Studies on Resource Allocation for Spectrum Sharing considering Interference Constraint of Primary System

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プライマリシステムの干渉制限を考慮した周波数共用のためのリソース割り当てに関する研究

稲毛　契

概要

現在、無線通信において周波数リソース不足が深刻な問題となっており、抜本的な対策技術としてコグニティブ周波数共用が注目されている。本論文では、周波数共用において既存システムの周波数帯を他システム（2 次システム）が二次利用するために干渉制限指標及びリソース割り当てに関する研究を行った。一つ目の研究では、既存システムに与える与干渉状態の評価指標について提案を行い，幅広い通信品質の既存システムを保護可能な干渉制限について評価を行った．評価ではシステムのリンクが静的モデルおよび動的なリソース配分で変更される動的モデルを用いた．二つ目の研究では，その干渉制限達成可能な送信電力制御の検討を行った。送信電力制御を行う際に，外部からチャネル情報の一部のみが得られると仮定し，確率的に変動するフェージング要素について所望のアウテージ確率を満足できるように数値解析を行い，厳密設計および簡易設計について提案を行った．三つ目の研究では、既存システムが複数端末に対して無線リソースをスケジューリングするモデルへと拡張し，2 次システムが干渉を回避しつつ，効率的リソース割り当てに関する検討を行った。

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Abstract

In wireless communications, the improvement of spectral efficiency is required due to the shortage of frequency resource. As an effective solution, spectrum sharing has been attracted attention. A cognitive radio is promising technology for realization of spectrum sharing. In the spectrum sharing, cognitive user (secondary user) has to protect licensed user (primary user) according to the interference constraint. However, conventional metric of interference constraint cannot avoid large performance degradation in primary system with widely range of Signal to Noise Ratio (SNR) such as a cellular system. Additionally, conventional interference constraints do not considers scheduling behavior in cellular system. In order to solve these problems, this paper proposes novel metric of the interference constraint which supports the widely SNR region of the primary system, so called capacity conservation ratio (CCR). The CCR is defined as the ratio of the capacity of the Primary receiver without interference from the secondary transmitter, to the decreased primary capacity due to interference. Proposed interference constraint based on CCR can protect primary capacities over the widely SNR region. In addition, scheduling behavior of the primary system can be protected by using proposed interference constraint. In addition, we propose transmit power control schemes: exact and simplified power control. The exact power control can satisfy requirement of interference constraint

without large margin; however, transmit power cannot be derive without numerical analysis. In contrast, transmit power is closed-form solution in the simplified power control with satisfying the interference constraint. Finally, this thesis proposes the resource scheduling under the interference constraint. Proposed scheduling achieves the high throughput and high user fairness in the secondary system without increasing feedback information compared with conventional algorithm.

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Acronyms

3GPP Third Generation Partnership Project

CCR Capacity Conservation Ratio

CR Cognitive Radio

CR-HeNB CR-enabled HeNB

CR-HetNet CR-enabled HetNet

CRN Capacity Conservation Network

D2D Device to Device

DSA Dynamic Spectrum Access

DTV Digital Television

eNodeB evolved Node B

EPCS Exact Power Control Scheme

FCC Federal Communications Commission

HeNB Home eNodeB

HetNet Heterogeneous Networks

HUE Home UE

LTE Long Term Evolution

LTE-A Long Term Evolution-Advanced

MeNB Macro eNodeB

MUE Macro UE

OFDMA Orthogonal Frequency-Division Multiple Access

OFMDA orthogonal frequency-division multiple access

PU-RX Primary Receiver

PU-Tx Primary Transmitter

QoS Quality of Service

RB Resource Block

REM Radio Environment Map

SINR Signal-to-Noise-plus-Interference Ratio

SIR Signal-to-Interference Ratio

SNR Signal-to-Noise Ratio

SPCS Simplified Power Control Scheme

SU-Rx Secondary Receiver

SU-Tx Secondary Transmitter

UE User Equipment

WS White Space

Chapter 1

Introduction

This thesis represents studies regarding Resource Allocation for Spectrum Sharing considering Interference Constraint of Primary System. This chapter introduces the research background and the challenges first. Research motivation and objective is stated in the next section. Finally, the organization of the thesis is given with the description of our research finding in respective section of chapters.

1.1 Background

The variety of new information tools (netbooks, smart phones, tablet and other mobile internet devices) cause a significant increase in the traffic of the broadband communications. The Advancements are growing applicable scope, increasing data rate, low outage probability, small latency and so on. Based on the forecast data by Cisco, mobile traffic increases 66 times with an annual growth rate of 131% between 2008 and 2013 [1]. In addition, the number of wireless devices is also increased, hence the spectral efficiency and communication performances should be improved in environments of high-dense node and high traffic. In order to achieve high data rate, needed spectrum bandwidth is increased in both new and existing wireless systems. However, it is difficult to allocate the new radio resource to new system or to additionally allocate it to existing system due to shortage of spectral resource. However, the spectral efficiencies are not always high according to report of the Federal Communications Commission (FCC) [12]. In other words, this report suggest that potential spectrum resource can be found. Recently, the cognitive radio has been attracted attention as a promising technology to solve the shortage problem.

The CR is able to modify own communication methods, modulation methods, signal frequency, data rate and so on, according to the surrounding wireless environment. This capable of recognizing and adapting radio environment, enables Dynamic Spectrum Access (DSA) which is a new spectrum sharing paradigm that allows unlicensed users to access the licensed spectrum holes, white spaces (WSs) or gray spaces in the licensed spectrum bands [13]. In the CR networks, coexistence systems are divided into two types; licensed system such as a cellular system and Digital television, called a primary user (or system) has the high priority on spectrum access. In contrast, the CR system called the secondary user (or system) has lower priority, hence the secondary system should avoid the harmful interference toward the primary system when the secondary systems access the primary band. The spectrum sharing can improve the utilization of radio spectrum and can reduce the cost of complicated spectrum assignment.

The idea of coexistence has been focused on as a key technology of performance improvement in other wireless networks. A cellular network is one of coexistence networks, because the cellular networks specifically face with demand of communication quality improvement. The cellular network aims to increasing of system capacity, and improvement of performance in peer-to-peer communication in diverse ways. An orthogonal frequency-division multiple access (OFDMA) is one of the key technology for performance improvement in the cellular networks. In order to satisfy the increasing demands on wireless mobile networks with higher throughputs, OFDMA-based networks are being developed as down link in Long Term Evolution (LTE). In the OFDMA, the spectrum is orthogonally divided into time-frequency resource blocks (RBs), which increases flexibility in resource allocation, thereby allowing high spectral efficiency. Exploiting all RBs simultaneously to achieve so-called universal frequency reuse becomes a key objective toward deployment of future cellular networks such as the LTE and the LTE-Advanced (LTE-A).

However, the performance is closely achieved to theoretical limit due to high inter-cell interference in the peer-to-peer communication approach. In the LTE-A, one of two-tier networks so called Heterogeneous Network (HetNet) is employed as new approach [2, 3]. The HetNet consisted of the mixture networks of multiple cells with different coverage size, is supported in order to offload the local high traffic in the macro cell coverage. Usually, most of the high traffic is generated in an indoor environment or a small local area, hence it is difficult to support the traffic by only the Macro eNodeB (MeNB). The advantage of using the small cells that are located inside buildings is significant since 50% of voice calls and more than 70% of data traffic originate indoors [4]. The survive of the macro coverage essentially has a coverage holes in specific area (e.g., indoor environment), then low-power and small-coverage local nodes called Home eNodeB (HeNB) such as pico, femto, and relay nodes deployed at coverage holes. The HetNet aims to improve the system capacity by using the HeNB overlaid to the MeNB coverage. Moreover, it can be expected to increase not only total system capacity but also the throughput of the cell edge user.

HetNet characteristically has existence of MeNB-HeNB back-haul coordination, allowing modifications of existing macro-cells for HetNet deployment. In the view point of the spectral efficiency, the frequency band of the overlaid HeNB is designed using the same band of the MeNB with assistance of above condition. Accordingly, the inter-tier interference between HeNB/MeNB and Macro User Equipment(MUE)/Home UE (HUE) became more critical issue in the HetNet, because the big impact is sometimes arisen due to short distance of the inter-tier interference channel. In other words, the benefit is realized only when inter-tier interference between HeNB and MeNB cells is well managed. Therefore, inter-tier interference mitigation is most important topic in the HetNet. In Third Generation Partnership Project (3GPP) Release 10, cross-tier interference mitigation technique has been introduced. However, this scheme is considered on the assumption of the existence of modifications of existing macro-cells.

Interference mitigation in such two-tier HetNets faces practical challenges: random deployment of HeNBs, restricted/closed access, no coordination among MeNB and HeNBs and backward compatibility [6]. In these scenario, the CR is the most promising solution for interference mitigation. The new idea of DSA utilizing CR techniques which make effective reuse of licensed spectrum is attracted attention as an essential solution for the shortage of spectrum resource.

The idea of DSA can be applied to the HetNet environment with random distribution of HeNB for relax requirement. In other words, the MeNB and CR-enabled HeNB (CR-HeNB) are analogous to primary and secondary users in the CR model, respectively. Moreover, it is expected that effect of intra-tier interference among CR-HeNBs can be mitigated by CR capability. The CR-enabled HetNet (CR-HetNet) can greatly improve the system and user performances, even if the CR-HeNB manages wireless resources considering the cross- and inter-tier interference.

According to expansion of scope of coexistence networks, the CR occupies an important role in the future wireless networks. The cellular network is also even worth considering as one of the primary system in the spectrum sharing as already discussed. However, the CR networks with the primary system which has widely signal-to-noise ratio (SNR) range and dynamically resource allocation, such as the cellular system, have been studied under regulated conditions. Especially, existing interference constraints cannot protect the primary (or macro-tier) communication with widely SRN range without adaptive modification of threshold. Additionally, the dynamic resource allocation such as the scheduling transmission is not considered in studies of interference constraint. In order to realize the spectrum sharing within cellular system, the interference constrain which support the wide SNR range of primary system by certain threshold and a method of satisfying constraint are necessary.

This thesis focuses at some of these problems. Then we thesis proposes the interference constraint considering dynamic primary system and power control schemes for satisfying this constraint, moreover scheduling algorithm for secondary system in cross- and intra-interference environment for improvement of secondary performance.

1.2 Problem of Spectrum Sharing within Cellular System

Improvement of throughput is one of the main challenges in two-tier cognitive networks as well as spectrum sharing within cellular systems. However, in spectrum sharing withing the cellular system, interferences mitigation and/or coordination are necessary due to overlapping coverages of two systems. Interferences among primary and secondary systems negatively affect throughput of both systems, additionally spectrum sharing with overlapping coverage and multiple users occurs multi-interferences over the frequency and space. In this section, interference problems are described by using term used in the field of 3GPP release documents.

Throughputs of the Macro-tier and Femto-tier seriously degrades as the number of HeNB increases. This is due to the interferences from neighbor eNBs. Interference in two-tier networks can be classified into two types,

Cross-tier Interference Cross-tier interference between the HeNB/MeNB and MUE/HUE occurs when macro-tier and femto-tier cells are closely located. The performances of two-tier cells are degraded by interference from each transmitters (eNB and/or UE). The interference form MeNB is large due to transmit with high power, since the all HUEs are received strong interference. On the other hand, MUEs are likely to be exposed to receive strong interference form HeNB, nevertheless transmit power of HeNB is small. Because the HeNB are located over the Macro-tier cell, and distance among the MUE and HeNBs occasionally is very short. It is shown in the Fig. 1.1.

Intra-tier Interference Intra-tier interference among HeNBs and HUE connected other HeNB is caused by environment in high density of HeNBs as well as inter-cell interference of Macro-tier cell. Even if the HeNB transmit with low power, aggregate intra-tier interference is increased depended on the number of HeNBs in a macro-cell. The Intra-tier interference is shown in the Fig. 1.2.

In two-tier heterogeneous networks, cross- and intra-interference is one of the major problems. Specifically these interferences mitigation is critical issue in HetNet environment with random distribution of HeNB.The difference between the random distribution of HeNBs and methodologically designed layout of HeNBs is shown in Fig. 1.3.

