, r_{2,j}, \xi_{2,j}) \cdot f_Y (y_{2,j}) \, dy_{2,j}$$

$$= \int_0^\infty \{ 1 - F_Y [\gamma_j y_{2,j} + \beta_j] \} \cdot e^{-y_{2,j}} dy_{2,j}$$

$$= \int_0^\infty e^{-(\gamma_j y_{2,j} + \beta_j)} \cdot e^{-y_{2,j}} dy_{2,j}$$

$$= \int_0^\infty e^{-(1+\gamma_j) y_{2,j}} \cdot e^{-\beta_j} dy_{2,j}$$

$$= \frac{e^{-\beta_j}}{1 + \gamma_j} \quad , \tag{4.20}$$

Considering the propagation distance $r_{2,j}$ and shadowing effects $\xi_{2,j}$, we can calculate the success probability under the propagation distance $r_{1,j}$ and shadowing effects $\xi_{1,j}$ are given as

$$p_s^I\left(C_{1,j}, C_{2,j}|r_{1,j}, \xi_{1,j}\right) = \int_0^\infty \int_{R_2} p_s^I\left(C_{1,j}, C_{2,j}|r_{1,j}, \xi_{1,j}, r_{2,j}, \xi_{2,j}\right) f_{R_{2,j}}\left(r_{2,j}\right) f_\xi\left(\xi_{2,j}\right) dr_{2,j} d\xi_{2,j} \quad , \tag{4.21}$$

where R_2 is the set of the distance between transmitter at cell 2 and receiver at cell 1 for the j-th subchannel. Then, we can obtain the success probability with inter-cell interference as following:

$$p_s^I\left(C_{1,j}, C_{2,j}\right) = \int_0^\infty \int_{R_1} p_s^I\left(C_{1,j}, C_{2,j}|r_{1,j}, \xi_{1,j}\right) f_{R_{1,j}}\left(r_{1,j}\right) f_\xi\left(\xi_{1,j}\right) dr_{1,j} d\xi_{1,j} \quad , \tag{4.22}$$

where R_1 is the set of the distance between transmitter and receiver at cell 1 for the jth subchannel.

4.5 Success Probability in the Frequency-Selective Fading Channel

4.5.1 Effective Subchannel Gain in the Frequency-Selective Fading Channel

In the frequency-selective fading environment, each subcarriers of a subchannel always have different multi-path delay fading that is $h_{i,j,1} \neq h_{i,j,2} \neq ... \neq h_{i,j,M_{sub}}$, where M_{sub} is the number of subcarriers are grouped as a subchannel. Hence, we can formulate received power $P_{r_{i,j}}$ for the j-th subchannel as following:

$$
\begin{aligned}
P_{r_{i,j}} &= \sum_{k=1}^{M_{sub}} P_{r_{i,j,k}} \\
&= P_t(C_{i,j}) P_{Loss}(r_{i,j}) 10^{\frac{\xi_{i,j}}{10}} \left(\frac{1}{M_{sub}} \sum_{k=1}^{M_{sub}} (h_{i,j,k})^2 \right) \\
&= \left(\frac{1}{M_{sub}} P_t(C_{i,j}) \right) P_{Loss}(r_{i,j}) 10^{\frac{\xi_{i,j}}{10}} \left(\sum_{k=1}^{M_{sub}} z_{i,j,k} \right) \\
&= P_t(C_{i,j,k}) P_{Loss}(r_{i,j}) 10^{\frac{\xi_{i,j}}{10}} z_{i,j} \quad , \qquad (4.23)
\end{aligned}
$$

where $P_t(C_{i,j}) = M_{sub} \cdot P_t(C_{i,j,k})$. The $z_{i,j}$ is the effective subchannel gain which is the summation of M_{sub} sub-carriers gain and distributes as an Erlangian random variable with the pdf and cdf as following:

$$
f_Z(z) = \frac{z^{M-1} e^{-z}}{(M-1)!} \quad , \qquad (4.24)
$$

$$
F_Z(z) = 1 - \sum_{t=0}^{M-1} \frac{z^t e^{-z}}{t!} \quad . \qquad (4.25)
$$

However, the effective $SINR_{1,j}$ on the j-th subchannel of transmitter is located in cell 1 under a frequency-selective fading channel can be represented as

$$
SINR_{1,j} = \frac{P_t(C_{1,j}) P_{Loss}(r_{1,j}) 10^{\frac{\xi_{1,j}}{10}} z_{1,j}}{\sum_{i=2}^{I} P_t(C_{i,j}) P_{Loss}(r_{i,j}) 10^{\frac{\xi_{i,j}}{10}} z_{i,j} + N_0 W_c} \quad , \qquad (4.26)
$$

4.5.2 Success Probability without Inter-Cell Interference in a Frequency-Selective Fading Channel

The success probability without inter-cell interference under conditions of $z_{1,j}$,$r_{1,j}$, $\xi_{1,j}$ are given can be defined as

$$p_s^N\left(C_{1,j}|z_{1,j},r_{1,j},\xi_{1,j}\right)$$

$$= P_r\left\{SNR_{1,j} > r_{th}\right\}$$

$$= P_r\left\{\frac{P_t(C_{1,j})P_{Loss}(r_{1,j})10^{\frac{\xi_{1,j}}{10}}z_{1,j}}{N_0W_c} > r_{th}\right\}$$

$$= P_r\left\{z_{1,j} > r_{th}\frac{N_0W_c}{P_t(C_{1,j})P_{Loss}(r_{1,j})10^{\frac{\xi_{1,j}}{10}}}\right\}$$

$$= P_r\left\{z_{1,j} > \beta_j\right\}$$

$$= 1 - F_Z\left[\beta_j\right] \quad . \tag{4.27}$$

For considering the propagation distance $r_{1,j}$ and shadowing effects $\xi_{1,j}$, the success probability without inter-cell interference can be evaluated as:

$$p_s^N\left(C_{1,j}\right)$$

$$= \iint p_s^N\left(C_{1,j}|z_{1,j},r_{1,j},\xi_{1,j}\right)\cdot f_{R_{1,j}}(r_{1,j})f_\xi(\xi_{1,j})dr_{1,j}d\xi_{1,j}$$

$$= \iint \left\{1 - F_Z\left[\beta_j\right]\right\}\cdot f_{R_{1,j}}(r_{1,j})f_\xi(\xi_{1,j})dr_{1,j}d\xi_{1,j}$$

$$= \int_{-\infty}^{\infty}\iint_{S_1}\left[\sum_{t=0}^{M-1}\frac{\left(\beta_j\right)^t e^{-\beta_j}}{t!}\right]\cdot\frac{e^{-\frac{\left(\xi_{1,j}\right)^2}{2\sigma^2}}}{\sqrt{2\pi}\sigma}dx_{1,j}dy_{1,j}d\xi_{1,j} \quad , \tag{4.28}$$

4.5.3 Success Probability with Inter-Cell Interference in the Frequency-Selective Fading Channel

The success probability subjects to the inter-cell interference for the j-th subchannel in cell 1 under conditions of $z_{1,j}$,$r_{1,j}$,$\xi_{1,j}$,$z_{2,j}$,$r_{2,j}$ and $\xi_{2,j}$ are given can be defined as follows:

$$p_s^I\left(C_{1,j}, C_{2,j}|z_{1,j}, r_{1,j}, \xi_{1,j}, z_{2,j}, r_{2,j}, \xi_{2,j}\right)$$

$$= P_r\left\{SINR_{1,j} > r_{th}\right\}$$

$$= P_r\left\{\frac{P_t(C_{1,j})P_{Loss}(r_{1,j})\cdot 10^{\frac{\xi_{1,j}}{10}}z_{1,j}}{P_t(C_{2,j})P_{Loss}(r_{2,j})\cdot 10^{\frac{\xi_{2,j}}{10}}z_{2,j}+N_0W_c} > r_{th}\right\}$$

$$= P_r\left\{z_{1,j} > r_{th}\left(\frac{P_t(C_{2,j})}{P_t(C_{1,j})}\right)\left(\frac{P_{Loss}(r_{2,j})}{P_{Loss}(r_{1,j})}\right)10^{\frac{\xi_{2,j}-\xi_{1,j}}{10}}z_{2,j} + r_{th}\frac{N_0W_c}{P_t(C_{1,j})P_{Loss}(r_{1,j})\cdot 10^{\frac{\xi_{1,j}}{10}}}\right\}$$

$$= P_r\left\{z_{1,j} > \gamma_j z_{2,j} + \beta_j\right\}$$

$$= 1 - F_Z\left[\gamma_j z_{2,j} + \beta_j\right] \quad . \tag{4.29}$$

For considering effects of channel fading $z_{2,j}$, the equation (4.29) can be integrated by Gauss-Laguerre quadrature method. The numerical analysis Gauss-Laguerre quadrature is using for approximating the value of integrals like the following equation:

$$\int_0^{\infty} e^{-x} f(x)\,dx \approx \sum_{x=1}^{n} w_s f(x_s) \quad , \tag{4.30}$$

where x_s is the s-th root of Laguerre polynomial $L_n(x)$ and the weight w_s is given by

$$w_s = \frac{x_s}{(n+1)^2\left[L_{n+1}(x_s)\right]^2} \quad . \tag{4.31}$$

By using Gauss-Laguerre quadrature method, we can approximate the integration of $z_{2,j}$. Hence, the success probability under the conditions of $r_{1,j}$,$\xi_{1,j}$,$r_{2,j}$ and $\xi_{2,j}$ are given can be represented as following:

$$
\begin{aligned}
& p_s^I\left(C_{1,j}, C_{2,j} | r_{1,j}, \xi_{1,j}, r_{2,j}, \xi_{2,j}\right) \\
& = \int_0^\infty p_s^I\left(C_{1,j}, C_{2,j} | z_{1,j}, r_{1,j}, \xi_{1,j}, z_{2,j}, r_{2,j}, \xi_{2,j}\right) \cdot f_Z(z_{2,j}) dz_{2,j} \\
& = \int_0^\infty \left\{1 - F_Z\left[\gamma_j z_{2,j} + \beta_j\right]\right\} \cdot \frac{z_{2,j}^{M-1} e^{-z_{2,j}}}{(M-1)!} dz_{2,j} \\
& = \int_0^\infty \sum_{t=0}^{M-1} \frac{\left(\gamma_j z_{2,j} + \beta_j\right)^t e^{-(\gamma_j z_{2,j} + \beta_j)}}{t!} \cdot \frac{z_{2,j}^{M-1} e^{-z_{2,j}}}{(M-1)!} dz_{2,j} \\
& = \int_0^\infty e^{-z_{2,j}} \cdot \left[\sum_{t=0}^{M-1} \frac{\left(\gamma_j z_{2,j} + \beta_j\right)^t e^{-(\gamma_j z_{2,j} + \beta_j)}}{t!} \cdot \frac{z_{2,j}^{M-1}}{(M-1)!}\right] dz_{2,j} \\
& = \int_0^\infty e^{-z_{2,j}} \cdot f(z_{2,j}) dz_{2,j} \\
& \approx \sum_{s=1}^{n} w_s \cdot f\left(x_s\right) \ , \qquad (4.32)
\end{aligned}
$$

where

$$
f(x) = \sum_{t=0}^{M-1} \frac{\left(\gamma_j x + \beta_j\right)^t e^{-\gamma_j x + \beta_j}}{t!} \cdot \frac{x^{M-1}}{(M-1)!} \ . \qquad (4.33)
$$

Then, we can also use the equation (4.21) and (4.22) to calculate $p_s^I(C_{1,j}, C_{2,j})$ under a frequency-selective fading channel.

4.6 Various Traffic Probability in Two Cell Environment

4.6.1 Wireless Access Points in Queueing System

We model data transmissions and arrival data calls as a birth-death process [25], [26] and [27]. Each incoming calls arrives and leaves according to Poisson process with λ and

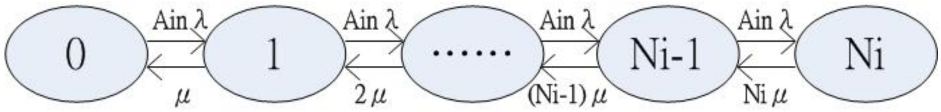

Figure 4.3: Markov chain of transmission state for the inner region.

μ. According to different uplink/downlink service requirements of two cells, each MS arriving at its serving cell will request the uplink/downlink requirement which is same as the requirement of the base station that can support. The statistical traffic model is Markov chain with $M/M/m/m$, where m is the maximum number of MS that can be served in the system. The transmission state probability is given by the product form [28]:

$$\Pi(c) = \frac{\frac{\rho^c}{c!}}{\tau}, \tag{4.34}$$

$$\tau = \sum_{c=0}^{m} \frac{\rho^c}{c!}, \quad \rho = \frac{\lambda}{\mu} \quad ,$$

where $\Pi(c)$ is the probability of c MSs arrive in the cell and τ is a normalization constant.

We allocate the number of subchannels to two regions (inner and outer) labelled N_{in} and N_o according to number of subchannels that can be used.

Inner region

The inner region can be modelled a $M/M/N_{in}/N_{in}$ queueing system as shown in Fig. 4.3:

$$\Pi^{in}(c^{in}) = \frac{\frac{(\rho_{in})^{c^{in}}}{c^{in}!}}{\tau^{in}} \quad , \tag{4.35}$$

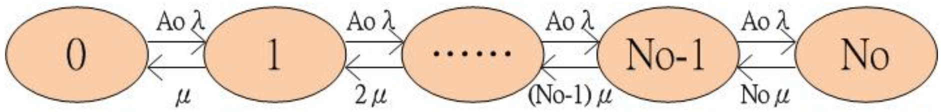

Figure 4.4: Markov chain of transmission state for outer region.

where

$$0 \le c^{in} \le N_i, \ \ \tau^{in} = \sum_{c^{in}=0}^{N_i} \frac{(\rho_{in})^{c^{in}}}{c^{in}!}, \ \ \rho_{in} = A_{in}\frac{\lambda}{\mu} \ \ ,$$

$$N_i = m \cdot A_{in}, \ \ A_{in} = \frac{\pi\,(r_{in})^2}{A}, \ \ A = \frac{3\sqrt{3}}{2}r^2 \ \ ,$$

where r_{in} is the inner region radius, r is cell radius and A is the cell area..

Outer region

The outer region can be modelled a $M/M/N_o/N_o$ queue system like Fig. 4.4:

$$\Pi_o(c_o) = \frac{\frac{(\rho_o)^{c_o}}{c_o!}}{\tau_o} \ \ , \tag{4.36}$$

where

$$0 \le c^{o} \le N_o, \ \ \tau^{o} = \sum_{c^{o}=0}^{N_o} \frac{(\rho_o)^{c^{o}}}{c^{o}!}, \ \ \rho_o = A_out\frac{\lambda}{\mu} \ \ ,$$

$$N_o = m \cdot A_out \cdot \frac{1}{FFR}, \ \ A_out = \frac{A - \pi\,(r_{in})^2}{A} \ \ ,$$

where A_o is the ratio that MSs locates at outer region and FFR is the frequency reuse factor in outer region.

Full loading rate

Each cell allocates N_{in} subchannels to arriving MSs at the inner region and N_o subchannels be supported for MSs arrive at the outer region according to the uplink and downlink requirement of the MS within one time slots. If the subchannels or time slots are not enough to serve MS requirement, the MS's request will be blocked immediately. Thus, the system with full loading rate can be written as:

$$\chi = A_{in} \cdot \Pi^{in}(N_{in}) + A_o \cdot \Pi^{o}(N_o) \ . \tag{4.37}$$

4.6.2 Various Traffic Probability of the Transmission Mode in Cell 1 (C_1) is Given

Using the queueing theory and regular assignment approach, we can analyze the probability of arriving numbers of MS in each region. We can use the following method to analyze $P_r(C_2|C_1$ is given) that causes in the inner region.

For **uplink case**, the *non-cross probability* in cell 1 on j-th subchannel is

$$P_r(C_{2,j} = U|C_{1,j} = U) = \sum_{c_1^{in}=0}^{N_{in}} P_r(C_2 = U|C_{1,j} = U, c_1^{in})P_r(c_1^{in}) \ , \tag{4.38}$$

where

$$\begin{aligned} &P_r(C_{2,j} = U|C_{1,j} = U, c_1^{in}) \\ &= \sum_{c_2^{in}=0}^{N_{in}} \Pi_2^{in}(c_2^{in}) \cdot \min\{1, \frac{\text{UL slots in cell 2}}{\text{UL slots in cell 1}}\} \\ &= \sum_{c_2^{in}=0}^{N_{in}} \Pi_2^{in}(c_2^{in}) \cdot \min\{1, \frac{T(c_2^{in}\Delta_2^{UL}, N_{in}, j)}{T(c_1^{in}\Delta_1^{UL}, N_{in}, j)}\} \ . \end{aligned} \tag{4.39}$$

Note that the term of $T(\cdot,\cdot,\cdot)$ in (4.39) is defined as:

$$T(a, b, j) = \lfloor \frac{a}{b} \rfloor + \psi(a, b, j) \ , \tag{4.40}$$

where the indicator function is defined as:

$$\psi(a,b,j)=\begin{cases}1\ , & \text{if } j\le(a\ \ mod\ \ b)\\ 0\ , & \text{if } j>(a\ \ mod\ \ b)\ .\end{cases} \tag{4.41}$$

The *cross probability* for uplink case in cell 1 on j-th subchannel is

$$P_r(C_{2,j}=D|C_{1,j}=U)=\sum_{c_1^{in}=0}^{N_{in}} P_r(C_{2,j}=D|C_{1,j}=U,c_1^{in})P_r(c_1^{in})\ , \tag{4.42}$$

where

$$\begin{aligned}&P_r(C_{2,j}=D|C_{1,j}=U,c_1^{in})\\ &=\sum_{c_2^{in}=0}^{N_{in}}\Pi_2^{in}(c_2^{in})\cdot\max\{0,\frac{\text{crossed slots}}{\text{UL slots in cell 1}}\}\\ &=\sum_{c_2^{in}=0}^{N_{in}}\Pi_2^{in}(c_2^{in})\cdot\max\{0,\frac{T(c_1^{in}\Delta_1^{UL},N_{in},j)+T(c_2^{in}\Delta_2^{DL},N_{in},k)-N}{T(c_1^{in}\Delta_1^{UL},N_{in},j)}\}\ .\end{aligned} \tag{4.43}$$

The probability of the j-th subchannel is unused in cell 2, while that in cell 1 in the uplink mode is

$$P_r(C_{2,j}=X|C_{1,j}=U)=1-\{P_r(C_{2,j}=U|C_{1,j}=U)+P_r(C_{2,j}=D|C_{1,j}=U)\}\ . \tag{4.44}$$

For the **downlink** case, the *non-cross probability* in cell 1 on j-th subchannel is

$$P_r(C_{2,j}=D|C_{1,j}=D)=\sum_{c_1^{in}=0}^{N_{in}} P_r(C_{2,j}=D|C_{1,j}=D,c_1^{in})P_r(c_1^{in})\ , \tag{4.45}$$

where

$$P_r(C_{2,j} = D | C_{1,j} = D, c_1^{in})$$
$$= \sum_{c_2^{in}=0}^{N_{in}} \Pi_2^{in}(c_2^{in}) \cdot \min\{1, \frac{\text{DL slots in cell 2}}{\text{DL slots in cell 1}}\}$$
$$= \sum_{c_2^{in}=0}^{N_{in}} \Pi_2^{in}(c_2^{in}) \cdot \min\{1, \frac{T(c_2^{in}\Delta_2^{DL}, N_{in}, j)}{T(c_1^{in}\Delta_1^{DL}, N_{in}, j)}\} \ . \quad (4.46)$$

The *cross probability* of cell 1 on j-th subchannel in the downlink case is

$$P_r(C_{2,j} = U | C_{1,j} = D) = \sum_{c_1^{in}=0}^{N_{in}} P_r(C_{2,j} = U | C_{1,j} = D, c_1^{in}) P_r(c_1^{in}) \ , \quad (4.47)$$

where

$$P_r(C_{2,j} = U | C_{1,j} = D, c_1^{in})$$
$$= \sum_{c_2^{in}=0}^{N_{in}} \Pi_2^{in}(c_2^{in}) \cdot \max\{0, \frac{\text{crossed slots}}{\text{DL slots in cell 1}}\}$$
$$= \sum_{c_2^{in}=0}^{N_{in}} \Pi_2^{in}(c_2^{in}) \cdot \max\{0, \frac{T(c_1^{in}\Delta_1^{DL}, N_{in}, j) + T(c_2^{in}\Delta_2^{UL}, N_{in}, j) - N}{T(c_1^{in}\Delta_1^{DL}, N_{in}, j)}\} \ . \quad (4.48)$$

Further, the probability of the kth subchannel is unused in cell 2 and cell 1 transmits downlink signal is

$$P_r(C_{2,j} = X | C_{1,j} = D) = 1 - \{P_r(C_{2,j} = U | C_{1,j} = D) + P_r(C_{2,j} = D | C_{1,j} = D)\} \ . \quad (4.49)$$

Thus, the average total subchannels that are used in the inner region can help compute $P_r(C_2|C_1)$ just like following equation,

$$P_r\left(C_2|C_1\right) = \frac{1}{N_{in}}\left[\sum_{j=1}^{N_{in}} P_r\left(C_{2,j}|C_{1,j}\right)\right] \quad . \tag{4.50}$$

Then, we can analyze the result total success probability (4.8) and the related parameters are listed in Table 4.1.

4.7 Numerical Results

In this chapter, we investigate the outage performance for the FFR-based TDD-OFDMA system in the full loading case. Note that the full loading case yields higher probability of generating the cross-slot interference. The arriving MSs are assumed to be uniformly distributed in a cell and request the time slots for uplink and downlink within a TDD-frame duration during a period of serving time. Let the numbers of uplink and downlink slots in cell 1 is symmetric traffics ($\triangle_1^{DL}$:$\triangle_1^{UL} = 7 : 7$) and the interfering cell 2 has vary downlink/uplink ratios. That is, CTS=-6 $\backsim$ 6. We analyze and simulate the success probability versus the inner radius for various CTS region between cell 1 and cell 2. We demonstrate how the inner radius be designed to maximize spectrum utilization subject to the required success probability.

Flat-Fading Channel

In Fig. 4.5, the success probability is evaluated according to the equation (4.8) for various CTS environments. As shown in the figure, this analysis method can compute the success probability for the FFR-based TDD-OFDMA system. The little inaccuracy may be caused by limitation simulation time. While size of inner region is small, the success probability can be maintained higher than link reliability requirement (> 0.9). However, the larger

Table 4.1: Simulation Parameters in Two-Cell Environment.

Parameter	Value
Number of Macrocells (I)	**2**
Number of time slots for TDD-frame (N)	**14**
Δ^{DL}:Δ^{UL} in cell 1	**7:7**
Radius of Macrocell	**1000 m**
Carrier Frequency (f_c)	**2500 MHz**
System Bandwidth (W)	**10 MHz**
BS/MS Antenna	**Omni-directional**
BS/MS Transmit Power (P_{bs}/P_{ms})	**43dBm /27 dBm**
Noise Power Spectrum Density (N_0)	**-174 dBm/Hz**
Standard Deviation between BS to BS (σ_{bs})	**3dB**
Standard Deviation between MS to BS (σ_{ms})	**10dB**
Pathloss Exponent Factor (α)	**4**
Outage Threshold (γ_{th})	**0 dB**
link reliability	**0.9**
FFT size (M)	**1024**
Sub-carrier Bandwidth (W_{sub})	**10.938 kHz**
Number of Null Sub-carriers	**184**
Number of Pilot Sub-carriers	**120**
Number of Data Sub-carriers	**720**
Number of Sub-channels (m)	**40**
Sub-carriers in each sub-channel	**18**

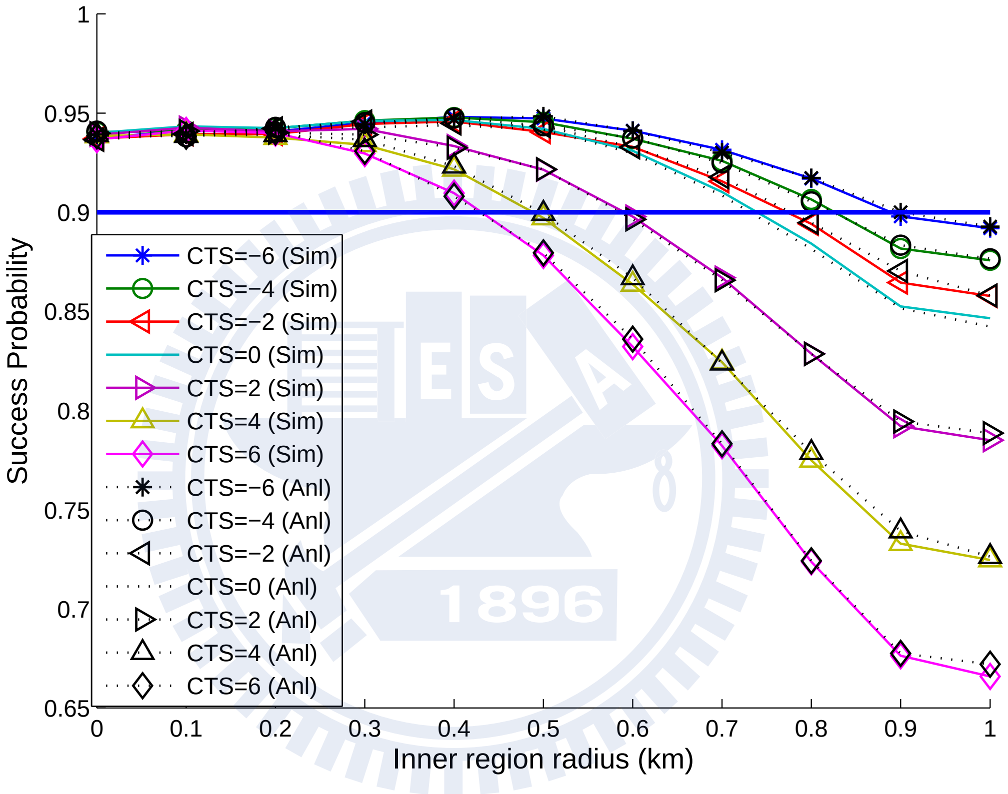

Figure 4.5: Effects of asymmetric traffic ratios on the size of inner region under the flat-fading channel in FFR-based TDD-OFDMA systems.