Additionally, in the cellular networks, not only throughput but also the user fairness and/or latency is important performance. The fairness among UEs and

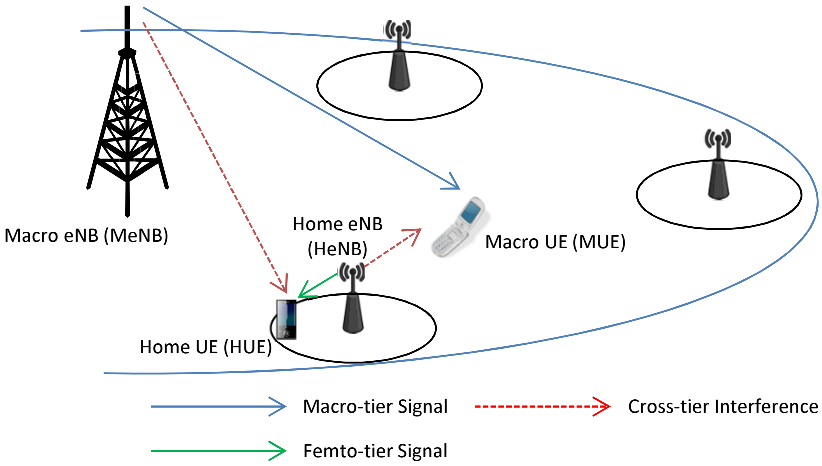


Figure 1.1: Cross-tier interference.

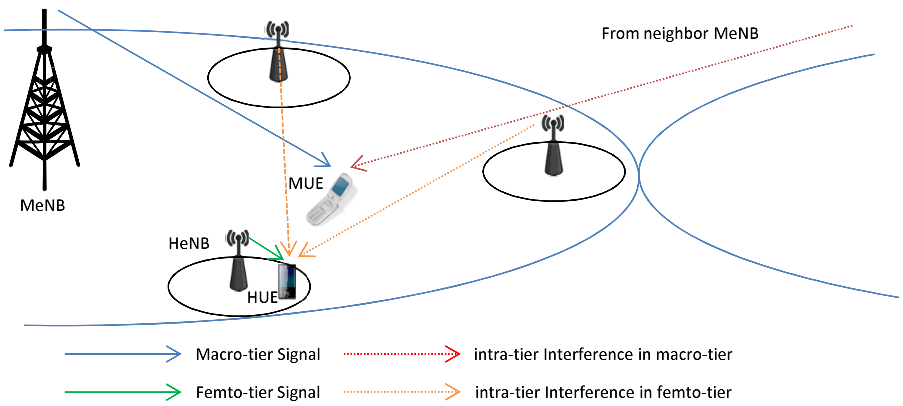


Figure 1.2: Intra-tier interference.

latency are depended on the resource allocation such as the scheduling algorithm. In the spectrum sharing within cellular systems, the throughput and fairness of both macro- and femto-tier cells should be simultaneously improved. Hence, in the cross- and intra-tier interference environment, it is prior important to design the scheduling algorithm. However aware scheduling is required to large overhead or coordination between Macro-and femot-tier and/or among HeNBs. Moreover, the HeNB has to maintain the performance of scheduling behavior in the macro-tier cell by the applicable design of the interference constraint and transmit power control according to this constraint. In other words, the HeNB has three objects: protection of the macro-tier cell, improvement of the throughput and fairness in

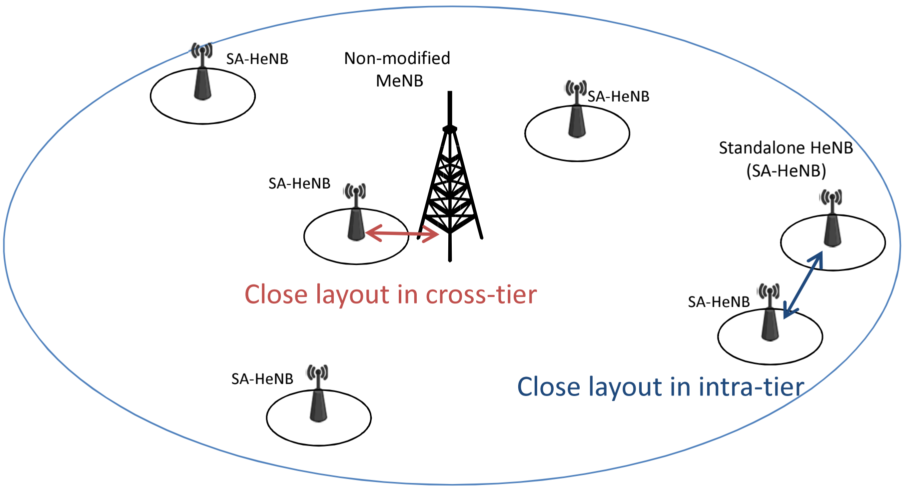


Figure 1.3: Non-coordination HetNet.

all femto-tier cells, avoidance of the increasing overhead for advanced channel-aware scheduling.

1.3 Main Contributions

In the wireless communication, the shortage of wireless resource is critical issue. Many researchers and industrial companies aim the improvement of spectral efficiency and also the high system performance. As one of effective solution, the coexistence of different systems has been attracting attention, such as the spectrum sharing by cognitive radio and heterogeneous networks. By allowing the coexistence on the same frequency band and the same location, gain of universal frequency reuse can be obtained to existing system and newer systems.

However, intra-system interference arises as the key problem in the coexistence environment. The intra-system interference leads the degradation of system performance in both systems, in other words coexistence is benefit only when the intra-system interference is well managed. In order to achieve the high spectral efficiency and high performances of both system, interference mitigation and resource allocation become key technology. The coexistence environment is considered as the hierarchic or two-tier system, one of coexisted systems plays the role of the lower layer (or tier). By appalling these architecture, intra-system (or cross-tier) interference toward system of higher tier can be avoid by the controlling own behavior on lower-tier systems.

Under the these idea, to simultaneously solve three problems is required: definition of the higher-tier system protection, a method of achievement for protection constraint and efficiency resource allocation in the lower-tier systems. In the spectrum sharing, there is no single definition for definition of the higher-tier system protection. Since, a method of achievement for protection constraint and efficiency resource allocation in the lower-tier systems are also no single. In addition, the lower-tier system has to achieve the high performance in poor channel states due to interference from higher-tier system. Efficiency resource allocation with constraint is significant.

Some constraints have been proposed; however, these constraint cannot be applied to performance with wide range SNR environment. Because, to adaptively change threshold of constraint is required in order to protect the users with high and low SNR in the same time. An interference constraint based on Capacity Conservation Ratio, investigated in Chap. 4 provides the definition of the higher-tier system protection. The novel interference constraint can support the system and user performance over with wide range SNR environment, differently from conventional constraint. Additionally, Chap. 5 show that proposed constraint may has applicability to system with scheduling transmission such as the cellular system.

Proposed constraint requires transmit power control at the lower-tier system. The transmit power control schemes shown in Chap.4 are methods of achievement for protection constraint. These two schemes can achieve the outage probability of the constraint without the instantaneous value of channel gain between the transmitter of lower-tier system and receiver of higher-tier system. The design of two schemes is derived through the analytical results, one of schemes called exact transmit power control can accurately achieve the required outage probability with numerical analysis of non-closed form. Another one so called simplified transmit power control can also satisfy the requirement from closed-form with larger margin than exact scheme.

Finally, we propose the resource allocation under the interference constraint. Existing channel-aware (or link-adaption) allocations requires large overhead compared with traditional allocation (or scheduling algorithm). Proposed allocation dose not increased overhead of feedback information relative to proportional fair scheduling. This contribution is higher performance can be achieved and no modify of feedback interface.

In this thesis, assumed system is considered as the lower-tier system in the heterogeneous networks. However, our proposals can be also applied to cellular-based cognitive system. These proposed contents have a contribution to make realization of spectrum sharing, and heterogeneous networks.

1.4 Motivation and Objectives

For future wireless network the demand for the bit rate and traffic is rapidly growing year by year. One of the ways to deal with this current situation is to increase the throughput in the cellular network. Resource allocation in the HetNet which affects the system capacity is the most important factors. We have proposed interference constraint and scheduling algorithm in this thesis. First one is the protection of macro-tire communication and the second one is the environment aware scheduling for cognitive radio-enabled HeNBs (CR-HeNBs). The objectives of this research lie in the following aspects:

- To design a suitable interference constraint for protection of wireless communication with large coverage such as the cellular system
- Transmit power control schemes to satisfy the interference constrain for femto-tier eNB
- Under the transmit power limitation in HeNB, efficiency resource allocation is proposed in existence of cross-tier interference.
- In the random distribution of HeNBs, proposed scheduling maintains the performance under the cross- and intra-interferences.
- To design algorithm to maintain an overhead of environment aware scheduling compared with conventional proportional fair scheduling.

1.5 Organization of the Thesis

The thesis summarizes our research works on resource allocation for spectrum sharing considering interference constraint of primary System. The thesis consists of six chapters as follows.

Chapter 1 Introduces the research background, requirements and research motivation and objectives.

Chapter 2 This chapter presents the overview of the cellular and heterogeneous networks. In addition the explanation of conventional scheduling algorithms and the interference mitigation technique in LTE and LTE-A are given in this chapter.

Chapter 3 The basics of the cognitive radio technology and CR networks with some spectrum sharing strategies are explained in this chapter. The protection method design challenges are also described in this chapter.

Chapter 4 This chapter presents the interference constraint and transmit power control considering the fading effects through the analytical results. Furthermore, this chapter focus on the protection performance in the view point of spacial domain in the proposed method compared with other interference constraint.

Chapter 5 Interference aware scheduling for the cognitive-enabled femto-tier cell in heterogeneous is studied in this chapter. The problem of cross- and intra-interferences mitigation is explained in details. A novel scheduling algorithm to improve the throughput and/or fairness in the random distribution of femto-tier cells is proposed in this chapter.

Chapter 6 Summarizes the research contribution of the thesis and explores future works.

Chapter 2

Cognitive Radio wireless Networks

CR networks (CRNs) provides a new promising solution for improvement of the spectrum utilization made possible by coexistence of different systems. Some basic concepts about the CRNs are introduced in this chapter 3. Research on CRNs has mainly focused on MAC and physical layer. Especially, resource allocation under the interference constraint is the critical issue to deal with in order to construct all kind of CR networks.The classifications of the spectrum sharing strategies and protecting method are explained in this chapter.

2.1 Cognitive Radio Technology

The CR technology enables that cognitive terminal recognizes surrounding radio environment, and changes own communication parameter such as transmit power, modulation scheme, carrier frequency, protocol and so on, according to the results of recognized environment. The CR can increase communication opportunities through cognition of surrounding environment and adaptively-changed parameter. Dr. J. Mitola has been proposed Cognition Cycle which means state transition diagram from cognition to beginning communication, as illustrated Fig. 2.1. The cognitive radio communicate based on Cognition Cycle.

At first, cognitive radio obtains variety of information by observed surrounding radio environment. This obtained information is oriented priority from analysis,

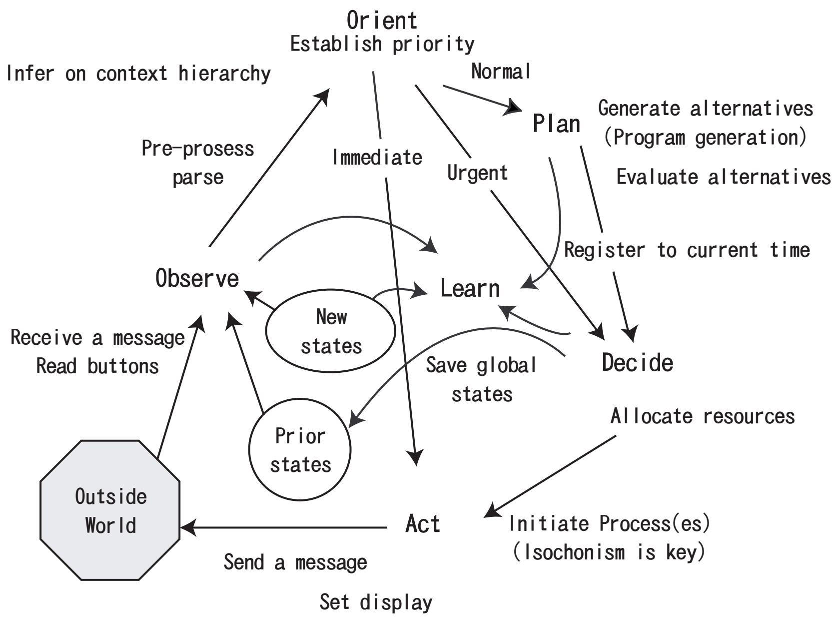


Figure 2.1: Cognition Cycle.

and categorized based on requirement speed of processing. If obtained information means immediate response, cognitive radio takes appropriate action without sorting priority. For example, all communication at the cognitive radio should be shutdown if emergency stop code is received. In the urgent case, the cognitive radio decides next action based on obtained information, and implements activity. The urgent case is to cognize which the cognitive radio interferes other systems. In this case Response activity is deciding the parameter to avoid or suppress interference and changing its parameter. In last case is called normal case, the cognitive radio generates alternative of action with moving obtained information. After that, activity is decided from alternative and implemented. Normal case is process to start communications, which are cognize environment, decide optimal parameter and implement activity.