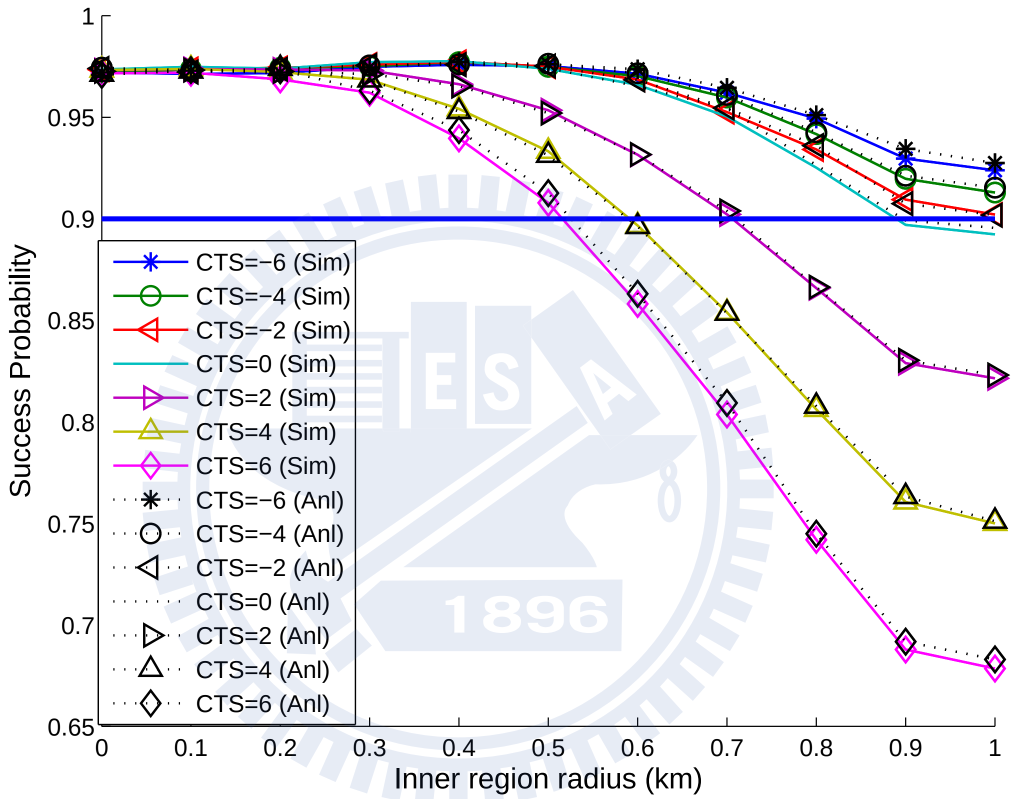

Figure 4.6: Effects of asymmetric traffic ratios on the size of inner region under the frequency-selective fading channel in FFR-based TDD-OFDMA systems.

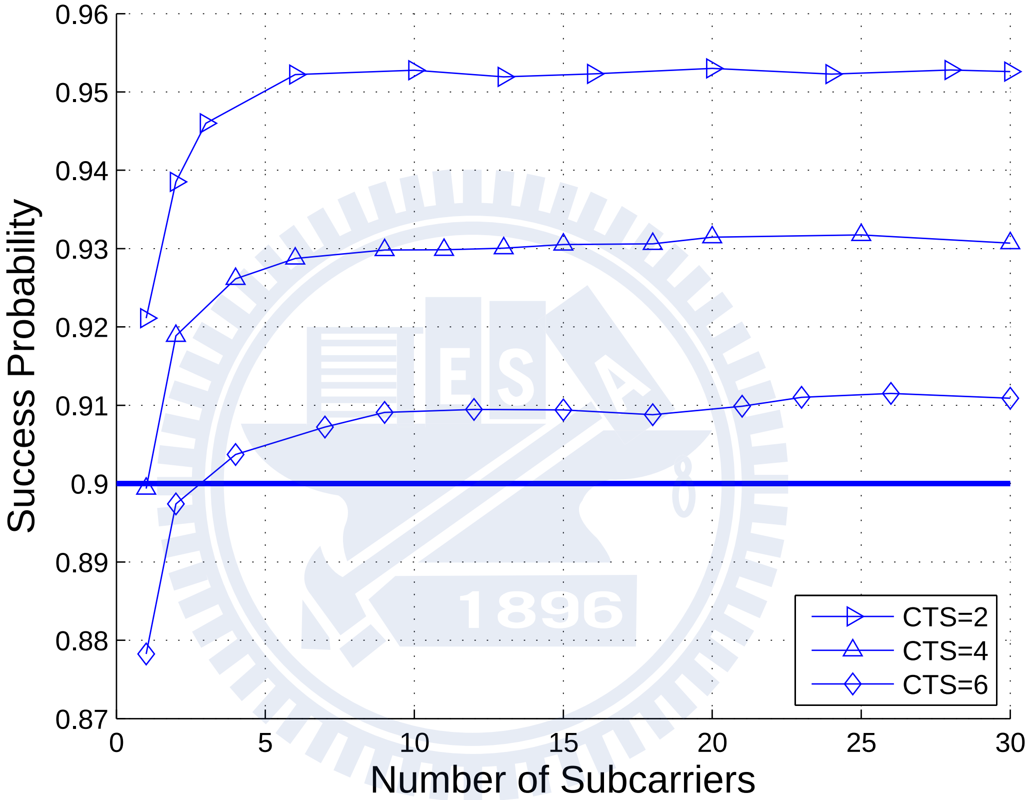

Figure 4.7: Effects of frequency diversity gain under the frequency-selective fading channel in FFR-based TDD-OFDMA systems with inner region radius equals to 500 m.

inner region radius is determined, more subchannel units are allocated in inner region. The success probability is higher than system is unused inner region, because the subchannels be assigned to MS located in inner region will have higher received signal power than MS located in outer region. Nevertheless, if inner region size is too large, the serious inter-cell interference will degrade SINR levels and decrease success probability. For the various traffic environment, we can observe that the CTS=6 that will generate serious BS-to-BS cross-slot interference. Hence, the system must reduce the inner radius to 400 meters to guarantee the success probability at the cost of sacrificing spectrum efficiency. For CTS=-6, the system can increase the inner radius up to 900 meters to increase spectrum efficiency because of MS-to-MS cross-slot interference just have minimal degradation for receive SINR. Therefore, we can adaptively design the inner radius for various CTS values to reduce the effects of cross-slot interference and maintain success probability in the FFR-based TDD-OFDMA systems.

Frequency-Selective Fading Channel

The numerical result of the frequency-selective fading channel with 18 subcarriers are grouped as a subchannel is shown in Fig. 4.6. We can observe the analytical approach almost matches simulation result and little error may be caused by limitation simulation time and number of arrival MSs. Comparison results of Fig. 4.5 and Fig. 4.6, we can realize there will has some advantages to improve success probability in the frequency-selective fading. It almost improve 0.03 in the frequency-selective fading channel than in flat-fading channel because of the frequency diversity gain. Fig. 4.7 shows the success probability versus the number of subcarriers are grouped as a subchannel for cell 1 receivers receive serious inter-cell interference with CTS=[2,4,6] and inner region radius design as 500 m. More than one subcarriers are grouped as a subchannel will get frequency diversity gain. However, it will approximate a maximum value no matter how many subcarriers are increased for grouping a subchannel. In the two-cell scenario, if the number of subcarriers is almost larger than 5, the outage performance will not be better.

Now we consider the worst case of CTS=7 and traffic load $\rho = \frac{\lambda}{m\mu} = 1$ to do a simulation to observe the probability of generating cross-slot interference for randomly and regularly assignment approach. We can using (4.38), (4.42), (4.45), (4.47) to analyze the probability of generating each inter-cell interference. As we know, the probability of $[C_1, C_2] = (U, U)$ and $[C_1, C_2] = (D, U)$ is zero because CTS=7 and observed cell 1 is symmetric traffic. As simulation shown, Fig. 4.10 illustrates the randomly assignment will has higher cross probability (the case of $[C_1, C_2] = (U, D)$) than the regular assignment shown in Figs. 4.8, 4.9. Hence, using the regular method to assign resource to MS can limit the probability of generating cross-slot interference especially when traffic load is low. From simulation result of Figs. 4.5, 4.6, 4.8 and 4.9, we can realize the analytical approach can help us to design FFR factors and calculate probability of generating each inter-cell interference as more accuracy.

4.8 Conclusions

In this chapter, we propose an analytical approach to find out the suitable inner region size to guarantee the link reliability in a FFR-based TDD-OFDMA system. In addition, we adopt the queueing theorem to analyze the full loading case for time-frequency resource allocation method in a TDD-OFDMA system. As the simulation results shown, the analytical approach can effectively help design the inner region size of FFR system in the multi-cellular environment with various ratios of the uplink to downlink traffics among cells.

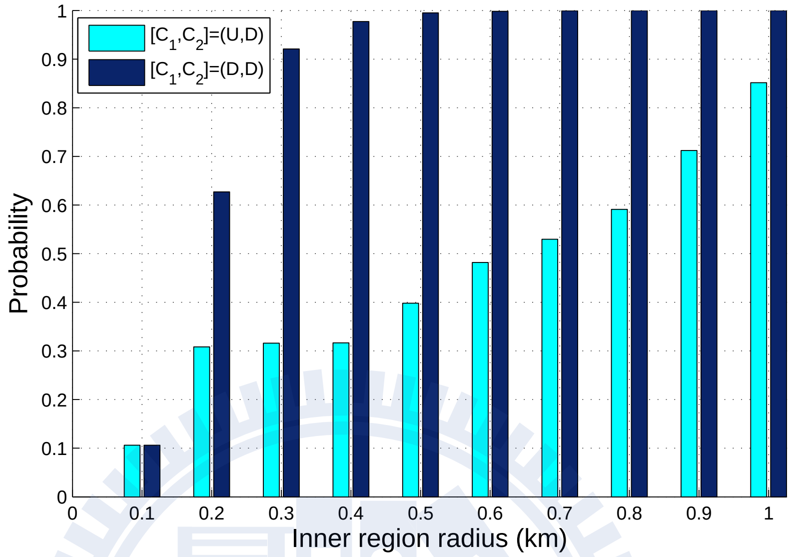

Figure 4.8: Probability of each interference with regular resource assignment (Analysis).

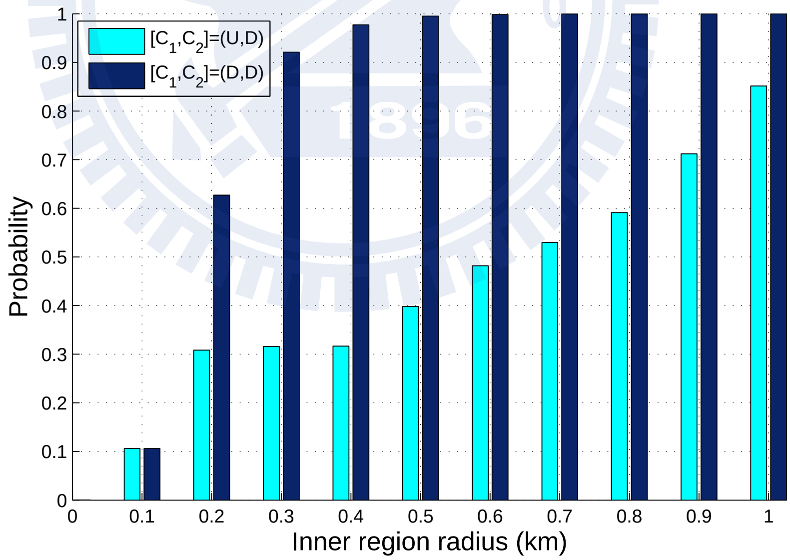

Figure 4.9: Probability of each interference with regular resource assignment (Simulation).

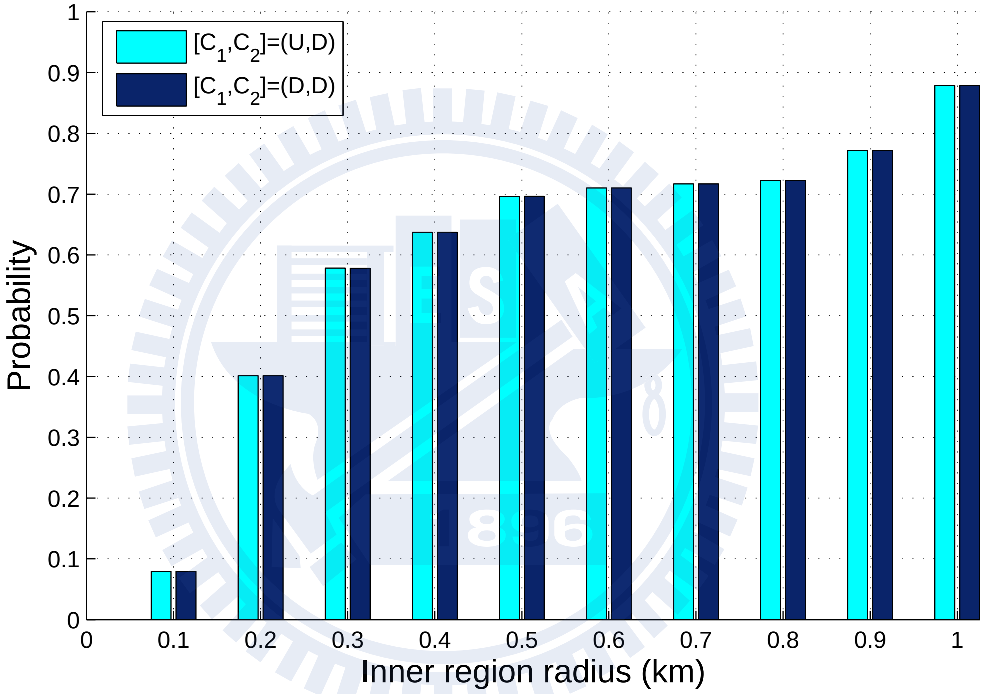

Figure 4.10: Probability of each interference with random resource assignment.

CHAPTER 5

Outage Performance Analysis for Fractional Frequency Reused TDD-OFDMA Systems with Asymmetric Traffics: Multi-Cellular Case

In this chapter, we consider FFR based TDD-OFDMA multi-cellular systems to investigate the effects of inter-cell interference especially the cross-slot interference while supporting asymmetric traffics. In multi-cellular systems, each cell will be surround in a strong inter-cell interference environment while the frequency reuse is one. Furthermore, the FFR schemes is an effective approach to solve the problems of inter-cell interference because FFR scheme separates different frequency bandwidth to different cells and assigns this group of bandwidth regularly for saving spectrums and reduce the effects of inter-cell interference.

In TDD-OFDMA multi-cellular systems with asymmetric traffic services, the neighboring cells may execute different transmission modes, such as uplink or downlink. The serious BS-to-BS cross-slot interference affect the design factors of FFR scheme. However, the higher flexibility in supporting various uplink/downlink is determined, the more spectrum most be sacrificed to maintain link reliability. Thus, spectrum usage ratio and effects of inter-cell interference become the trade off especially in supporting asymmetric traffic environments. In this chapter, we investigate relationship between various traffic ratios and the effects of inter-cell interference in the FFR based TDD-OFDMA multi-cellular system

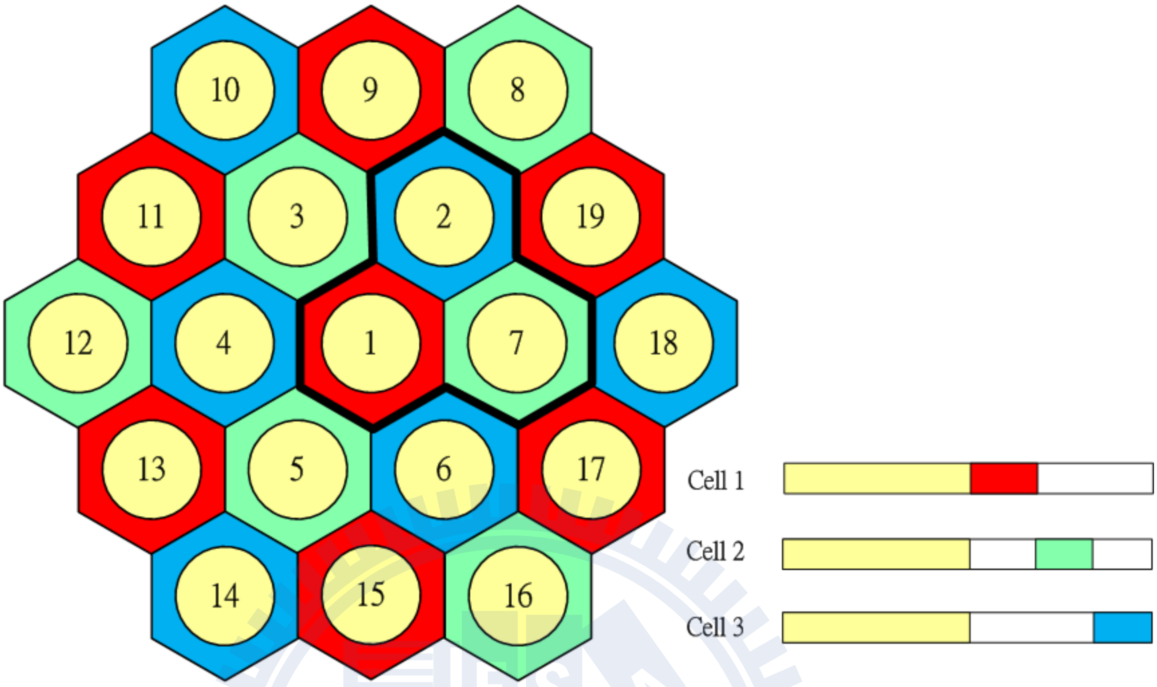

Figure 5.1: The architecture of a 19-cell system by employing interference avoidance at outer region scheme of FFR and determine outer region reuse factor is three.

for acquiring higher system throughput with guaranteeing the link reliability.

5.1 System Model

5.1.1 Multi-Cellular Scenario

We consider 19-cell multi-cellular environment that are labelled 1,2,....,19 and employee FFR scheme in a TDD-OFDMA system. There are traditional frequency reuse scheme and FFR scheme will be explored and design each factors dynamically in this chapter. Traditional frequency reuse scheme is effective to reduce the effects of inter-cell interference, but it extremely decades total frequency bandwidth which can be used in a cell. For instance,

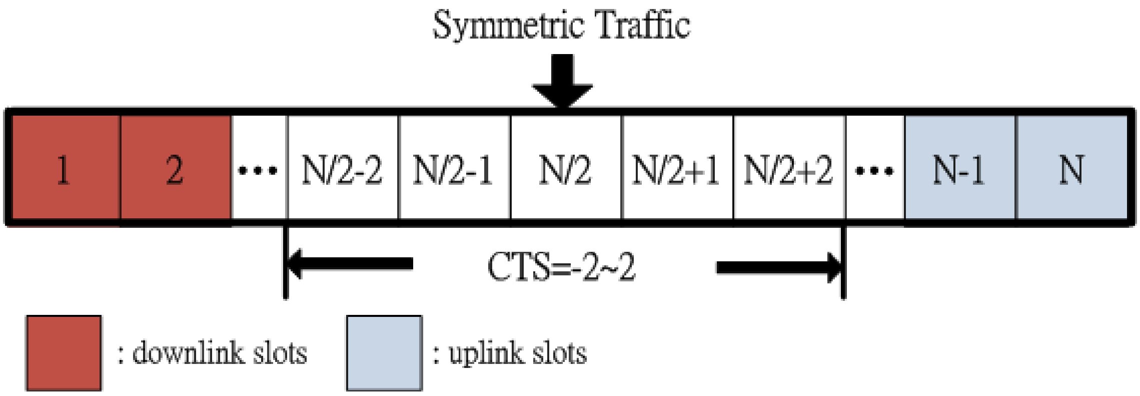

Figure 5.2: The definition of random asymmetric traffics and cross time slot region in multi-cellular TDD-OFDMA system.

traditional frequency reuse scheme with reuse factor is three that can avoid inter-cell interference from first tier since BS only uses a third spectrum in a cell coverage. Thus, traditional frequency reuse scheme is improved to FFR scheme that can increase spectrum usage ratio and also against inter-cell interference for MS locates in outer region and maintain its link quality. On the other hand, traditional frequency reuse scheme is a special case of FFR scheme while the size of inner region is none just likes Fig. 5.1. For considering a various asymmetric traffic in the multi-cellular system, the strong cross-slot interference will play an important issue on system performance. Hence, we must suitable design several factors, such as size of inner region , frequency reuse factor, and subchannel allocation in each region within a group.

5.1.2 Random Asymmetric Traffic in Multi-Celluar Systems

In this thesis, the random asymmetric traffic (Δ_{rand}) is defined as a dynamic switching point that means the ratios of uplink and downlink slot within a frame length N. The Δ_{rand} presents downlink slots of cell's requirements and $N - \Delta_{rand}$ presents uplink slots requirement. However, Δ_{rand} could be changed dynamically by considering current uplink/downlink traffic requirement.

In the traditional wireless transmission systems, symmetric traffics is always determined for supporting voice and text message transmissions. In the asymmetric traffic environments, system will allow a CTS size for each BS and the Δ_{rand} can be determined by $\frac{N}{2}$+CTS. It means the beginning of time slot toward the Δ_{rand}-th time slot is used for downlink transmission. On the other hand, the $\Delta_{rand} + 1$ to the end of frame is executing uplink transmission.

For supporting asymmetric traffics arbitrarily, the Δ_{rand} may be changed within a CTS region in a multi-cellular environment that illustrated in Fig. 5.2. The CTS is introduced in Chapter 4. However, the CTS value is determined by comparing with the cell's uplink/downlink traffic and asymmetric traffic. The negative value of CTS means the BS supports less downlink than symmetric traffic system. Oppositely, positive value of CTS is that the system has more downlink slots can be used than symmetric traffic systems. Hence, larger region of CTS can be supported in multi-cellular systems, the higher probability of generating cross-slot interference and seriously degrade system throughput and link reliability.

5.2 Performance Metrics

5.2.1 Signal to Interference-Plus-Noise Ratio (SINR)

For each BS and MS transmission links, subcarriers receive signal and interference power from serving MS and neighboring cells, respectively. In wireless transmissions, the k-th subcarrier for serving m-th MS receives signal power level as following:

$$P_{Rx}^{m}(k) = \frac{P_{Tx}^{m} \cdot P_{Loss}^{m} \cdot |h_m(k)|^2}{M} \quad , \tag{5.1}$$

where P_{Tx}^{m} is total transmit power from BS or m-th MS that labelled as P_{bs} and P_{ms}, respectively. We consider $|h_m(k)|^2$ as the frequency selective multi-path channel fading that is described by the Stanford University Interim-3 (SUI-3) channel model which has three taps with different distribution delays [29]. M is the total number of subcarriers in the system. However, the P_{Loss}^{m} is the path loss just like equation (4.1).

There are I cells in the multi-cellular system and the m-th MS locates at cell 1. For considering the inter-cell interference power level with co-channel bandwidth at the k-th subcarrier of m-th MS is formulated as:

$$P_{ICI}^{m}(k) = \sum_{c=2}^{I} P_{ICI}^{c,m}(k) = \sum_{c=2}^{I} \frac{P_{Tx}^{c,m} \cdot P_{Loss}^{c,m} \cdot |h_{c,m}(k)|^2}{M} \quad , \tag{5.2}$$

where $P_{ICI}^{c,m}(k)$ is inter-cell interference power level from the c-th cells that may execute uplink or downlink transmission. I is the number of inter-cell interference sources. Hence, the SINR of each m-th MS on the k-th subcarrier is:

$$SINR^{m}(k) = \frac{P_{Rx}^{m}(k)}{N_0 \cdot W_{sub} + P_{ICI}^{m}(k)} = \frac{P_{Rx}^{m}(k)}{N_0 \cdot W_{sub} + \sum_{c=2}^{I} \frac{P_{Tx}^{c,m} \cdot P_{Loss}^{c,m} \cdot |h_{c,m}(k)|^2}{M}} \quad , \tag{5.3}$$

where N_0 is thermal noise density and W_{sub} is size of bandwidth be used on m-th subcarrier.

In a TDD-OFDMA system, the subchannel is smallest unit for transmitting signal. Each subchannel is grouped by several subcarriers. Hence, we can use the mean instantaneous capacity (MIC) approach to calculate the effective SINR on a subchannel. The MIC approach is introduced in next section.

5.2.2 Effective SINR and Mean Instantaneous Capacity (MIC)

In the wireless system with frequency-selective fading channel, we can compute the instantaneous capacity by considering instantaneous channel state. Hence, a mean instantaneous capacity approach is used to calculate effective SINR and capacity for a subchannel in the OFDMA system. By using the shanon capacity formulation, the capacity of the k-th subcarrier for m-th MS is formed as:

$$C^{m}(k) = \log_2 (1 + SINR^{m}(k)) \quad . \tag{5.4}$$

(5.5)

However, the MIC approach by averageing per subcarrier capacities to compute capacity of a subchannel is following:

$$MIC = \frac{1}{M_{sub}} \sum_{k=1}^{M_{sub}} C^{m}(k) \quad , \tag{5.6}$$

(5.7)

where M_{sub} is number of subcarriers groups a subchannel and compute effective SINR as $SINR_{eff}$ of each subchannel formulated as:

$$\log_2 (1 + SINR_{eff}) = MIC \tag{5.8}$$

$$\Rightarrow \; SINR_{eff} = 2^{MIC} - 1 \quad , \tag{5.9}$$

(5.10)

where effective SINR of per subchannel is computed according to the location of transmitter and receive, the channel gain of the subcarriers combined as a subchannel, and per subcarrier interfers from neighboring cells. In addition, if the effective SINR is less than outage threshold r_{th}, the transmission link can not be demodulated that just like equation (4.7). Hence, we must guarantee the link reliability in our simulation for the FFR based TDD-OFDMA system with supporting asymmetric traffics.