The wireless communications utilizing the cognitive radio technology are attracted attention as a solution to improve efficiency of the spectrum utilization. The cognitive radio can adapt communication scheme according to surrounding radio environment without interference toward other systems. As a result, unused spectrum can be detected by cognitive radio, and utilized effectively. The cognitive radio is grouped into two general categories. First one is multi-mode cognitive radio network type, and second one is dynamic spectrum access type.

2.2 Category of Cognitive Radio

As previously mentioned, CRNs can be separated into the two categories: Multi-mode CRNs and Dynamic Spectrum Access. The details of two categories is described in the following subsections.

2.2.1 Multi-mode Cognitive Radio Network

As illustrated Fig. 2.2, in the multi-mode CRN, cognitive system equips multi licensed system such as Cellular network, IEEE 802.11, IEEE 802.15.1(Bluetooth) and so on. Therefore, the cognitive system detects available system which is authorized the licensed spectrum, and utilizes spectrum with behavior as licensed system of that spectrum. In addition to detect the licensed system, the cognitive terminal obtains system state information; congestion level, achievable throughput, and so on. After that, cognitive terminal selects system according to cognition results. If requirement Quality of Service (QoS) cannot be achieved by utilizing one of systems, the cognitive terminal selects other systems.

To realize the multi-mode cognitive radio network is easier than Dynamic Spectrum Access. Because communication method of each licensed system, has been established. However, it is considered that improvement effect of multi-mode cognitive radio network is not high due to spectrum utilization is limited by behavior of licensed system. Thus upper limit of utilization efficiency in each spectrum depends on communication scheme of each licensed systems.

2.2.2 Dynamic Spectrum Access

In the Dynamic Spectrum Access, the cognitive (secondary) system detects available spectrum and accesses that spectrum with lower priority than licensed (primary) system of that spectrum. This access scheme is divided into two types by definition of available spectrum; overlay spectrum sharing and underlay spectrum sharing. In Fig. 2.3, access to spectrum of system A is overlay type, and access

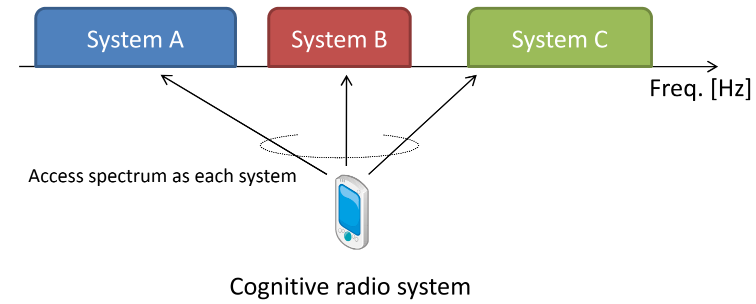


Figure 2.2: Multi-mode Cognitive Radio Network.

to spectrum of system C is underlay types. However most important feature is common to overlay and underlay spectrum sharing, it is that the cognitive system is required to protect the communication of the primary system due to different each priority.

In the Dynamic Spectrum Access, behavior of the cognitive radio is not limited with the exception to interfere toward the primary system. In other words, the secondary system should ensure both primary protection and own performance at the same time with utilizing reliable communication method. However it is expected that protection method depends on the primary system. Thus, it is difficult to realize spectrum sharing based on Dynamic Spectrum Access.

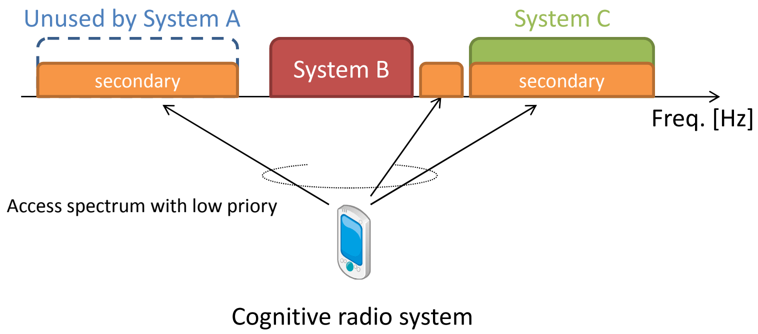


Figure 2.3: Dynamic Spectrum Access.

2.3 Underlay and Overlay spectrum sharing

In the Dynamic Spectrum Access, access scheme is divided into two types by definition of available spectrum; overlay spectrum sharing and underlay spectrum sharing. Figures 2.5 and 2.4 illustrate two spectrum sharing schemes, for example observable spectrum is there by the secondary system.

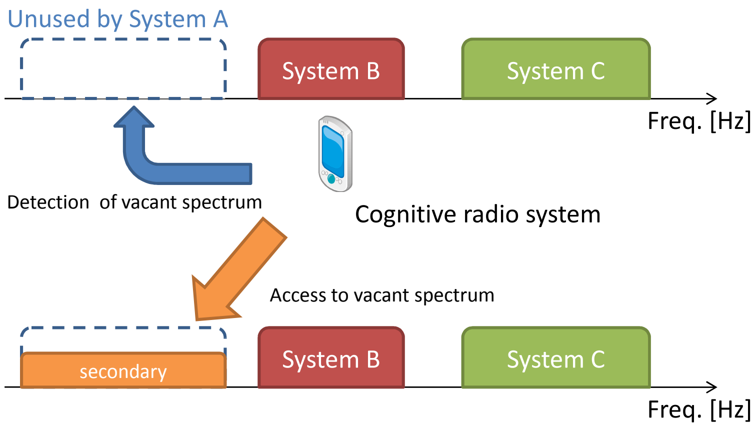


Figure 2.4: Overlay Spectrum Sharing Structure.

In the overlay spectrum sharing, the secondary system can only access when the vacant spectrum is detected through some observation (e.g., sensing). Thus, definition of available spectrum is unused spectrum (White Space) by the primary system. To evaluate primary spectrum as White Space, primary spectrum should be not utilized in time dimension, space dimension or both dimensions. For example, the secondary system detects idle time on the primary spectrum, or the secondary system is located in which the primary signal is unobservable because distance between the primary system and the secondary system is very large.

In the underlay spectrum sharing, it can be achieved to protect the primary system by utilizing geography or geolocation as a realistic way. However, spectrum available area of the secondary system is small, therefore improvement effect of spectrum utilization efficiency is not so high.

The concept of underlay spectrum sharing allows utilization of the primary spectrum which is accessed by the primary system, by the secondary system at the same time. However the secondary system is subject to the restriction of primary

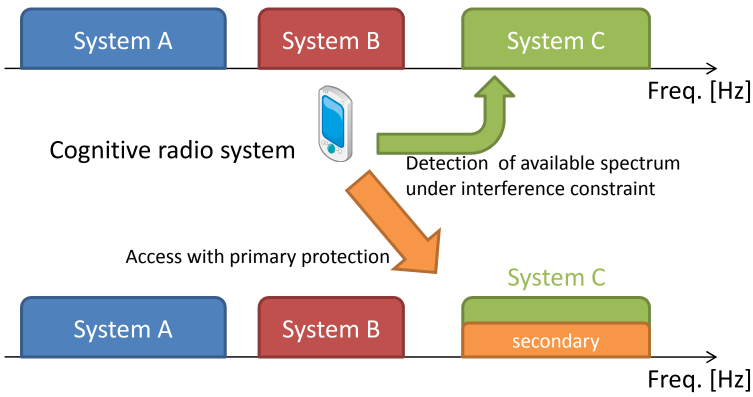


Figure 2.5: Underlay Spectrum Sharing Structure.

protection in the spectrum sharing. The detection of the available spectrum is different from the concept of the overlay spectrum sharing. The secondary system has to detect the available spectrum which the secondary system can achievable enough performance, under the interference constraint.

If the secondary system meets requirement, the secondary system can share spectrum with the primary system in the spectrum, time and space overlay. The available resource is increased from underlay spectrum sharing. Therefore great improvement effect of spectrum utilization efficiency is expected. However strict design of the spectrum sharing is required strict design of the spectrum sharing due to increasing risk of receiving harmful interference.

2.4 Supported-Information-based Spectrum Sharing

In order to protect the primary system, the overlay spectrum sharing requires strict design of communication method for the secondary system. In other words, the secondary system should obtain detailed information about the primary system, surrounding radio environment and so on. The sensing is a typical method for observation surrounding environment, however the secondary system cannot obtain all of required information through sensing.

The overlay spectrum sharing has a potentiality of great improvement, as alternated many information is required to achieve enough performance of the secondary system. Especially, in assuming the detailed information of the radio environment is given, the secondary system enables to design own communication almost to the limit. However it is very difficult to obtain about information of the radio environment includes propagation loss, fading model and so on. In addition, information of the primary system is beneficial for design of communication method. This information is also unobtainable without strong cooperation between the primary system and the secondary system.

As a one of solution to this problem, utilization database for the spectrum sharing has been proposed [21][22]. The structure of Supported-Information-based Spectrum Sharing is shown in Fig. 2.6. The database stores information which is registered by the secondary system or the primary system, and processes this information to proper form. The database can analyze and process this enormous volume of information because it has a higher processing ability than the secondary terminal. If some information is necessary, the secondary system obtains this information by access to database.

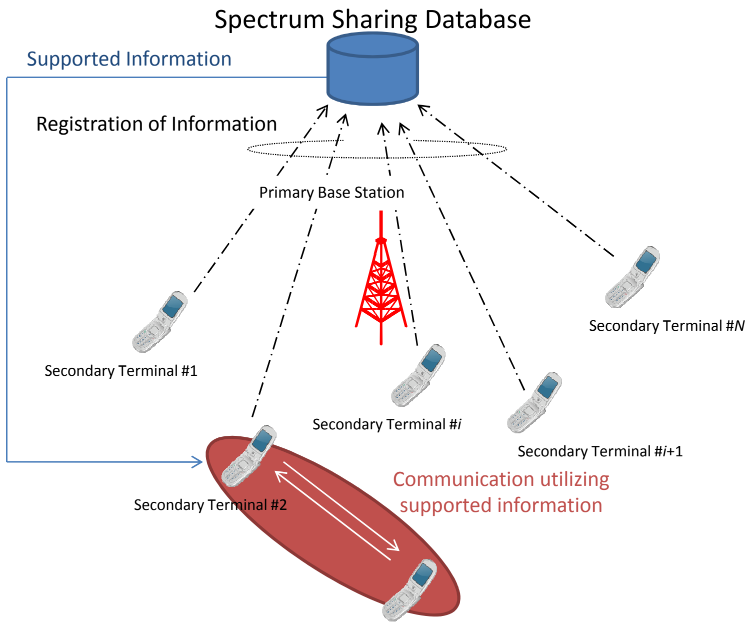


Figure 2.6: Supported-Information-based Spectrum Sharing Structure.

2.5 Related Works

As outlined in the previous chapter, it is required to cognize some states about in which are surrounding environment, the primary system, or other the secondary system and so on, by some kind of observation method. The secondary system decides availability of communication in the primary spectrum or appropriate parameter. The sensing is typical observation method as previous chapters have shown, however obtained information through the sensing is limited. Thus, it is difficult to perfectly gather the surround information by the sensing. In particular location information of the primary receiver is not observable; nevertheless this information is key factor for achieving high performance of the secondary system.

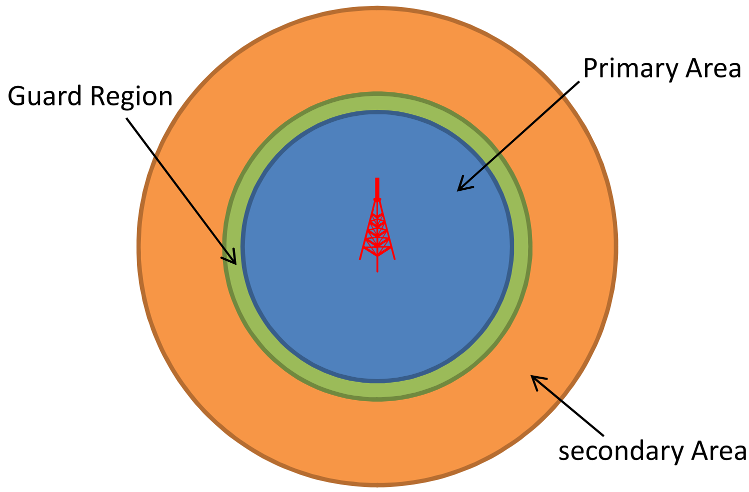


Figure 2.7: Primary Exclusive Region in Spectrum Sharing.