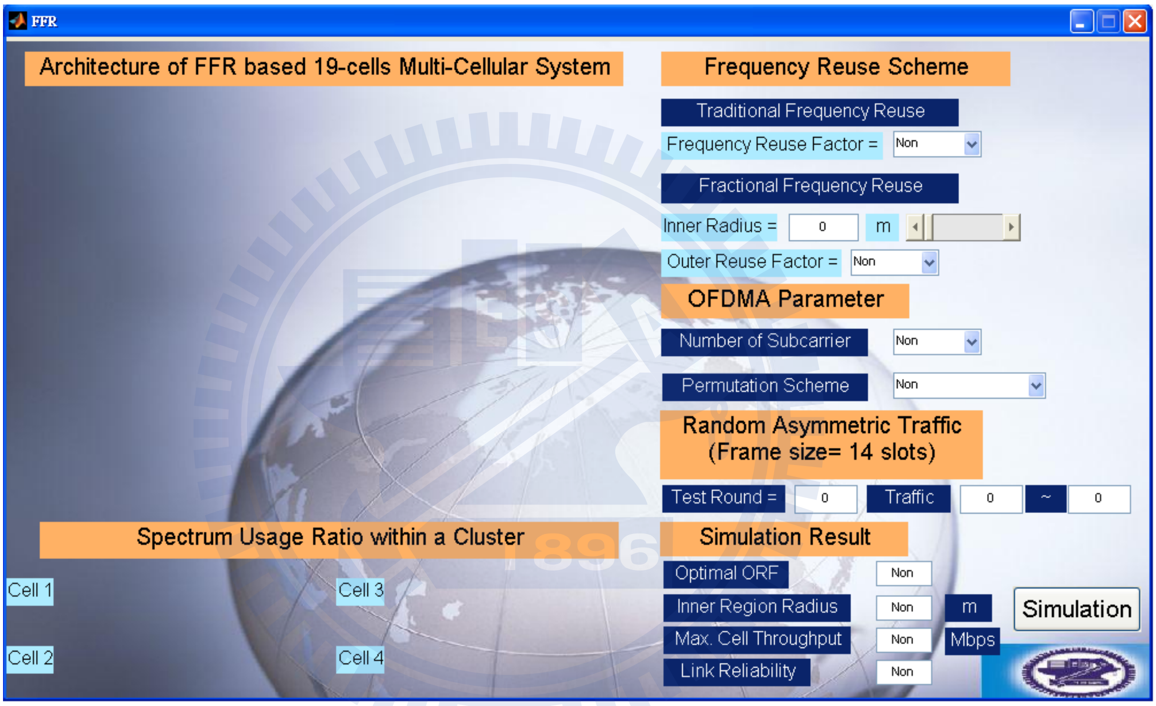

Figure 5.3: The initial state of GUI interface.

5.3 GUI Interface of FFR based TDD-OFDMA for Supporting Random Asymmetric Traffic Environment

We develop a tool on GUI interface of FFR based TDD-OFDMA system to dynamically change random asymmetric traffics and simulate results of system performance for traditional frequency reuse and FFR scheme. We can use this tool to realize how to implement system architectures of traditional frequency reuse and FFR scheme and how to allocate size of spectrum can be used in each region no matter inner region or outer region. Fig. 5.3 is the initial state of this simulation tool that divides into six group on the GUI interface.

First, architecture of FFR based 19-cells multi-cellular system is illustrated on the upper left corner that can show a 19-cells multi-cellular with cell radius equals to 1000 m and divides each cells into inner and outer region. Second, the spectrum usage ratio within a cluster is shown on the lower left corner. For each FFR design factors, each cells can use different size of spectrum. Thus, the spectrum planning can be observed on this part. Third, several design parameters of traditional frequency reuse and FFR scheme will be determined on the upper right corner. Traditional frequency reuse scheme must determine frequency reuse factor to reduce effects of inter-cell interference. For example, traditional frequency reuse scheme with frequency reuse factor equals to three is shown in Fig. 5.4. There are three cells grouped of a cluster and each cell just can use one third of frequency spectrum. In Fig. 5.5, the FFR scheme must consider size of inner region by adjusting inner region radius from zero to cell radius. The selection of outer reuse factor is used to reduce effects of inter-cell interference while MS request bandwidth at outer region. Larger number of outer reuse factor be determined, lower spectrum usage in each cell and less inter-cell interference will be received. However, FFR scheme with outer region reuse factor can use more spectrum than traditional frequency reuse scheme with frequency reuse factor equals to three.

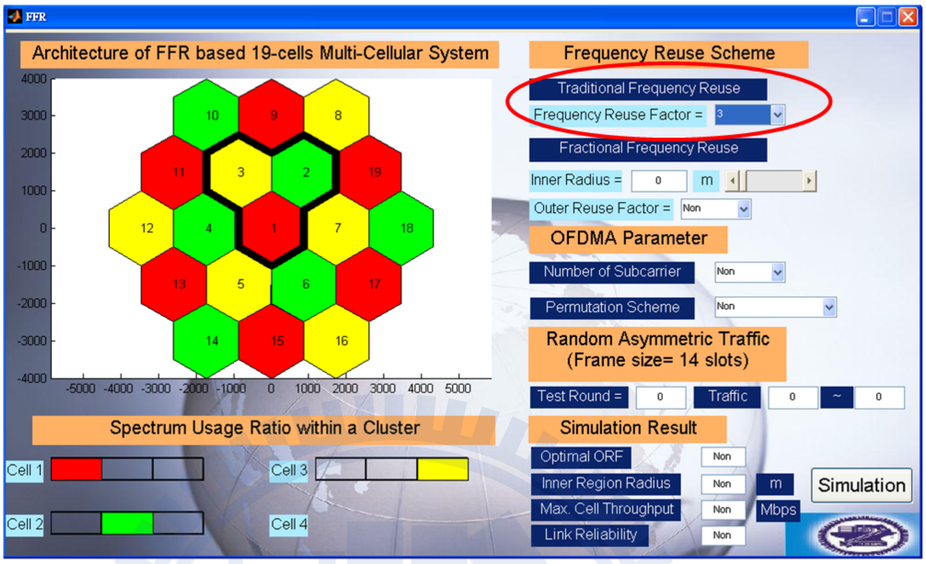

Figure 5.4: Setup frequency reuse factor of traditional frequency reuse scheme.

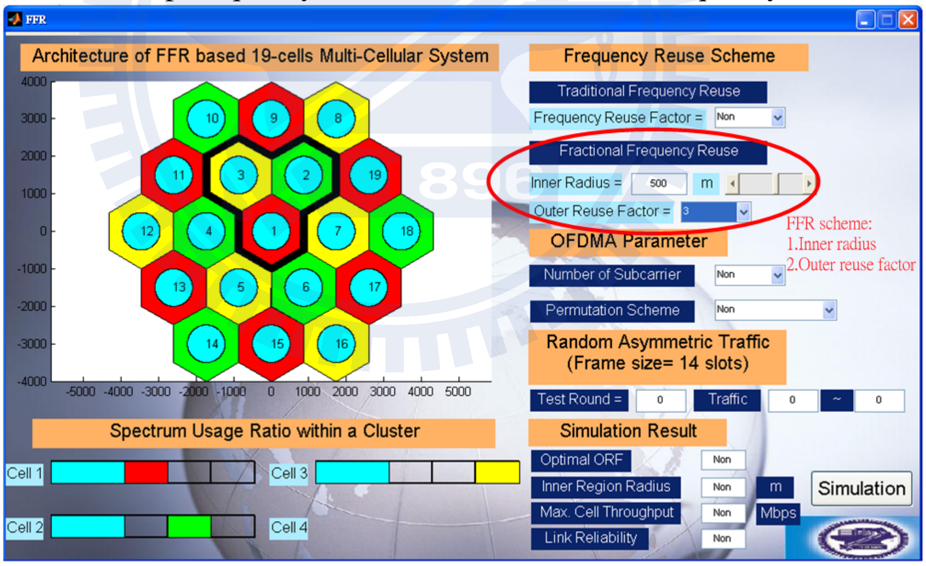

Figure 5.5: Setup design parameters of FFR scheme including inner radius and outer region reuse factor.

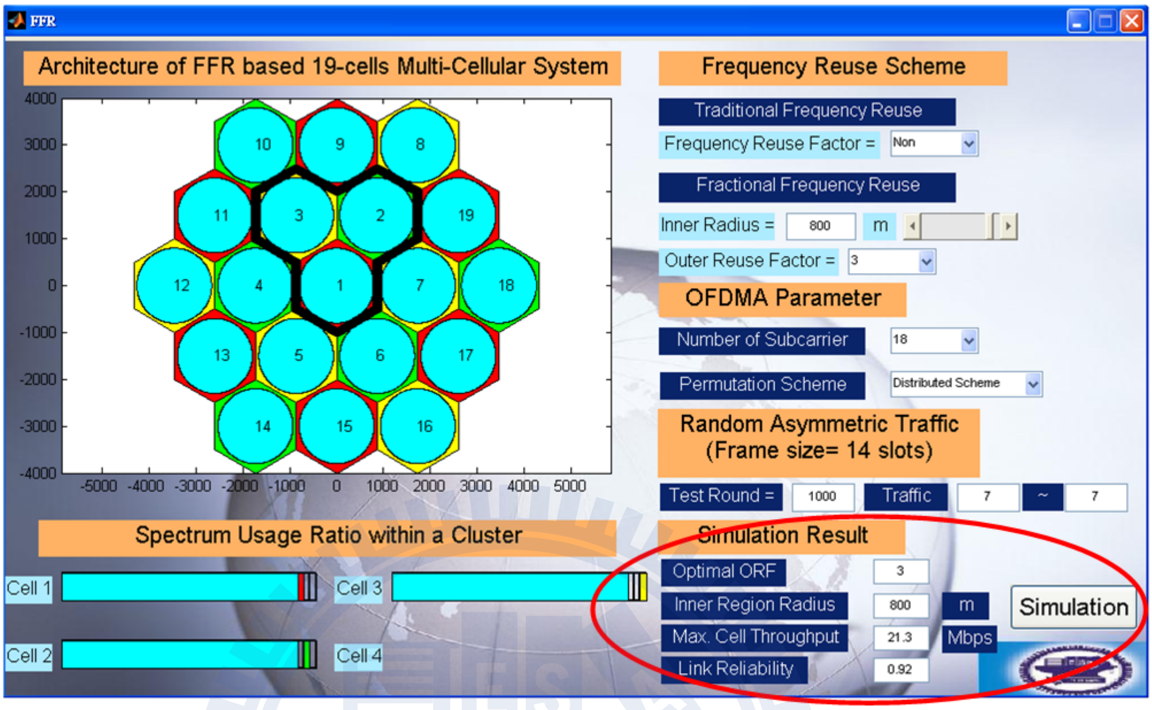

Figure 5.6: Cell throughput and link reliability for optimal design FFR factors.

Next, the block of the OFDMA parameter can select different types of the numbers of subcarrier are grouped a subchannel and permutation scheme to simulate numerical results. However, the random asymmetric traffics also are determined by considering test round and Δ_{rand} range. The test round is associated for simulation round of various traffics in each cell that means average samples of simulation. The Δ_{rand} range is used to determined range of random asymmetric traffics ($\Delta_{DL} : \Delta_{UL} = \Delta_{rand} : (N - \Delta_{rand})$). If large Δ_{rand} is supported, higher probability of generating strong cross-slot interference. However, we can push down the Simulation button to simulate inner region radius v.s link reliability and inner region radius v.s cell throughput for traditional frequency reuse scheme and FFR scheme. As using simulation result to find out optimal design factors of FFR scheme at random asymmetric traffic environment. Finally, we can find out the optimal design factors of inner region radius and outer region reuse factor to achieve maximum cell throughput with guaranteeing link reliability that is shown on the lower right corner just likes Fig. 5.6. The architecture of FFR based TDD-OFDMA and spectrum usage ratio will adjust to the optimal design. There are some simulation parameters are shown in Table. 5.1.

5.4 Numerical Results

We consider FFR technique based the TDD-OFDMA system for supporting asymmetric traffic. There are 40 arriving MSs supposed to be uniformly distributed in a cell and request the time slots for uplink and downlink within a TDD-frame duration during a period of serving time. The MS can only request the numbers of uplink and downlink time slot for the cell can support it. There are several permutation schemes can be selected in the simulation platform, such as adjacent subcarrier permutation, distributed permutation and Band AMC permutation. However, we can simulate different numbers of subcarrier are grouped a subchannel for transmitting signal which may be one, four, nine and 18. We also compare with the effects of frequency selective fading and flat fading. The shadowing fading is also be considered in this chapter. Thus, a subchannel is expected to experience permutation scheme, numbers of subcarrier are grouped a subchannel, specific propagation, interference conditions and specific channel fading. We simulate the throughput v.s. inner radius for various region reuse factor and link reliability v.s inner radius including traditional frequency reuse scheme and FFR scheme in different CTS regions. Finally, we demonstrate which scheme is better for long term observation and how to use the FFR technique by designing inner radius and outer region reuse factor to maximize cell throughput and show the improvement for link reliability in the random asymmetric traffic environments.

Table 5.1: Simulation Parameters in Muti-Cellular Environment.

Parameter	Value
Number of Macrocells (I)	**19**
Number of time slots for TDD-frame (N)	**14**
Radius of Macrocell	**1000 m**
Carrier Frequency (f_c)	**2500 MHz**
System Bandwidth (W)	**10 MHz**
BS/MS Antenna	**Omni-directional**
BS/MS Transmit Power (P_{bs}/P_{ms})	**43dBm /27 dBm**
Noise Power Spectrum Density (N_0)	**-174 dBm/Hz**
Standard Deviation between BS to BS (σ_{bs})	**3dB**
Standard Deviation between MS to BS (σ_{ms})	**10dB**
Pathloss Exponent Factor (α)	**4**
Outage Threshold (γ_{th})	**0 dB**
link reliability	**0.9**
FFT size (M)	**1024**
Sub-carrier Bandwidth (W_{sub})	**10.938 kHz**
Number of Null Sub-carriers	**184**
Number of Pilot Sub-carriers	**120**
Number of Data Sub-carriers	**720**

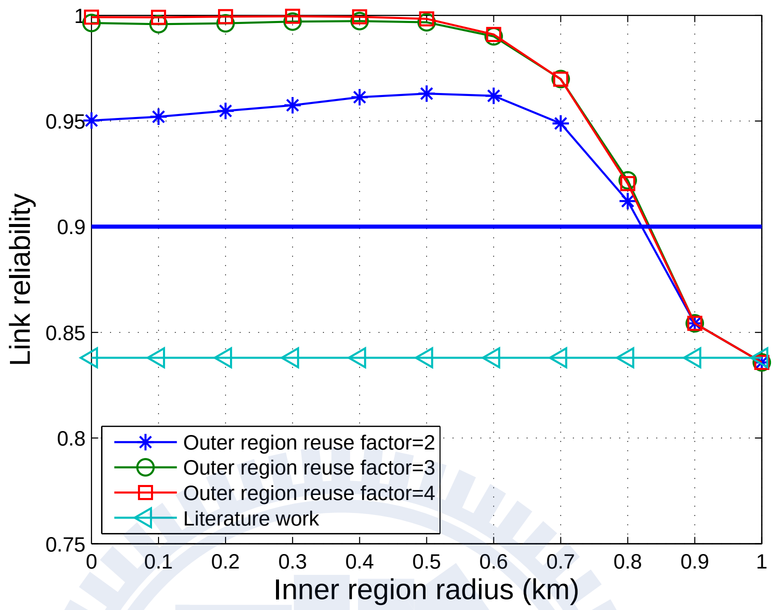

Figure 5.7: Link reliability for traditional frequency reuse scheme and FFR scheme in the symmetric traffic environment.

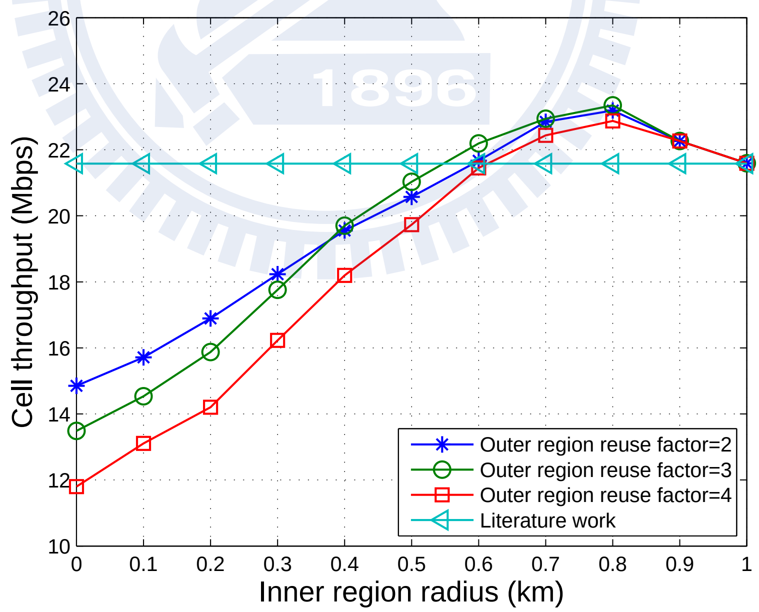

Figure 5.8: Cell throughput for traditional frequency reuse scheme and FFR scheme in the symmetric traffic environment.

5.4.1 Effect of Different Design Factors on Link Reliability and Cell Throughput for FFR scheme Under Each Traffics Environment

In Fig. 5.7, link reliability is simulated for literature work (location-TSA), traditional frequency reuse scheme and FFR scheme in symmetric environment with $\Delta_{DL} : \Delta_{UL} = 7 : 7$. We simulated reuse factor equals to two, three and for for traditional frequency reuse scheme and outer region reuse factor equals to two, three and four for FFR scheme. The traditional frequency reuse scheme is the case of inner region radius is determined as zero. Total spectrum will be divided n parts to avoid inter-cell interference. As the simulation shown, the traditional frequency reuse scheme can maintain higher link reliability which almost achieve 0.95, 0.99 and 1 while n=2, 3 and 4, respectively. The link reliability of traditional frequency reuse scheme with n=2, 3 and 4 always outperform the literature work that implement time slots strategy of considering MS location information because the literature work doesn't mitigate the effects of inter-cell interference. From views of cell throughput that is illustrated in Fig. 5.8, the literature work have higher cell throughput which equals to 21.8 Mbps than traditional frequency reuse scheme due to use total spectrum in a cell coverage which is better than traditional frequency reuse scheme just can use one n-th ratio of total bandwidth. The cell throughput is almost 15, 13.5 and 11.8 Mbps while using reuse factor equals to two, three and four, respectively. However, the traditional frequency reuse scheme is sacrificed many spectrum to exchange higher link reliability. Hence, using FFR scheme is better than traditional frequency reuse scheme due to using inner region and outer region to maintain spectrum utilization and mitigate inter-cell interference while MS locates at cell boundary.

In Figs. 5.7 and 5.8 also show the FFR scheme while inner region radius doesn't equal to zero. Due to increase inner region radius, more spectrum can be used in a cell coverage. More spectrum are assigned to inner region and MS transmit signal in small size of inner region always have higher transmission quality since the link reliability will

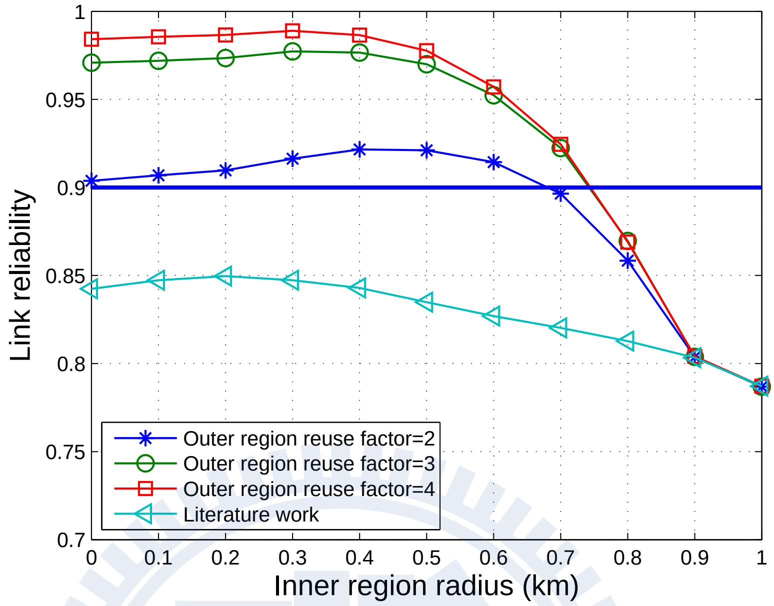

Figure 5.9: Link reliability for traditional frequency reuse scheme and FFR scheme in the Asymmetric traffic environment with Δ_{rand}=5-9.

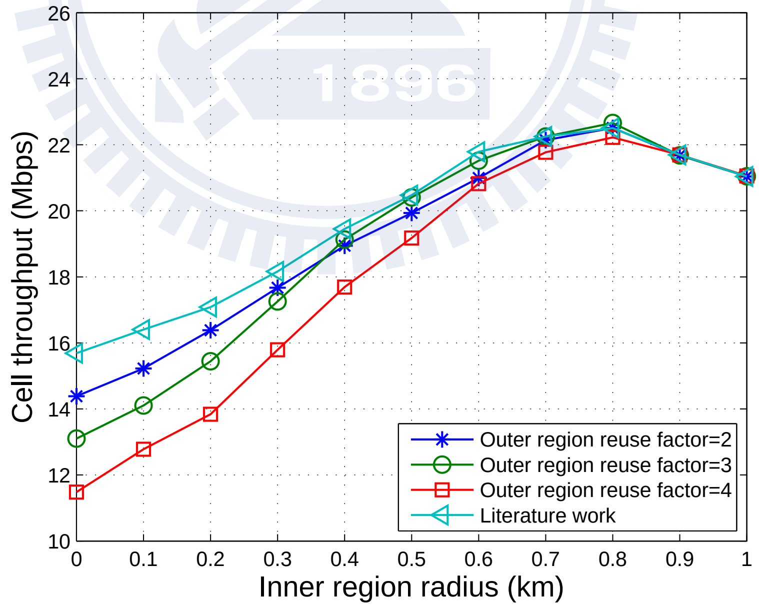

Figure 5.10: Cell throughput for straditional frequency reuse scheme and FFR scheme in the Asymmetric traffic environment with Δ_{rand}=5-9.

be promoted in small size of inner region. By observing Fig. 5.8, cell throughput will be improved due to more spectrum can be used and high transmission quality in small size of inner region. Nevertheless, while size of inner region becomes too large, more inter-cell interference come from neighboring cells will be received at receiver and degrade SINR level. Even though more spectrum can be use in a cell, the cell throughput become worse than small size of inner region due to the requirement of link reliability can be satisfied. In symmetric traffic environment, the maximum size of inner region with guaranteeing link reliability can almost achieve inner region radius equals to 800 m and cell throughput can be maximized as 23.4 Mbps while using outer region reuse factor equals to three. As the simulation shown, the FFR scheme is better than literature work by suitable design inner region radius and outer region reuse factor.

Figs. 5.9 and 5.10 shows link reliability and cell throughput for literature work (location-TSA), traditional frequency reuse scheme and FFR scheme in an asymmetric environment with $\Delta_{DL} : \Delta_{UL} = \Delta_{rand} : (N - \Delta_{rand})$, where $\Delta_{rand} = 5 - 9$ that means each cell may request bandwidth requirement of downlink and uplink within CTS size of -2 to 2. The largest size of generating cross-slot interference is four time slots range. We can observe the simulation result no matter traditional frequency reuse scheme and of FFR scheme have degrade their link reliability and cell throughput. The cell throughput is 14.4, 13.1 and 11.6 Mbps by using n=2, 3 and 4 for traditional frequency reuse scheme with achieving link reliability 0.91, 0.97 and 0.98, respectively. However, if we suitable design inner region radius equals to 700 m and outer region reuse factor n=3, system can maximize cell throughput to 22.1 Mbps with guaranteeing link reliability is higher than 0.9. The literature work have little advantages while inner region is small because the literature work is using an approach that avoid MS transmit signal and incur cross-slot interference at cell boundary. Hence, the frame will be divide two parts, CTS region and non-CTS region. The CTS region can be used for MS locates in inner region and non-CTS region can be supply to MS locates in overall cell no matter inner region or outer region. In the

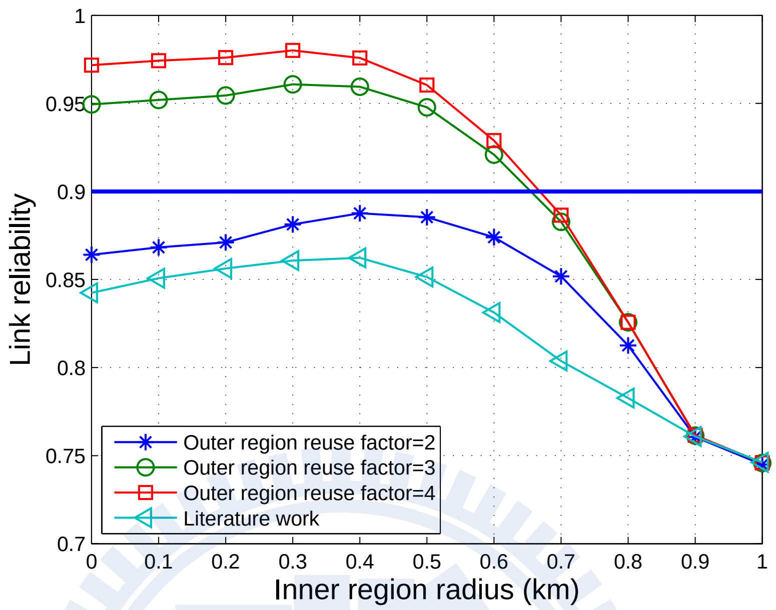

Figure 5.11: Link reliability for traditional frequency reuse scheme and FFR scheme in the Asymmetric traffic environment with Δ_{rand}=3-11.