In [23], spectrum sharing method without location information of the primary receiver has been proposed as countermeasures. This method designs the whole cognitive system included the primary system and the secondary system, for protecting the primary receiver where not unknown. As shown in Fig. 2.7, forbidden region for the secondary system is located in in the central region of the primary cell. In this proposal, the secondary system is required to suppress outage probability of the primary receiver in the cell edge as an interference constraint. This constraint can be written by following equation as spectrum sharing criterion.

$$\Pr\left[\text{primary user's rate} \leq C_0\right] \leq \beta \tag{2.1}$$

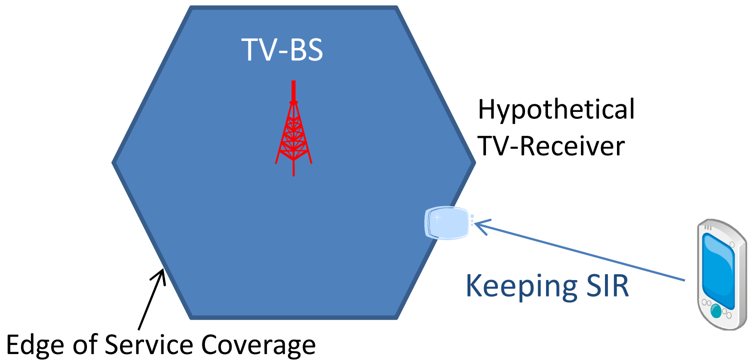


Figure 2.8: Spectrum Sharing Based on Keeping SIR of the Primary Receiver at Cell Edge.

The spectrum sharing by using service area information of the primary system has been proposed in [19] as shown in Fig. 2.8.. This method considers a TV service as a primary system. The secondary system utilizes information of the location of TV broadcasting tower, the transmission power and the service area of TV, and decides the communication parameters. It considers their own location information using Global Positioning System (GPS) before starting transmission to share the spectrum. A secondary terminal decides the transmit power to keep the signal-to-interference ratio (SIR) at the primary receiver, assuming the location at the nearest area edge using the external information.

Moreover, the spectrum sharing method by using location information of the primary receiver has been proposed in [16].In this system, a secondary system obtains location information from the sever like method shown in [19]. Antennas of Satellite communications system are anchored in the position, thus secandary terminal can obtain accurate location information of primary terminals, as shown in Fig. 2.9. Secondary terminal can decide the transmit power by estimating the interference toward location estimated primary terminals. This transmit power is calculated by the allowed interference power at the primary which is decided by considering a margin form thermal noise and propagation loss. Therefore,

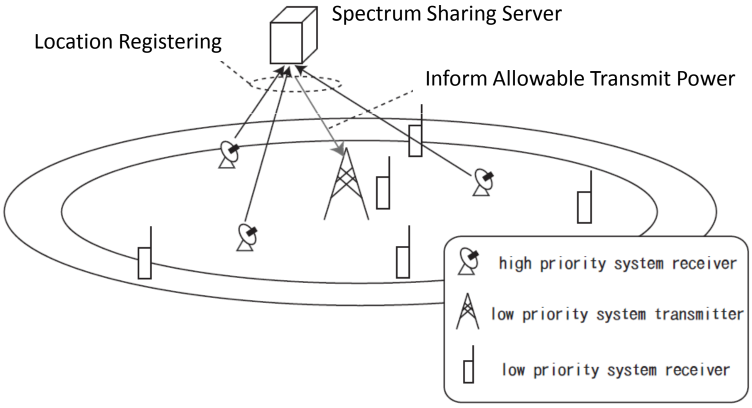


Figure 2.9: Spectrum Sharing Utilizing Supported Information for Protecting Satellite Communications.

the interference from the secondary system can be protected at each primary terminal.

Chapter 3

Cellular and Heterogeneous Networks

Some basics information regarding the cellular and heterogeneous networks are introduced in this chapter. The multi-use access for cellular networks such as the scheduling algorithm also present in this chapter.

3.1 Introduction

The basic premise behind cellular system is to exploit the signal power is decreased with increasing distance from transmitter in order to reuse the same frequency resource in spatial domain. Specifically, in cellular system a given large spatial area is divided into non-overlapping cells which are assigned certain resource as shown in Fig. 3.1. Under the mitigation of the inter-cell interference by spatial resource pattern, the base station allocates the resource (or channel) to multi-users by using the multiple access technique such as frequency division multiple access (FDMA), time division multiple access (TDMA), and code division multiple access (CDMA). In addition, with increasing the number of the mobile node in the cellular system, the distance of frequency reuse and cell radius is reduced for improvements of the throughput and cell capacity, spectral efficiency and so on.

In the current cellular network, in order to satisfy the increasing demands on wireless mobile networks to support data applications with higher through-

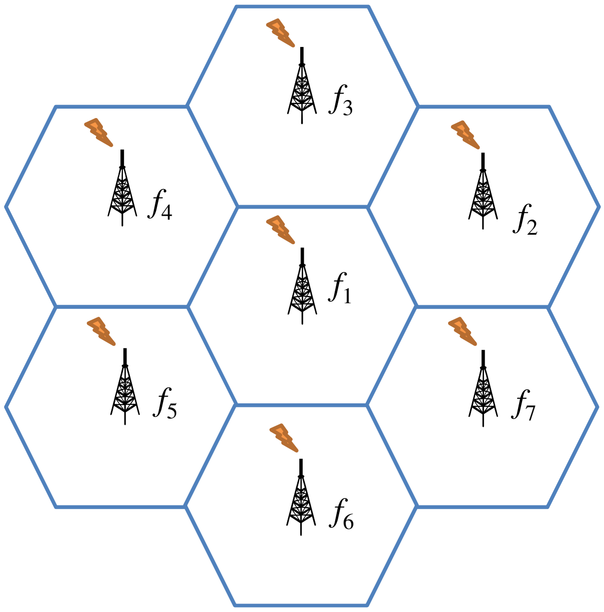


Figure 3.1: Cellular system in reuse factor = 7.

puts, orthogonal frequency-division multiple access (OFDMA)-based networks are being developed. In OFDMA, the spectrum is orthogonally divided into time-frequency resource blocks (RBs), which increases flexibility in resource allocation, thereby allowing high spectral efficiency. However, in already dense deployments in today's networks, cell splitting gains can be severely limited by high inter-cell interference. Moreover, high capital expenditure cost associated with high power macro nodes further limits viability of such an approach.

As the new paradigm, an alternative strategy where low power nodes are overlaid within a macro network, creating what is called to a heterogeneous network (or two-tier network), is considered in the next generation cellular system. This low power nodes such as femto, pico, relay base stations, may improve the cell capacity by off-loading of the local high traffic in macro coverage. Because, 50% of voice calls and more than 70% of data traffic originate indoors [4]. However, HetNet requires appropriate behavior to overall nodes in system, therefore complexities of system design and controlling process are increased.

Firstly, next section presents fundamental of general cellular system such as design of cellular system, multiple access technique, scheduling algorithm and evaluation indicator of cellular performance. Second, heterogeneous network which is extended the approach of cellular system is described. The type of heterogeneous network is introduced, then some related works as interference mitigation or coordination is presented.

3.2 Cellular system

In recent years, intense research has been focused on broadband multimedia systems, offering rate-demanding services such as audio, video and internet applications. Additionally, the kinds of devices get more varied every year, such as laptop, netbooks, smart phones, tablets and other mobile internet devices. These devices provide the internet access function as well as the Wi-Fi function. In the majority of cases, the internet access is provided by the cellular networks, then it is expected to increase even more traffic of the cellular networks. Past cellular networks faced on the problem the improvement of system capacity, spectral efficiency and user performance under the peer-to-peer communication approach.

Modification of multiple access technique brings improvement of the spectral efficiency, because the newer multiple access can reduce margin for channel orthogonalization. Moreover, the frequency reuse factor can be reduced by modification of multiple access. Another approach called cell splitting also contribute the improvement of spectral efficiency. In this section, these approaches and scheduling algorithm are described. After that, heterogeneous network as the new paradigm is described.

3.2.1 Evaluation Indicator of Cellular Performance

In general wireless networks, some indicators have been considered to evaluate the system performance. Throughput and latency are typical and common indicator over the wireless networks. However, the cellular networks has different features compared with other wireless networks. For example, the number of nodes, size of coverage, valid application and so on. Therefore, indicator of requirement performance is depended on the system architecture and/or application. In the cellular networks, many indicators are used for performance evaluation, and the cellular network should often satisfy better performance in the view point of more than one indicator. These indicators can be divided into three types: throughput, latency and fairness.

3.2.1.1 Throughput Indicator

In the general wireless networks, throughput (or rate) is one of most important factor. The cellular networks are, of course, required high throughput; however, in the cellular networks, the definition of throughput is no one. Because, there are many users distributed over a large coverage in the cellular network, and available channel(s) is assigned to users according to the scheduling algorithm. In other words, it is difficult to evaluate the cellular throughput from many directions by using only one definition. Therefore, following throughputs are used as often as required.

Cell Throughput Cell throughput is calculated by summation of user throughput through the scheduling behavior. When throughputs of all users are summed, each throughput is normalized by the bandwidth and scheduling time for elimination the effect of resource parameter. On the other words, cell throughput normalized by time and frequency domain, means the system capacity and diversity gain of used scheduling algorithm. Since, if any scheduling algorithm assigns users with best or better channel, cell throughput is increased by multi-user diversity. Furthermore, in the cellular system, cell throughput is regarded as a spectral efficiency per cell. In the view point of the resource utilization, it is preferable that cell throughput is larger.

User Throughput Total throughput show only one of cell performance; however, throughput per user is also important. In most cases, user throughput is derived as the mean of the all users with normalizing in time and frequency domain, because individual throughput is depended on the channel state (e.g., propagation loss, shadowing and fading distribution) and relationship of channel state among other users. However, user throughput is rapidly decreased with increasing the number of user, differently from cell throughput. For evaluation of the some schemes or algorithms, user throughput is rarely used.

Cell-edge Throughput Throughput of cellular networks is strongly influenced by many parameters: channel model, spatial distribution of user and scheduling algorithm. As a result, it is difficult to discuss using maximum (or minimum) throughput due to probabilistic behavior. On the other hand, cell-edge throughput is very important factor, because cell-edge users are affected inter-cell interference form base station of neighboring cells. Then, the most of literature related cellular networks use cumulative distribution function (CDF) of throughput for evaluation of cell-edge performance. In these literatures, 5% CDF of throughput is considered as the cell-edge throughput. The cell-edge throughput is considered to minimum performance of algorithm. In the recent studies, the improvement of cell-edge throughput is one of key topics such as the interference coordination or mitigation technique. In the scheduling or resource allocation, it is preferable that cell-edge throughput is also larger with cell throughput.

3.2.1.2 Latency Indicator

In the cellular network, available resources are shared among users according to result of scheduling decision. In other words, packet-based and transmission scheduling not necessarily mean that each users is continuously obtained the wireless resource (or channel) for establishment of communication. There are resource-unassigned users depending on scheduling algorithm even if the number of channel is larger than the number of users. However, it is better to avoid no-assignment time (slot) at the all users, because this contribute to the occurrence of the latency.

In the cellular networks, to satisfy the Quality of Service (QoS) such as the throughput, latency and so on, is required. The latency is a particularly key performance for video application and other wireless applications. The latency is depended on the scheduling behavior, relationship and resource and the number of users. In the view point of the throughput, it is difficult to evaluate the instantaneous performance. Therefore, the cellular system should be designed in order to compensate short- and long-term performance.

3.2.1.3 User Fairness Indicator

By its properties of the cellular networks, it is necessary that wireless resource is shared among a lot of users. In order to seek to improve the cell throughput, scheduling algorithm just selects the users with best channel state. However, this will be only a partial solution in the multi-user environment. Since, users with poor channel states can not achieve the minimalist throughput, latency. Selection of best user in the scheduling algorithm does not provide multiple access independent channel states of the all users. In other words, the cellular networks should consider a fairness among users though the scheduling transmission.