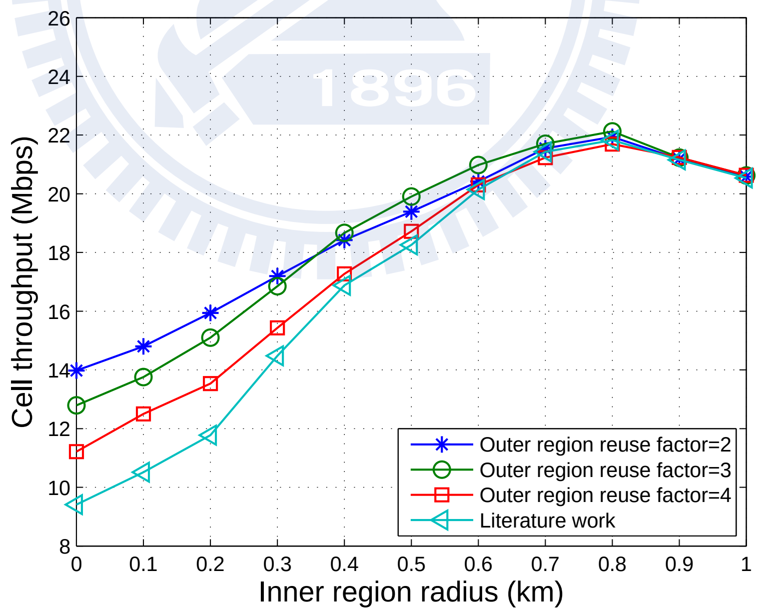

Figure 5.12: Cell throughput for traditional frequency reuse scheme and FFR scheme in the Asymmetric traffic environment with Δ_{rand}=3-11.

asymmetric traffic environment with $\Delta_{rand} = 5 - 9$, there will generate CTS size is four time slots and non-CTS size is ten time slots. While inner region is small, some MS locates in inner region can use the CTS time slots. Although MS transmit signal and incur cross-slot interference effect in inner region, the stronger received signal power can maintain SINR levels and guarantee link reliability. Hence, the link reliability will be improved in small inner region. However, the link reliability still isn't better than traditional frequency reuse scheme and FFR scheme because the literature work doesn't mitigate effects of inter-cell interference in each case.

We simulate large size of CTS in the TDD-OFDMA system with $\Delta_{DL} : \Delta_{UL} = \Delta_{rand} : (N - \Delta_{rand})$, where $\Delta_{rand} = 3 - 11$ that means CTS size is eight time slots from -4 to 4. The simulation result is shown in Fig. 5.11 and 5.12. The strong cross-slot interference degrade system performance seriously. The link reliability of traditional frequency reuse scheme by using reuse factor n=2, 3 and 4 are reduced to 0.86, 0.95 and 0.97, respectively. However, FFR scheme must reduce inner region radius to 600 m and use outer region reuse factor n=3 to guarantee link reliability and achieve cell throughput to 21 Mbps. For literature work, larger CTS region will be generated, lower spectrum utilization is used in overall cell because system must avoid MS located in outer region and incur cross-slot interference effect immediately. Hence, there are less resource unit can be used in outer region while size of CTS region is large. The simulation shows the literature work have poor cell throughput than FFR scheme. Finally, we consider the serious effect of cross-slot interference environment that $\Delta_{DL} : \Delta_{UL} = \Delta_{rand} : (N - \Delta_{rand})$ and $\Delta_{rand} = 1 - 13$. The link reliability and cell throughput result are simulated in Figs. 5.13 and 5.14. The FFR scheme can maintain inner region radius equals to 600 m, but system must use outer region reuse factor n=4 to guarantee link reliability and the cell throughput can achieve 20 Mbps. However, the literature work will waste many resource unit to avoid cross-slot interference effects. In the large size CTS environment, the FFR scheme is better than literature work.

From observing several simulation result, the FFR scheme can effectively reduce the effects of inter-cell interference by adjusting inner reign radius and outer region reuse factor especially surrounding in random asymmetric environment. We can use revise this two factors to maximize cell throughput with guaranteeing link reliability. However, we will show advantages of FFR scheme in different random asymmetric traffic environments in next section.

5.4.2 Effect of Different Random Asymmetric Traffics on Link Reliability and Cell Throughput for FFR scheme Under Different Design Factors

We investigate inner radius v.s link reliability and inner radius v.s cell throughput for different random asymmetric traffics environment. In Figs. 5.15 and 5.16, the FFR scheme with outer region reuse factor equals to two is considered. The simulation result shows this FFR scheme just can be used in a symmetric traffics and an asymmetric traffics with $\Delta_{rand} = 5 - 9$ environment. In symmetric traffics environment, FFR scheme with outer region reuse factor equals to two can maximize inner region radius to 800 m and achieve cell throughput to 23 Mbps. However, the inner region radius must reduce to 700 m to guarantee link reliability in random asymmetric traffics environment with $\Delta_{rand} = 5 - 9$. On the other hand, the link reliability can't be guaranteed by using outer region reuse factor n=2 in larger CTS size environment. In Fig. 5.15, we can observe that there are serious inter-cell interference in asymmetric traffic environment because of the effect of cross-slot interference. Larger size of CTS can support in each cell, serious cross-slot interference will be generated to reduce link reliability and cell throughput. Thus, we need to waste more spectrum to exchange higher link reliability. However, if we want to maintain link reliability in each cell for large CTS size, we should use higher reuse factors in outer region for FFR scheme.

The FFR scheme with outer region reuse factor equals to three is considered in

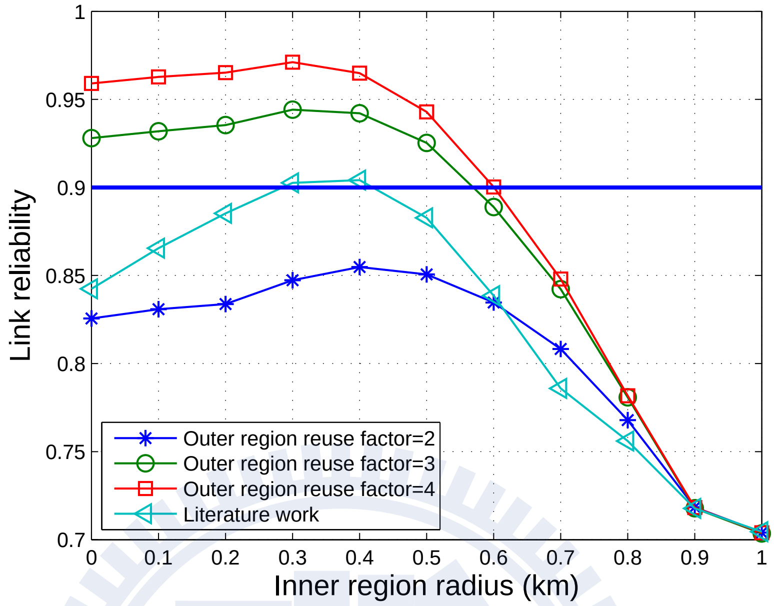

Figure 5.13: Link reliability for traditional frequency reuse scheme and FFR scheme in the Asymmetric traffic environment with Δ_{rand}=1-13.

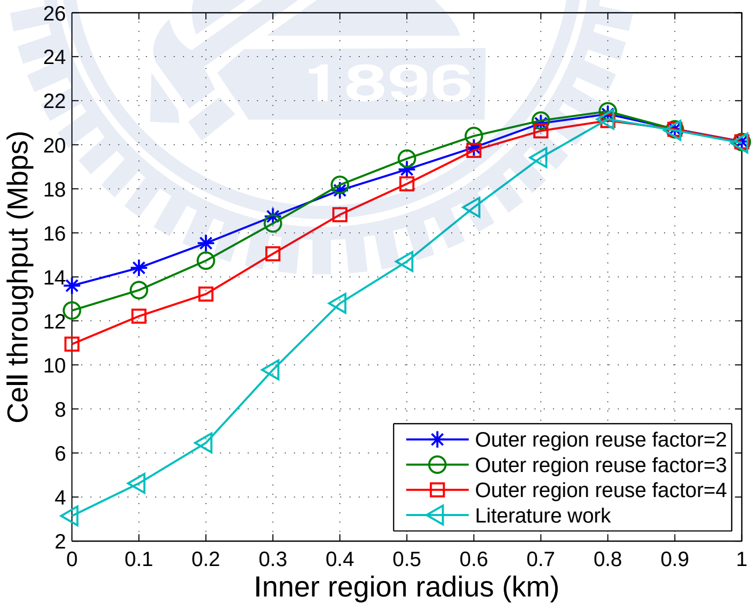

Figure 5.14: Cell throughput for traditional frequency reuse scheme and FFR scheme in the Asymmetric traffic environment with Δ_{rand}=1-13.

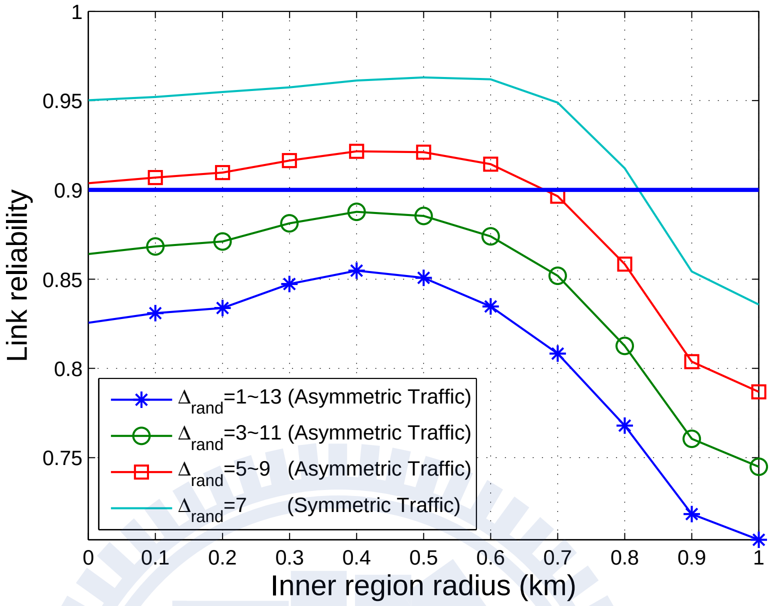

Figure 5.15: Link reliability for traditional frequency reuse scheme and FFR scheme with outer region reuse factor equals to two for different random asymmetric traffics.

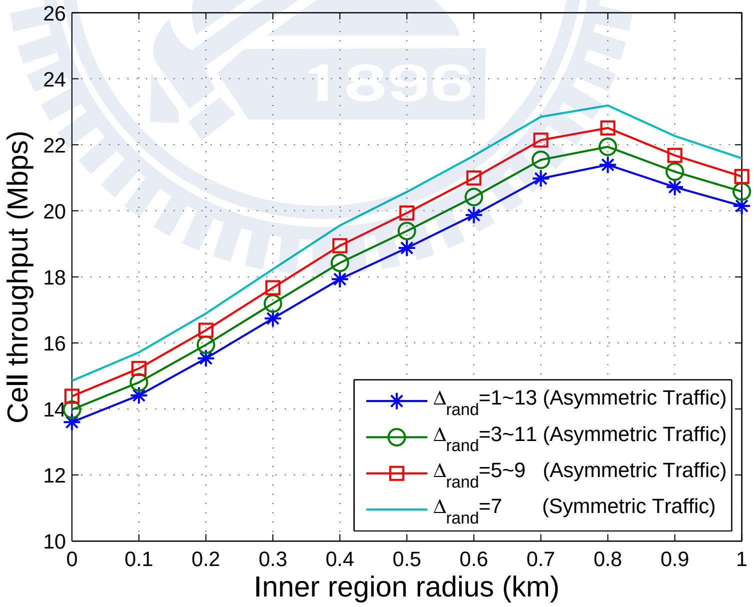

Figure 5.16: Cell throughput for traditional frequency reuse scheme and FFR scheme with outer region reuse factor equals to two for different random asymmetric traffics.

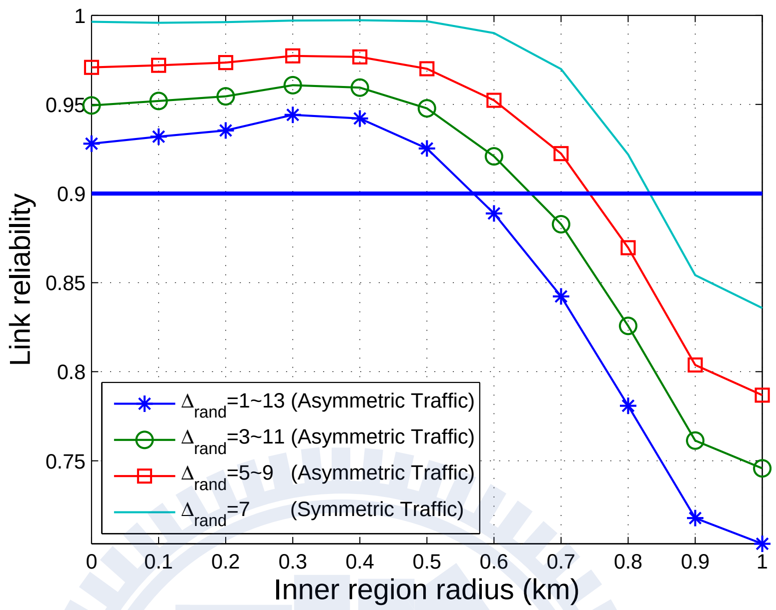

Figure 5.17: Link reliability for traditional frequency reuse scheme and FFR scheme with outer region reuse factor equals to three for different random asymmetric traffics.