In wired communications, user fairness definition is straightforward, a scheduler is specified to be fair if the resources are shared equally among the users, since a fair share in resources results in equalized user data-rates. Because, difference of channel states among users in the wired communication is slight. In wireless communications, the fairness definition is not as straightforward, since a fair share in resources usually does not result in equalized user data-rates. This is because users have different geometries and channel distribution, which result in different achievable data-rates. Consequently, the following two fairness criteria are defined and are used, for evaluation of user fairness;

Allocation Fairness An allocation fairness F_A is calculated by the amount of allocated resource within a given scheduling term as defined in [7]:

$$F_A(\Delta T) = \left(\sum_{m=1}^{M} A_m(\Delta T) \right)^2 / \left(M \cdot \sum_{m=1}^{M} A_m(\Delta T)^2 \right), \qquad (3.1)$$

where M is the number of users and $A_m(\Delta T)$ is the number of allocation units scheduled to user m in time interval ΔT. Let F_A denotes user fairness in view point of number of assigned resource or assignment probability. In other words, F_A is closely-linked to the latency, therefore a number of user has large latency if F_A is reduced close to zero.

Data-rate Fairness A data-rate fairness refers to the achieved data-rate (or throughput) within a given scheduling term, which is equivalent to fairness criterion definde in [8]:

$$F_R(\Delta T) = \left(\sum_{m=1}^{M} R_m(\Delta T) \right)^2 / \left(M \cdot \sum_{m=1}^{M} R_m(\Delta T)^2 \right), \tag{3.2}$$

where $R_m(\Delta T)$ denotes the data-rate user m within the interval ΔT. Usually, $F_R(\Delta T)$ is used in order to evaluate the user fairness in most of literatures and is also called *Jain's fairness index*.

In both cases, a fairness value of one corresponds to optimal fairness within a given time interval ΔT with respect to the defined criterion. Of course, $F_A(\Delta T) = 1$ and $F_R(\Delta T) = 1$ indicate that all users received identical resources/data-rates within the time interval ΔT.

3.2.2 Multiple Access Technique

3.2.2.1 Multiple Access employed from 1G to 3G Networks

Efficient allocation of signaling dimension between users is key technology for wireless networks with multiple users. When dedicated channels are allocated to users it is often called multiple access. Dedicated channels are obtained from the system signal space using a channelization method such as time division, frequency division, code division and some combination of these techniques. The most common methods to divide up the signal space are along the time, frequency and/or code axes. The different user channels are created by an orthogonal division along these axes; time-division multiple access (TDMA), frequency-division multiple access (FDMA) are orthogonal channelization methods, whereas code-division multiple access (CDMA) is orthogonal and nonorthogonal channelization method, depending on the code design.

In first-generation (1G) of wireless telephone technology or mobile telecommunications, FDMA shown in Fig. 3.2 is employed for multiple access. The FDMA is dedicated channels are divided into frequency axis into non-overlapping channels for orthogonal channelization. The property of FDMA is continuously assigned to

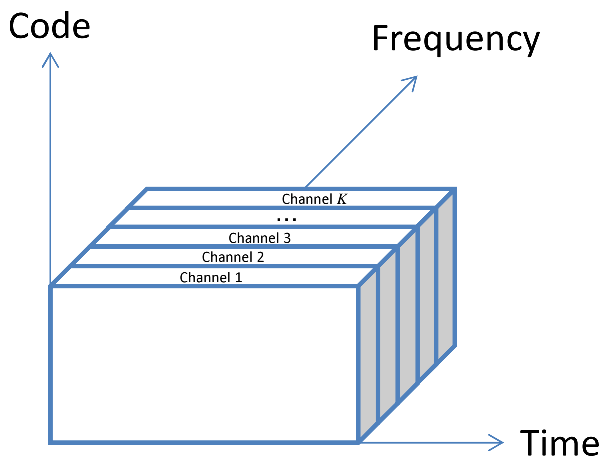


Figure 3.2: Frequency-division multiple access.

users, therefore it is not required to packet-based communication. However, the FDMA system should set the guard interval between channels in order to compensate for imperfect filters, adjacent channel interference, and spectral spreading due to Doppler. Moreover, it is difficult to assign multiple channels to the same user simultaneously under FDMA, since this requires the radios to simultaneously demodulate signals received over multiple frequencies.

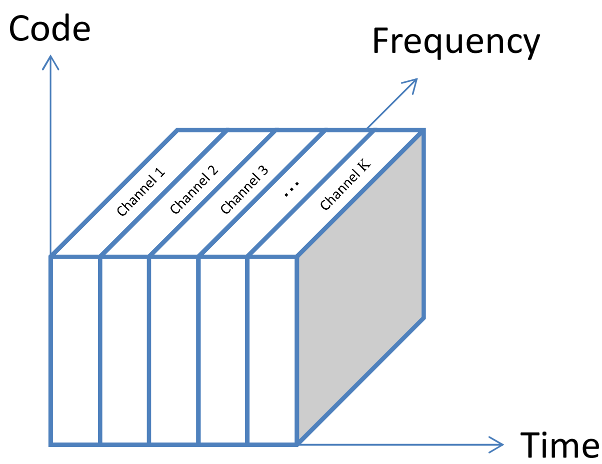


Figure 3.3: Time-division multiple access.

Second-generation (2G) employs TDMA shown in Fig. 3.3 for multiple access. In TDMA, the wireless resources are divided along the time axis into non-overlapping channels. TDMA has advantages that it is simple to assign multiple channels to a single user by simply assigning multiple time slots. This means the improved flexibility of scheduling, and frequency diversity can be used under TDMA. However, TDMA faces problems different from FDMA; transmission is not continuity, since buffering of transmission data are required. Another problem is that TDMA channel is formed the entire system channel. This is typically wideband, so some mitigations of Inter Symbol Interference (ISI) caused by frequency selective fading, are required. In order to achieve the high efficiency communication, tightly synchronization between the base station and user is necessary.

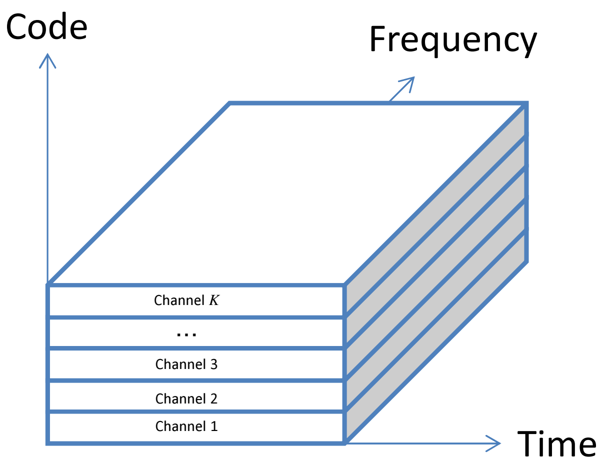


Figure 3.4: Code-division multiple access.

In CDMA, signal space is channelized into code axis, therefore multiple transmit signals are overlapped in the frequency and time domain. By dividing orthogonal or non-orthogonal codes, transmit signals to other users can be ignored due to code orthogonality, or can be reduce to small interference caused by low cross-correlation among codes. In the down link, orthogonal spreading codes are often used, since multiple signals are transmitted from the same transmitter. On the other hand, each transmit signals is modulated by non-orthogonal spreading codes, because of synchronization among transmit nodes.

In FDMA and TDMA, it is limited how many channels are obtained; however, there is no hard limit on the number of channels in CDMA. Nevertheless, the number of channels is depended on the code design, non-orthogonal spread codes can obtain the large number of channels compared with orthogonal codes.

In CDMA, the number of channel and level of interference is trade-off. To increase the number of channel in CDMA causes high level interference in the multiple access communication. In third-generation (3G) networks, CDMA has been employed for the reasons set forth above. Compared with TDMA, CDMA can obtain highly-confidential communication, high data-rate and high quality sound. Additionally, the number of users per bandwidth can be increased and also frequency reuse factor can be directly reduced to 1 by using CDMA due to spreading properties.

3.2.2.2 Orthogonal Frequency Division Multiple Access (OFDMA)

In the 4G networks, multiple access technique enables the high spectral efficiency and throughput, is required. Other multiple access techniques are channelized into frequency, time and code axises, therefore degrees of freedom in the scheduling is only one. In the wideband digital communication, transmit signals are affected by frequency selective fading due to multi-path, this effects lead the performance degradation. However, the Orthogonal Frequency-Division Multiple Access (OFDMA) is a multi-user version of the popular orthogonal frequency-division multiplexing (OFDM) digital modulation scheme.

The primary advantage of OFDM as shown in Fig. 3.5 over single-carrier schemes is its ability to cope with severe channel conditions (for example, attenuation of high frequencies in a long copper wire, narrowband interference and frequency-selective fading due to multipath) without complex equalization filters. Channel equalization is simplified because OFDM may be viewed as using many slowly modulated narrowband signals rather than one rapidly modulated wideband signal. The low symbol rate makes the use of a guard interval between symbols affordable, making it possible to eliminate inter-symbol interference (ISI) and utilize echoes and time-spreading to achieve a diversity gain, i.e. a signal-to-noise ratio improvement.

OFDMA allows simultaneous low-data-rate transmission from several users by assigning subcarriers to different users. The difference between the OFDM and OFDMA is shown as Fig. 3.6. While OFDM addresses communications in noisy smart grid environments,it is still insufficient to achieve reliable communications

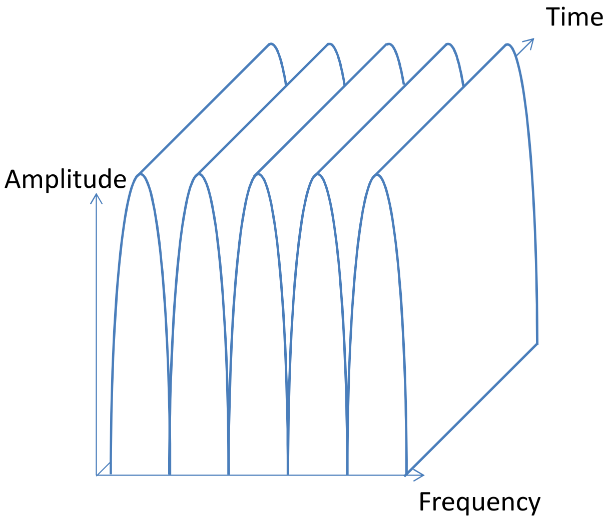


Figure 3.5: Orthogonal frequency-division multiple access.

in the very harsh conditions To further improve reliability the OFDM method can be combined with a multiple access scheme. This allows simultaneous transmission of several individual data streams. OFDMA further improves OFDM robustness to fading and interference, but more importantly the individual data streams can be used either to communicate with multiple nodes (power meters) simultaneously or for redundancy, thus greatly improving the reliability of the system.

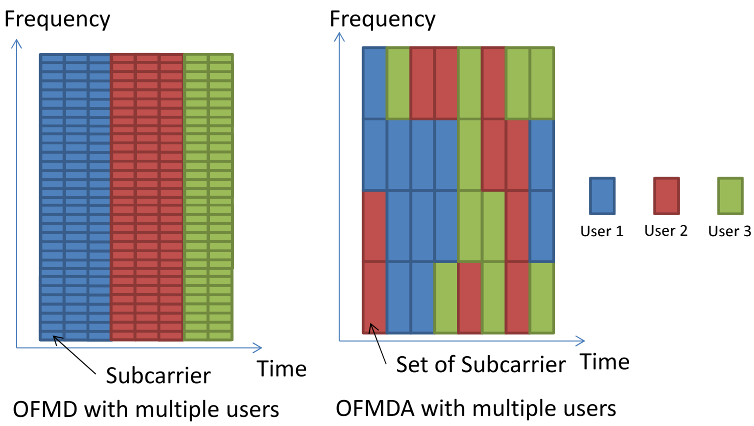


Figure 3.6: Difference of resource assign in the scheduling between OFDM and OFMDA.

3.2.3 Scheduling Algorithm

The cellular networks have to support the multi-user communication regardless of the number of available channels. As previously mentioned in the Sec. 3.2.2, the available resource is divided into some dimension such as space, frequency, time and code, in order to support the multi-user communications. However,multiple access techniques provide only mechanism for flexible use of wireless resource, does not show an assigning channel to users in systematic method called transmission scheduling. The random access techniques such as pure ALOHA[9], slotted ALOHA[10] and Carrier-Sense Multiple Access (CSMA)[11], are also one of the multiple access. However, if users have long strings of packets or continuous-stream data, random access protocols show poor performance due to collisions. In the cellular environment, it is difficult to achieve to high performance by applying random access protocols.

In the wireless networks with many users, the multi-user diversity can be taken by transmission scheduling as the advantages for improvement of the system capacity and/or performance. By transmitting to users with best or better channel at any given time, so called *opportunistic scheduling*, wireless (or system) resources can be allocated efficiently in the view point of the spectral efficiency. The idea of the opportunistic scheduling is premised on selection diversity which selects the users with best channel in any given fading state. To select the users with best channel leads increasing the total capacity of a coverage; however not necessarily correspond to simultaneously improve other performance factor. The cellular system should decide the channel assignment considering not only throughput but also other factors. In order to improve the cellular performances, typical scheduling algorithms have been proposed. This subsection describes details of three scheduling algorithms: Round Robin, Max-CIR and Proportional Scheduling.

Round Robin Scheduling The round-robin scheduling has been considered as process scheduler of personal computer in order to schedule processes fairly. This scheme can be applied to wireless networks for scheduling transmission as the simplified fair algorithm. The algorithm lets every active data flow that has data packets in the queue to take turns in transferring packets on a shared channel in a periodically repeated order. By assignment in a periodically repeated order, allocation fairness F_A can be achieved to 1 under the round-robin algorithm. However, in the wireless networks, round-robin scheduling does not utilize wireless resource with multiuser diversity caused by difference of channel states among users. Higher throughput and system spectrum efficiency may be achieved by channel-dependent or -aware scheduling, for example a proportional fair algorithm, or maximum throughput scheduling.

Maximum Throughput Scheduling In order to utilize the wireless resource with high efficiency, scheduling algorithm is required to aware the channel states of users. The maximum throughput scheduling is one of the channel-aware or link-adaptive scheduling. According to the feedback information of channel states from users, this algorithm selects the users with best channel states under the orthogonal signalization multiple access such as FDMA or TDMA. In the CDMA with nonorthogonal channelization, the carrier-to-interference ratio (CIR) is used as the channel states, so called Max-CIR algorithm. Assignment users of maximum throughput scheduling are decided according to the following equation,

$$m^*(t) = \arg\max_{1 \leq m \leq M} D_m(t), \tag{3.3}$$

where $m_i^*(t)$ is assignment user at the time t and $D_m(t)$ is denotes the data rate of user m, potentially achievable in the present time slot t. The strategy of maximum throughput scheduling can improve the system throughput; however this algorithm often fail to achieve high user fairness. Because, instantaneous channel states is only used for metric of assignment, namely that indicates low probability of assignment to users with poor channel states.

Proportional Fair Scheduling The scheduling algorithm should aim to achieve high cell throughput and high user fairness in the same time. By selecting the maximum throughput scheduling can only high cell throughput at the cost of the user fairness. This is caused by ignoring the historical assignment results of users, which are throughput, fairness, latency and so on.

In order to achieve balancing of throughput and fairness, proportional fair scheduling has been considered. The proportional fair scheduling uses the ratio of throughout estimated by feedback CSI into next slot and average assigned throughput until current slot, as the metric of scheduling. Assignment users of proportional fair scheduling are decided according to the following equation:

$$m^*(t) = \arg\max_{1 \leq m \leq M} \frac{D_m(t)}{R_m(t)}, \tag{3.4}$$

where $R_m(t)$ is the historical average throughput of user m. Definition of $R_m(t)$ is often used Moving Average for consideration of historical assignment results. Users with poor channel have lower $R_m(t)$, then the metric is increased even if the $D_m(t)$ is low. Additionally, if users with better channel states is not assigned over the long term, $R_m(t)$ becomes small value as time advances. Therefore, proportional fair scheduling can balance the throughput, user fairness and latency.

3.3 Heterogeneous Network

In the recent years, new paradigm form peer-to-peer communication in the cellular networks has been attracted attention. Currently, cell coverage become smaller and smaller such as pico and femto cells, and frequency reuse factor is reduced to 1, in order to improve the system capacity. However, past peer-to-peer communications approach theoretical limit due to high inter-cell interference. As a efficient solution of this problem, the mixture network so called Heterogeneous Network will be employed in forth-generation (4G) networks. The HetNet is consist of the macro- and femto-tier cells, femto-tier cells are located over the macro coverage, as shown in Fig. 3.7.

The advantage of using the femto-tier that are located inside buildings is significant since 50% of voice calls and more than 70% of data traffic originate indoors [4]. The survive of the macro coverage essentially has a coverage holes in specific area (e.g., indoor environment), then low-power and small-coverage local nodes such as pico, femto, and relay nodes deployed at coverage holes. The HetNet aims to improve the system capacity by using the HeNB overlaid to the

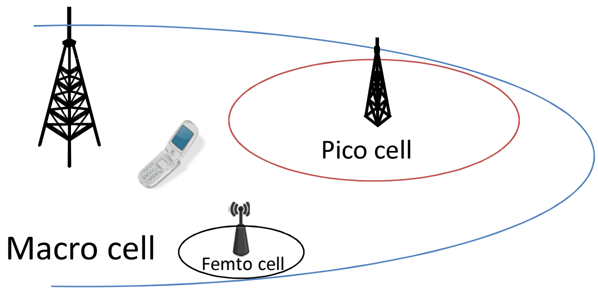


Figure 3.7: Heterogeneous Networks.

MeNB coverage. Moreover, it can be expected to increase not only total system capacity but also the throughput of the cell edge user.

However, HetNet structure faces both cross- and inter-tier interference problems in the same time. LTE is designed for frequency reuse 1 to maximize spectrum efficiency, which means that all the neighbor cells are using same frequency channels and therefore there is no cell-planning to deal with the interference issues. There is a high probability that a resource block scheduled to cell edge user, is also being transmitted by neighbor cell, resulting in high interference, eventually low throughput or call drops. Traffic channel can sustain upto 10% of BLER in low SINR but control channels cannot. Neighbor interference can result in radio link failures at cell edge. Heterogeneous networks require some sort of interference mitigation, since pico- and/or femto-tier cells and macro-tier cells are overlapping in many scenarios

In this section, interference mitigation or improvement of cell-edge performance, introduced in 3GPP Release are described. However, it is premised on that existence of MeNB-HeNB back-haul coordination, allowing modifications of existing macro-cells for HetNet deployment are tolerated in contrast to cognitive heterogeneous (or two-tier) networks Then, it is difficult to employ these techniques to cognitive HetNets, because pico- and/or femto-tier cells are considered as the secondary system.

3.3.1 Inter-Cell Interference Coordination (ICIC)

Inter-cell interference coordination (ICIC) is introduced in 3GPP release 8. ICIC is introduced to deal with interference issues at cell-edge, since the improvement of cell-edge performance is one of key challenges for 4G networks. ICIC uses power and frequency domain to mitigate cell-edge interference from neighbor cells by using the spatial resource pattern.

One scheme of ICIC is where neighbor eNBs use different sets of resource blocks through out the cell at given time i.e. no two neighbor eNBs will use same resource assignments for their UEs. This greatly improves cell-edge SINR. The disadvantage is decrease in throughput throughout the cell, since full resources blocks are not being utilized. In the second scheme, all eNBs utilize complete range of resource blocks for centrally located users but for cell-edge users, no two neighbor eNBs uses the same set of resource blocks at give time.

In the third scheme, all the neighbor eNBs use different power schemes across the spectrum while resource block assignment can be according to second scheme explained above. For example, eNB can use power boost for cell edge users with specific set of resources (not used by neighbors), while keeping low signal power for center users with availability of all resource blocks.In order to employ, X2 interface is used to share the information between the eNB.

3.3.2 Enhanced Inter-cell Interference Coordination (eICIC)

Enhanced Inter-cell Interference Coordination (eICIC) is introduced in 3GPP release 10 to deal interference issues in Heterogeneous Networks (HetNet). The eICIC mitigates interference on traffic and control channels by using transmit power, frequency and also time domain to mitigate intra-frequency interference in heterogeneous networks

One of eICIC introduces concept of "Almost blank subframe" (ABS). ABS subframes do not send any traffic channels and are mostly control channel frames with very low power. If macro cell configure ABS subframes then UEs connected to pico/femto cells can send their data during such ABS frames and avoid interference from macro cell.

Additionally, the throughput of pico/femto can be improved when the MeNB sets the ABS, because the cross-tier interference is reduced or disappeared by setting ABS. However, the ABS scheme is only improvement of users connected to HeNB, the performance degradation of users connected to MeNB should be avoid by another technique.

3.4 Chapter Summery

We introduces the introduction of relationship between cellular network and heterogeneous networks. The design challenges for a cellular system are: efficiency frequency reuse, improvements of system capacity and cell-edge performance, efficiency scheduling with high user fairness and so on. By allowing the overlapping of multi-cells with different cell size, to solve these issues and we apply the cognitive radio technology investigated in chapter 3, and propose a efficiency resource allocation under the interference constraint.

Chapter 4

Interference Constraint based on Capacity Conservation Ratio

This chapter presents an interference constraint based on the Capacity Conservation Ration(CCR). The CCR is defined as the ratio of the decreased capacity due to the interference from secondary user to the original capacity of a system. By utilizing the CCR as a metric of the interference constraint to protect the primary user, a secondary user can achieve sufficient performance without a large degradation in the primary capacity.

In this chapter, we consider the two primary model in the spectrum sharing. Firstly, the static model of the primary user affected by channel fluctuation such as propagation loss, shadowing and fading, when a primary link is established. Second one is the dynamic model of the primary system which dynamically allocates the wireless resource in the both time and frequency domains.

In order to protect the primary systems in the static and dynamic model, to design the interference constraint enables protect the primary behavior is necessary. The proposed interference constraint can protect both primary model by using the CCR as novel metric. In the static model, protection performance is evaluated through the numerical analysis which derive the spacial and probability distribution of primary capacity. In addition, protection performance in the dynamic model is evaluated through the computer simulation which models the scheduling transmission in the primary system.

The remainder of this chapter is organized as follows. Section 4.2 introduces a novel metric called the CCR and a CCR-based constraint to protect the primary user. Analytical equations for evaluating the performances of the primary protection in the static model are developed and numerical examples are shown in Section 4.3. Section 4.4 presents simulation results in the dynamic model, and the conclusions are provided in Section 4.5.

4.1 Introduction

In wireless communications, it is necessary to improve the spectral efficiency attributed to the shortage of frequency resources. However, according to a report of the FCC, a vacant spectrum called White Space is observed [12]. Spectrum sharing utilizes cognitive radio techniques that make effective use of white space and has attracted attention as an essential solution [13]. Cognitive radio is able to change communication methods, modulation methods, signal frequency, data rate, and other parameters according to the surrounding wireless environment. Spectrum sharing can improve the spectral efficiency and can reduce the cost of a complicated spectrum assignment. However, when a cognitive (secondary) user accesses the licensed band, the secondary user is required to protect the licensed (primary) users by sufficient reliable primary protection methods.

Spectrum sharing is divided into the following two types, depending on the access strategy for the secondary users: overlay type [14] and underlay type [15]. Overlay type allows the secondary user to only transmit while the primary band is idle. In contrast, in underlay type, the secondary user and the primary user can simultaneously access the same band. Underlay type can provide the secondary users with more access opportunities than overlay type. However, the received interference at the primary receiver (PU-Rx) should be restricted to less than or equal to a predefined level on the basis of an interference constraint.

Several interference constraints for the underlay type have been proposed in many papers [16]–[24]. The first constraint uses the interference power at the PU-Rx as a metric of the interference limitation shown in [17], [18]. The second constraint restricts the interference power on the basis of the signal-to-interference ratio (SIR) of the PU-Rx [19], [20]. Other constraints are the restriction of interference by the outage constraint in the primary capacity [23] or the SIR of the primary user [24].

However, these interference constraints does not support the wide range of primary SNR, and dynamic resource allocation behavior of primary user. In the spectrum sharing, we need to consider the primary behavior in both the static and dynamic system models for designing the interference constraint. Firstly, in the static model, the interference constraint should consider channel fluctuation such as propagation loss, shadowing and fading, when a primary link is established. Because, in the view point of system level, it is necessary to protect the primary link affected by these channel effects. In other words, the interference constraint is required to support the primary protection over the wide range of primary SNR.