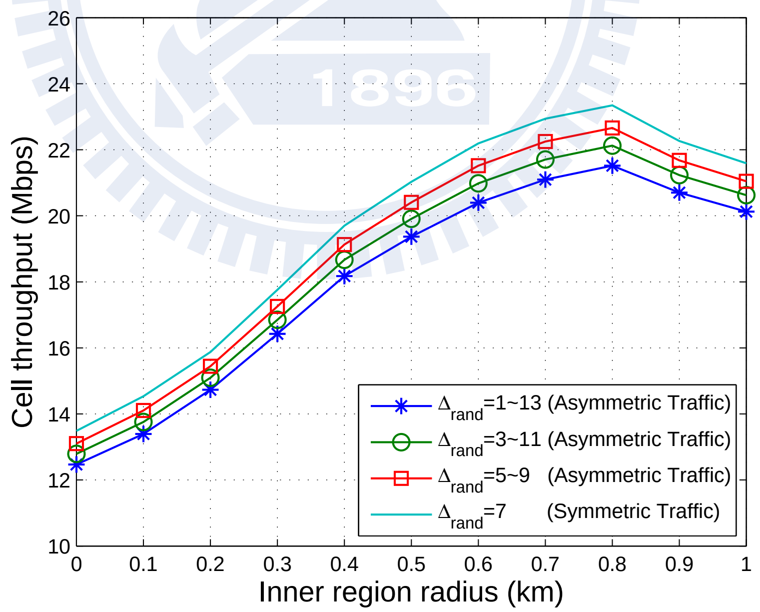

Figure 5.18: Cell throughput for traditional frequency reuse scheme and FFR scheme with outer region reuse factor equals to three for different random asymmetric traffics.

Figs. 5.17 and 5.18. The simulation result shows FFR scheme with outer region reuse factor equals to three can support four kinds of traffic environment by designing inner region radius are almost 800, 700, 600 and 500 m to reach cell throughput, 23.2, 22.1, 21 and 19.3 Mbps. System can support different asymmetric traffic by adjusting suitable inner region radius and outer region reuse factor. The larger size of CTS can be supported, the smaller inner region radius and larger outer region reuse factor need to be used in system. However, the FFR scheme with outer region reuse factors equals to 4 have same trend of design as FFR scheme with outer region reuse factors equals to three. It also can be used in each CTS size environment, but it may have different cell throughput levels.

The major advantage of FFR scheme used in asymmetric traffic environments is that it can adjust different asymmetric traffics to revise the design factors, inner region radius and outer region reuse factor. Second, the suitable design factors can increase cell throughput and maintain link reliability. Others, no matter non-cross interference or cross-slot interference also can be mitigated by using FFR scheme. In addition, the TDD-OFDMA has other advantages can be used to improve link reliability and cell throughput, such as different subchannel permutation schemes and numbers of subcarrier are grouped a subchannel. They will be compared in next section.

5.4.3 Effect of Different Permutation Scheme on Cumulative Distribution Function (CDF) of SINR Levels

The different subchannel permutation scheme will affect SINR levels on each subchannel. Fig. 5.19 shows three types of permutation scheme, adjacent permutation, adjacent permutation with multi-user scheduling (Band AMC) and distributed permutation scheme. By considering the outage threshold is 0 dB, Band AMC permutation will outperform than other permutation scheme because of muti-user diversity. However, the distributed permutation scheme is better than only adjacent permutation scheme because of frequency

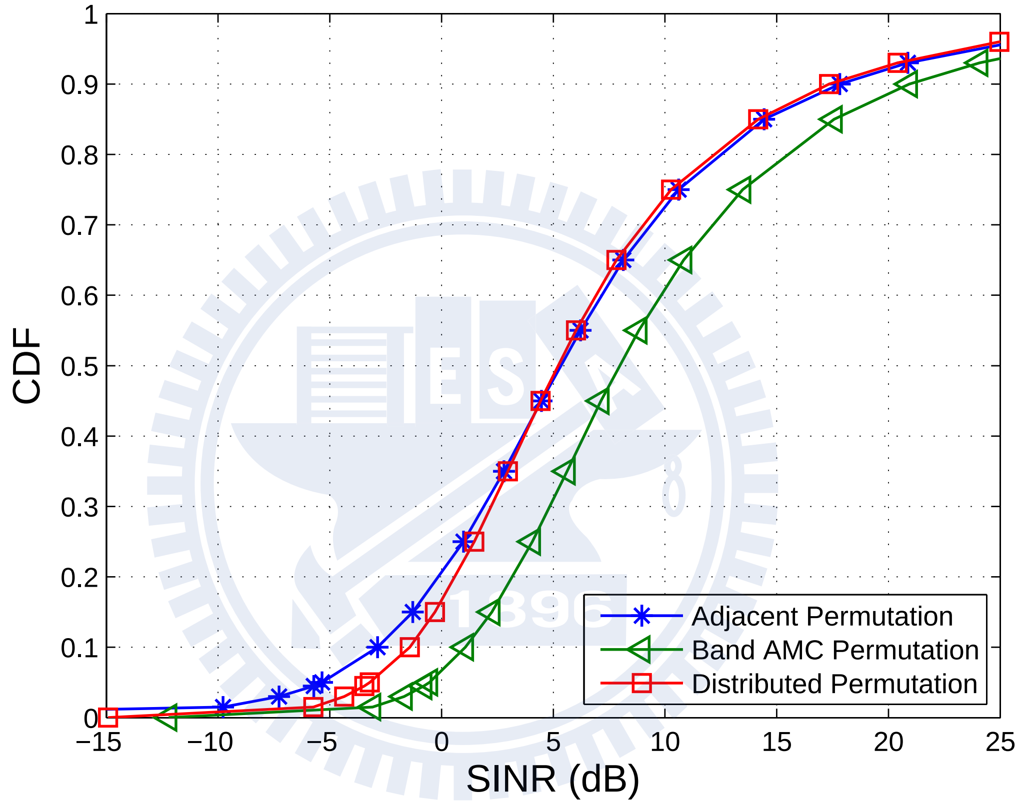

Figure 5.19: CDF of using different permutation schemes with 18 subcarriers are grouped a subchannel and under the symmetric traffic environment.

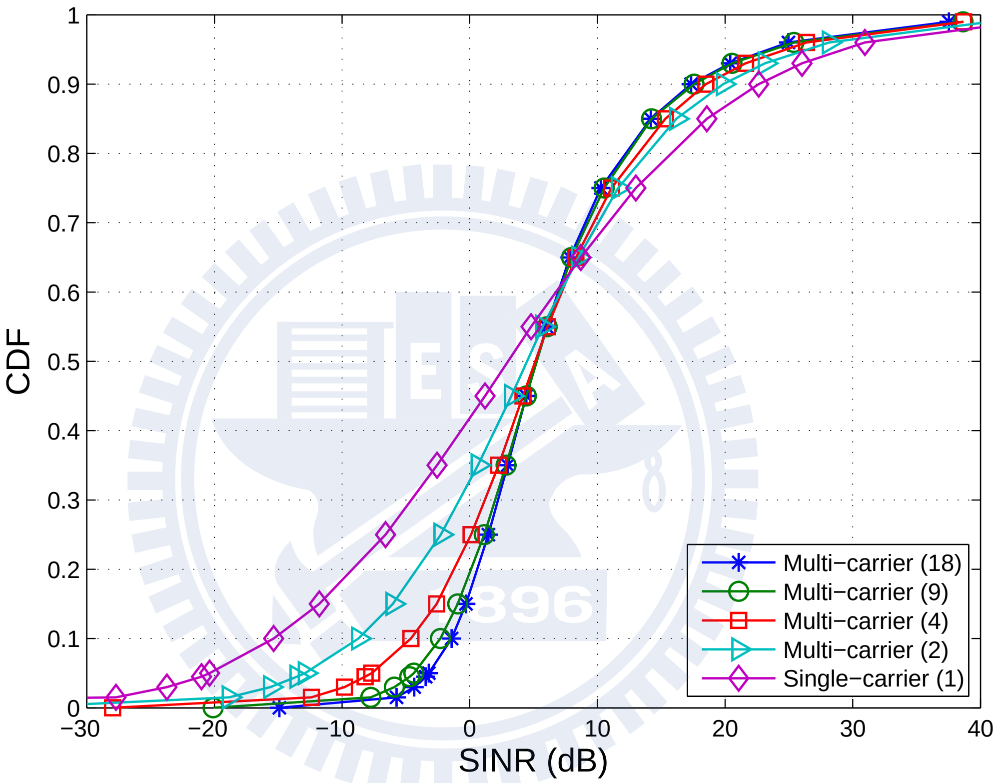

Figure 5.20: CDF of using different number of subcarrier are grouped a subchannel with distributed permutation scheme under the symmetric traffic environment.

diversity. Hence, we can use different permutation scheme in different environment. In general, the adjacent Band AMC subcarrier permutations can be properly used for fixed or low mobility environments because it can select higher channel gain of MS on each subchannel. The distributed subcarrier permutation perform very well in mobile applications because the channel state information can't be estimated very well. However, different number of subcarriers are grouped a subchannel also affect the frequency diversity gain on distributed permutation scheme. Fig. 5.20 shows five different numbers of subcarrier are grouped a subchannel. We can realize more numbers are grouped can improve outage probability, but less resource units can be used in system. For the single carrier case, the outage probability is almost 0.4 that is higher than link requirement. We can select multi-carrier case, such as multi-carrier (18). Then, the outage probability is improved to 0.15 since we can use less resource units to exchange higher link quality. These kinds of options enable the system designers to trade number of served MS for higher link quality in the TDD-OFDMA system.

5.5 Conclusions

In this chapter, we employee traditional frequency reuse scheme and FFR scheme in a TDD-OFDMA multi-cellular system for supporting asymmetric services. As the simulation results show, we suitably use FFR scheme by designing the inner radius and each region reuse factor that can maximize system throughput with guaranteeing link reliability. We can find out FFR scheme is more suitable used in random asymmetric traffic environments and is effectively mitigate strong cross-slot interference that is caused in random asymmetric traffic environments. In addition, if system want to maintain link reliability, it must use some spectrum to exchange higher link reliability. Hence, using FFR scheme in an asymmetric environment can provide better link quality and increase system throughput by adaptively revising each design factors.

CHAPTER 6

Conclusions and Future Research

6.1 Outage Performance Analysis for FFR TDD-OFDMA Systems with Asymmetric Traffics: Two Cell Case

In Chapter 4, we have analyzed the relationship of CTS and size of inner region of FFR scheme by the queueing theorem in a two-cells TDD-OFDMA system. We present an analytical formula that can evaluate the link successful probability for a FFR based on TDD-OFDMA system by using regular subchannels assignment. We provide the different CTS to show how to effect the successful probability and how to design the size of inner region. As the simulation results shown, the analytical approach can effectively help design the inner region size of FFR system and adaptively changing the size of inner region to guaranty the successful probability in the multi-cellular environment with various ratios of the uplink to downlink traffic among cells.

6.2 Outage Performance Analysis for FFR TDD-OFDMA Systems with Asymmetric Traffics: Multi-Cellular Case

In Chapter 5, we have developed a GUI interface to help us investigate FFR scheme in a TDD-OFDMA multi-cellular system for supporting asymmetric services. We can use the interface to observe different system performance under different random asymmetric traffic environments. As the simulation show, FFR scheme is more suitable to implement in a random asymmetric traffic environment than traditional frequency reuse scheme and literature work that using time slot strategy to avoid cross-slot interference. The FFR scheme can maintain link reliability by adjust inner region radius and outer region reuse factor. In a random asymmetric traffic environment, interference management is more important than spectrum efficiency because of the strong cross-slot interference. Thus, we must use lower usage ratios of spectrum to exchange higher link reliability. Hence, we propose FFR scheme that be implemented TDD-OFDMA system to solve the effects of inter-cell interference adaptively especially system can support random asymmetric traffic environments.

6.3 Future Research

For the future research of the thesis, we provide the following suggestions to extend our work:

- Power control can be considered in each transmission mode and region even considering soft frequency reuse scheme.
- Consider the different traffic load situation and see how to effect design factors of FFR scheme.
- Different subchannels assignment in frame duration and find out the optimal subchannels assignment in multi-celluar system with supporting asymmetric.

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Vita

Wei-Chi Li was born in Taiwan, R. O. C. in 1986. He received a B.S. in Electronic and Engineering from Chang Gaung University of Technology in 2008. From July 2008 to September 2010, he worked his Master degree in the Wireless Systems Lab in the Department of Communication Engineering at National Chiao-Tung University. His research interests are in the field of wireless communications.