Additionally, spectrum sharing in the dynamic system model is more complicated due to the scheduling transmission in the primary system. In the scheduling transmission, the primary system allocates the wireless resource in the time and frequency domain to multiple users. The most part of scheduling transmission, the assign behavior is decided according to the channel states in primary users and past scheduling results. Altogether, the performance of the primary system is depended on both current and past interference from the secondary users. In order to protect the primary system in the dynamic model, the interference constraint has to consider both temporal primary behavior to maintain the original primary performance.

The application scope of the spectrum sharing is extended behind above discussions. This underlay type has been attracted to apply to the cellular networks as the heterogeneous networks (HetNet) [25, 26, 27] or the Device to Device (D2D) communication [31],[32]. The HetNet and the D2D communication are the spectrum sharing between the cellular network and short range communication in the overlapped coverages. Usually, the high traffic is existed in an indoor environment or a small local area; hence it is difficult to support the traffic by only the macro base station.

The HetNet and/or D2D communication aims to improve the system capacity by the mixture network. The capacity improvements by HeNB and/or D2D have some advantages; smaller costs, smaller the control overhead; it is to expect that operators of the primary user and the secondary user is the same. In other words, the spectrum sharing in the cellular networks is an interesting topic [28, 29, 30]. However, in the cellular networks, the mobile node (as the primary user) has wide variance SNR due to the large coverage of a DTV White Space differently from the primary user model in the existing research.

Moreover, the wireless resource is allocated according to scheduling algorithm to primary users. In existing researches of the spectrum sharing, HetNet and D2D communication, this primary behavior is not considered when the interference constraint is designed. However, the system level performance of the primary system in the dynamic model is depended on the scheduling transmission behavior. It is very important to design the interference constraint considering the dynamic primary behavior.

Therefore, the new metric of the interference constraint to support the wide variance SNR of the PU-Rx and the scheduling transmission of the primary system are necessary. This chapter proposes an interference constraint based on the capacity conservation ratio (CCR) as a novel metric for advanced protection of the primary user. The proposed constraint can maintain the degradation ratio of the primary capacity. Then, it can support high- and low-capacity PU-Rxs with the same constraint threshold. Additionally, the proposed constraint can keep the original values of the scheduling performance indexes such as user fairness, delay and so on.

These results leads benefit behavior in the spectrum sharing with dynamic primary system, because the linearity property of protection against the primary SNR can keep original scheduling behavior in the spectrum sharing. Especially, our interference constraint has advantage in the link-aware scheduling such as the proportional fair scheduling. This protection performance is evaluated in the view points of the throughput, user fairness and delay in the primary system.

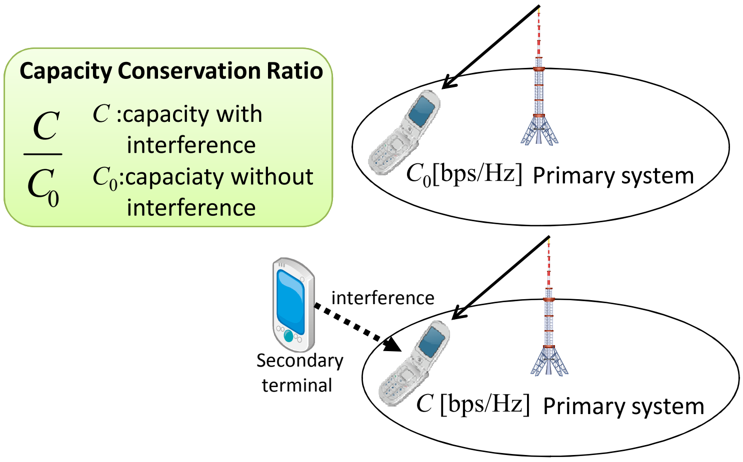


Figure 4.1: Proposed Metric: Capacity Conservation Ratio.

4.2 Capacity Conservation Ratio and Interference Constraint

The communication performance of the primary user can be evaluated on the basis of many factors, including the SIR, signal-to-noise-plus-interference ratio (SINR), channel capacity, throughput, delay time, outage probability, and received interference power. Thus, the secondary user has to control the interference on the basis of these factors to protect the primary user.

Utilizing the throughput as the evaluated metric protects the primary user better, because the throughput is directly related to the performance. However, consideration of the throughput in multilayer systems is complicated, and its value is difficult to estimate with high accuracy, even in the primary transmitter (PU-Tx). Hence, it is necessary to consider a single-layer value as a metric. In the physical layer, some simple values have been utilized to characterize the interference state, as outlined in the previous section. However, most values in the physical layer depend on not only the system parameters but also the surrounding environment. Thus, using a value in the physical layer as an evaluated metric requires the estimation of variables in the surrounding environment at the PU-Rx.

The maximum degradation of the primary capacity, based on the proposed constraint and the other three constraints, is shown in Fig. 4.2. The interference-based constraint, the SINR-based constraint and the SIR-based constraint use calculable values as metrics. The constraint based on the interference power at the PU-Rx can protect the primary user in a high-capacity region as shown in Fig. 4.2. When the primary capacity is high, the signal power is greater than the noise power. Thus, the restricted interference power is lower than the signal power, and the primary capacity is maintained at a high level. However, when the primary capacity is low, the Fig. 4.2 shows the restricted interference is relatively greater than the signal power. Therefore, the degradation of the both higher capacity and lower capacity PU-Rxs cannot be avoided without the adaptive control of the constant threshold.

The SIR-based constraint of the PU-Rx can protect the capacity of the primary user with high quality in the low-capacity region from Fig. 4.2. This constraint restricts interference based on the SIR; thus, the SINR is maintained at a high level when the primary capacity is low. However, in the high-capacity region, the restricted interference power becomes considerably greater than the noise power. Since, the primary capacity degrades by a large extent as shown in Fig. 4.2. Moreover, the outage constraint only guarantees the minimum quality not the maximum quality; the primary user with the higher performance has possibilities of the large degradation under this constraint. The SINR-based constraint has large problems; the SU-Tx cannot transmit the signal if the SNR at the PU-Rx is smaller than the threshold SINR, and the maximum SINR of the PU-Rx is restricted less than the threshold SINR as shown in Fig. 4.2. Altogether, if the primary user has large coverage, these constraint is not enough to protect the all primary user in the large variance SNR.

In this section, we focus on the channel capacity as an evaluated value. The capacity calculation also does not require complex calculations. However, we consider the possibility that utilizing only one value as a metric is not sufficient. The main reason for the large degradation of the primary capacity is the limitation of interference at a certain level as a threshold. The CCR is defined as the ratio of the capacity of the PU-Rx without interference from the secondary transmitter (SU-Tx), C_0 [bit/sec/Hz], to the decreased primary capacity due to interference,

C [bit/sec/Hz], given by the following equation:

$$CCR = \frac{C}{C_0}. \tag{4.1}$$

Figure 4.1 illustrates a proposed metric called the CCR. C_0 is calculated by

$$C_0 = \log_2 \left(1 + \frac{S_\mathrm{p}}{N_\mathrm{p}}\right), \tag{4.2}$$

where S_p is the received signal power at the PU-Rx, and N_p is the noise power. If the PU-Rx receives intra-system interference, this interference is included in the noise power. Then, C is calculated by

$$C = \log_2 \left(1 + \frac{S_\mathrm{p}}{N_\mathrm{p} + I_\mathrm{p}}\right), \tag{4.3}$$

where I_p is the interference power from the SU-Txs.

In the case of the CCR, the interference level is indicated by the differential ratio of the capacity. The CCR targets the capacity of the primary terminal and takes a value from 0 to 1. If this ratio is 1 or a similar value, then the received interference at the primary terminal is small. In the case of spectrum sharing, the secondary user is required to maintain the CCR at a high level. In addition, we need to consider that it is difficult to reduce the interference probability owing to the uncertainty of the wireless channel. Therefore, probabilistic protection of the primary user is necessary. By defining two types of constraint parameters, we satisfy this requirement. The proposed constraint based on the CCR is defined by

$$\Pr\left[\frac{C}{C_0} \leq \alpha\right] \leq \beta, \tag{4.4}$$

where α is the allowable minimum CCR, and β is the allowable maximum probability of the CCR dropping below α.

By using the CCR as a metric, we find that when the primary capacity is high, it can be maintained at a high volume. As a result, degradation of the primary capacity can be suppressed to a low level when the primary capacity is low. Figure 4.2 shows that the constraints based on the CCR can protect the different capacity terminals by utilizing the same threshold value.

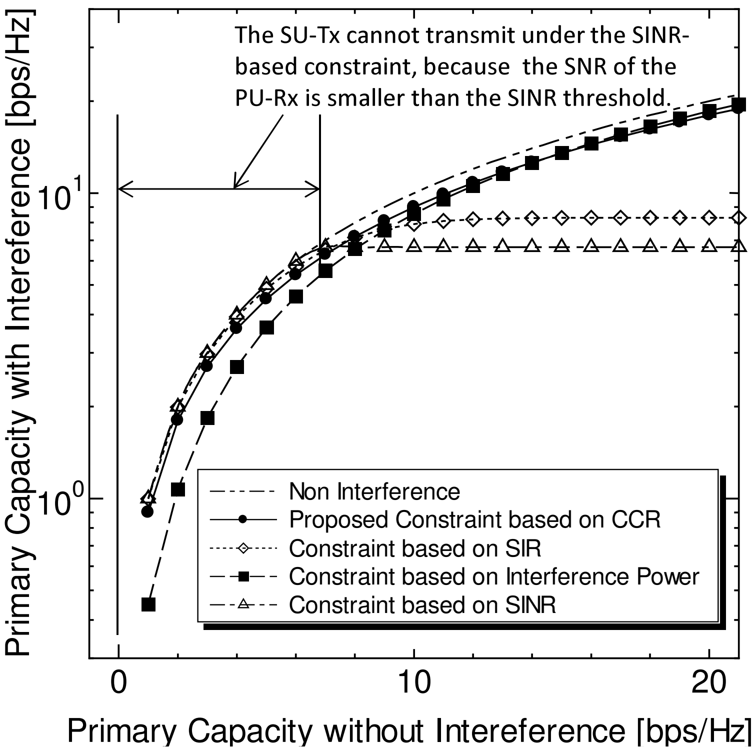


Figure 4.2: Protective characteristics of three constraints.

4.3 Numerical Analysis in Static Model

4.3.1 System Model

The target of our proposed constraint is spectrum sharing in an environment that has varying capacities for the PU-Rx attributed to varying locations and SNRs. For example, cellular systems have various types of receivers with high capacity or low capacity owing to a large coverage area. Our system model, which is utilized for the analysis, is shown in Fig. 4.3. In this figure, the circles denote the primary terminals and the triangles denote the secondary terminals. The symbols in white denote the receivers, and the symbols in black denote the transmitters. The large solid circle bounds the primary coverage area, and the smaller dotted circle bounds the secondary coverage area.

In our analysis, the following assumptions are considered. Here, the analytical object is only one primary cell; thus, inter-cell interference within the primary user

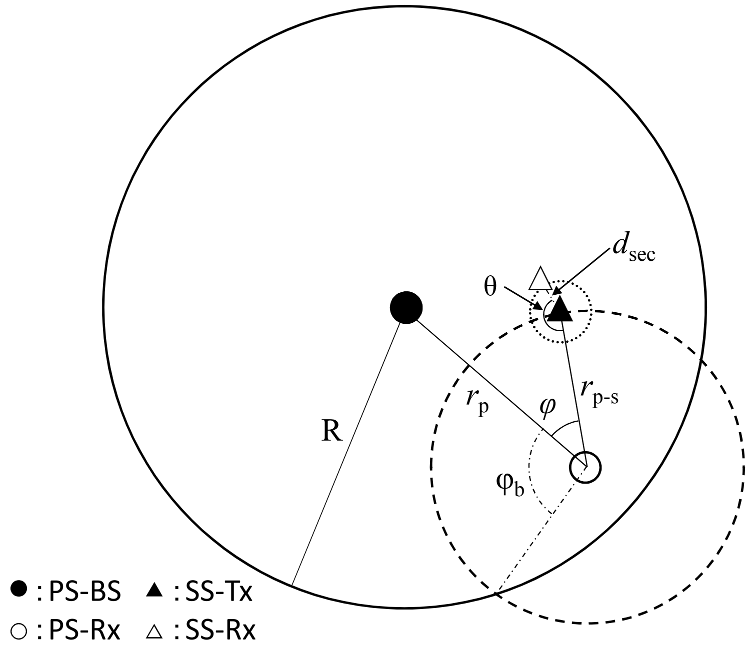


Figure 4.3: System model for capacity analysis.

is not considered. Additionally, the primary user does not have an adaptive power control function for easy analysis. The communication distance of the secondary user is significantly shorter than that of the primary user. In this thesis, the communication distance of the secondary user is fixed and one secondary pair is active in the primary cell. Therefore, the interference of the secondary user is only from the primary transmitter.

In this thesis, the channels between all terminals are assumed to be Rayleigh fading channels. Additionally, the path loss is given by

$$L_{\text{path}}(d) = -10\log_{10}\left(\frac{\lambda}{4\pi d_0}\right)^2 + 10n\log_{10}\left(\frac{d}{d_0}\right), \tag{4.5}$$

where λ is the wavelength of the carrier frequency, d_0 is the reference distance and d is the communication distance.

4.3.2 Spatial Distribution of Primary Capacity

In this subsection, we analyze the spatial distribution of primary capacity. First, we derive the average received power and the average received interference power. The average received power of the PU-Rx, which is located at a distance of r_{p}[m] from the transmitter, is calculated as

$$P_{\mathrm{rx,pri}}(r_{\mathrm{p}}) = 10^{\frac{P_{\mathrm{tx,pri,dBm}} - L_{\mathrm{path}}(r_{\mathrm{p}})}{10}}. \tag{4.6}$$

The average interference power is dependent on the interference constraint, given the transmit power constraint of the secondary user is not considered. In other words, the SINR of the PU-Rx is function of distance r_{p} and parameters of the interference constraint. In this section, we assume the interference at the PU-Rx equal to maximum value $I_{\mathrm{pri}}(r_{\mathrm{p}})$ which satisfies the interference constraint, then the primary capacity is expressed in the following equation:

$$C_{\mathrm{pri}}(r_{\mathrm{p}}) = \int_0^{\infty}\int_0^{\infty} \log_2\left(1 + \frac{g_{\mathrm{pri}} P_{\mathrm{rx,pri}}(r_{\mathrm{p}})}{N + g_{\mathrm{p\text{-}s}} I_{\mathrm{pri}}(r_{\mathrm{p}})}\right) e^{-(g_{\mathrm{p\text{-}s}} + g_{\mathrm{pri}})} dg_{\mathrm{p\text{-}s}} dg_{\mathrm{pri}}, \tag{4.7}$$

where g_{pri} is the fading factor between the primary transmitter and the PU-Rx, and $g_{\mathrm{p\text{-}s}}$ is the fading factor between the PU-Rx and the SU-Tx. Equation (4.7) is a function of the fading capacity of the primary user in variables r_{p}.

4.3.3 Complementary Cumulative Distribution Function of Primary Capacity

An evaluation by utilizing the average capacity of the system or the fading capacity cannot show the detailed effects of the proposed constraint and the power control schemes. Hence, the complementary cumulative distribution function (CCDF) of the primary capacity is derived to evaluate the proposed methods. Then, We analyze the CCDF of the primary capacity with interference from the secondary user. When the variable of the CCDF is fixed at C_{th}, the required condition of the SINR of the PU-Rx is given by

$$SINR_C \geq 2^{C_{\mathrm{th}}} - 1. \tag{4.8}$$

From eq. (4.8), we obtain the condition of the instantaneous value of the received signal power P given by

$$P \geq (N + I)(2^{C_{\mathrm{th}}} - 1). \tag{4.9}$$

With the interference from the SU-Tx, the fading fractions of the signal power and the interference power are considered simultaneously. Therefore, the average interference power is decided by only the average primary signal power.

Therefore, probability Pr satisfies the condition of eq. (4.9) while considering the average signal power $P_{\mathrm{rx,pri}}(r_{\mathrm{p}})$ and the average interference power, $I_{\mathrm{pri}}(r_{\mathrm{p}})$. As a result, we derive a joint probability shown in the following equation:

$$\Pr(r_{\mathrm{p}}, C_{\mathrm{th}}) = \frac{P_{\mathrm{rx,pri}}(r_{\mathrm{p}}) \exp\left(-\frac{N(2^{C_{\mathrm{th}}-1})}{P_{\mathrm{rx,pri}}(r_{\mathrm{p}})}\right)}{(2^{C_{\mathrm{th}}} - 1)I_{\mathrm{pri}}(r_{\mathrm{p}}) + P_{\mathrm{rx,pri}}(r_{\mathrm{p}})}. \tag{4.10}$$

From the assumption of the power constraint of the SU-Tx, it is not necessary to consider distance r_{p}. Thus, the CCDF of the primary capacity with interference from the secondary user is calculated by an integral of the product of eq. (4.10) with the probability of existence of the average signal power $P_{\mathrm{rx,pri}}(r_{\mathrm{p}})$ from the cell center to the cell edge. The CCDF is shown by following equation:

$$CCDF(C_{\mathrm{th}}) = \int_0^R \frac{2r_{\mathrm{p}}}{R^2} \frac{P_{\mathrm{rx,pri}}(r_{\mathrm{p}}) \exp\left(-\frac{N(2^{C_{\mathrm{th}}-1})}{P_{\mathrm{rx,pri}}(r_{\mathrm{p}})}\right)}{(2^{C_{\mathrm{th}}} - 1)I_{\mathrm{pri}}(r_{\mathrm{p}}) + P_{\mathrm{rx,pri}}(r_{\mathrm{p}})} dr_{\mathrm{p}}. \tag{4.11}$$

4.3.4 System Parameters

The target environment of the proposed constraint and two power control schemes is where the primary SNR is varied due to the differing location of the received terminal. In order to evaluate the performance considering the above environment, the radius of the primary cell is assumed to be $R = 1400$ m. As a result, the difference in the average signal power at the PU-Rx is approximately 50 dB between the terminal located at the cell center and the terminal located at the cell edge. Table 4.1 lists the system parameters used in this evaluation. The parameters of the primary user are determined on the basis of the IEEE 802.16e WiMAX standard [38]. The secondary user is considered to be a femto cell, in which the transmitter is distributed in the primary cell.

Table 4.1: Simulation Parameters.

Channel model		Rayleigh fading
Propagation factor	n	3 (cubic law)
Carrier frequency	f	2.5[GHz]
Noise floor	N_{dBm}	-95.38[dBm]
Radius of primary cell	R	1400[m]
Transmit power of primary	$P_{\text{tx,pri,dBm}}$	40[dBm]
Antenna height of PS-BS	H	32[m]
Communication distance of secondary	d_{sec}	50[m]
Reference distance	d_0	10[m]

4.3.5 Distribution of the Primary Capacity

In this section, we evaluate the performance of the protection of the primary capacity by using two different distributions of the primary capacity, i.e., the space distribution derived in Section 5.4.1 and the CCDF derived in Section 4.3.3. For the sake of comparison, we select two constraints and power control methods; they use interference power and SIR as metrics. For the first metric, the constraint of spectrum sharing and the allowable interference are given by

$$\Pr\left[I \geq I_{\text{th}}\right] \leq \beta, \tag{4.12}$$

$$I_{max,allow,int} = 10^{\frac{I_{\text{th}} - 10\log_{10}(|\ln\beta|)}{10}}, \tag{4.13}$$

where I_{th}[dBm] is the allowable maximum interference power.

To compare the performance, it is necessary to set the parameter of each constraint under the same conditions. The interference constraint based on the interference power has an advantage when the primary SNR is high. Hence, we set the parameter of the constraint to protect the PU-Rx located near the cell

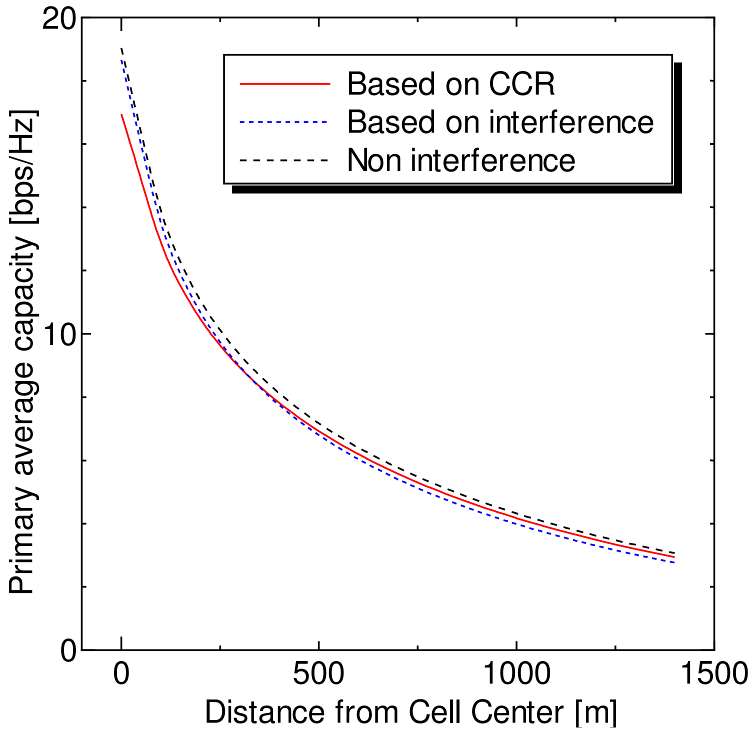


Figure 4.4: Space distribution of the primary average capacity from cell center to cell edge compared with non-interference, CCR, and interference cases.

center. In order to evaluate the capacity region in the system model, we focus on a capacity value with 5% CCDF. In the non-interference case, the primary user capacity is approximately 9.76 bps/Hz at 5% CCDF. Therefore, if the interference from the secondary user is considered, the primary capacity at 5% CCDF should be set as 9.4 bps/Hz in any power control scheme. In order to satisfy this requirement, parameter α in the constraint based on the CCR should be set as 0.66 and I_{th} as -93.5 dBm when $\beta = 0.01$.

Figure 4.4 shows the primary average capacity by changing the location of the PU-Rx from the cell center to the cell edge compared with the non-interference, CCR, and interference cases. As shown in Fig. 4.4, spectrum sharing based on interference can maintain a higher capacity region than spectrum sharing based on the CCR in the cell center area. Compared to the non-interference case, the interference metric can avoid the degradation of the capacity in the high-SNR region. However, in the low-SNR region, the degradation of the primary capacity

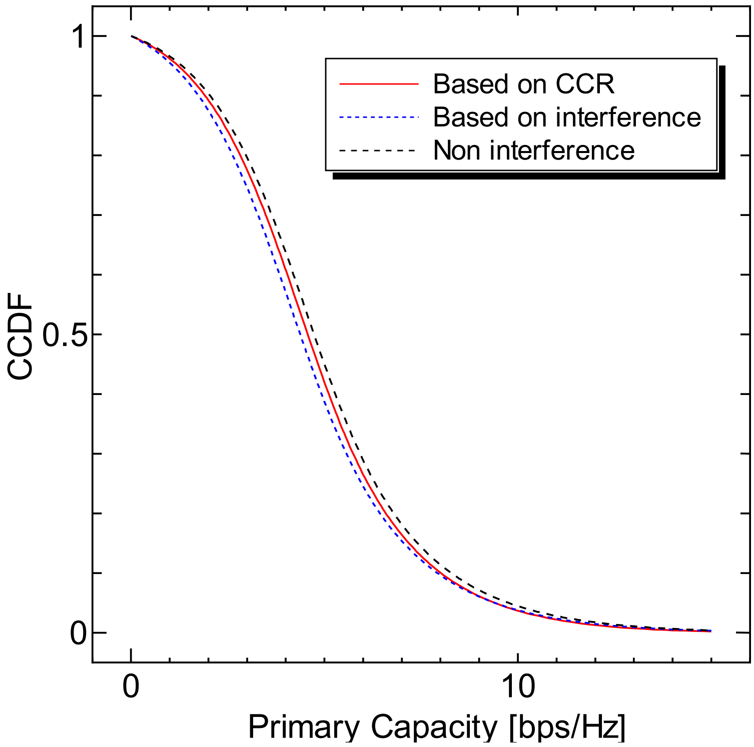


Figure 4.5: CCDF of the primary capacity in the system model compared with non-interference, CCR, and interference cases.

becomes larger than that of the system using the CCR metric. In contrast, the CCR metric can protect the primary capacity without significant degradation in each location by using one metric. Thus, we can confirm that the CCR metric can protect the primary user in a wide capacity region.

Next, the performance of the primary protection is evaluated in terms of the probability distribution. Figure 4.4 shows only the performance of protecting the capacity in the average SNR of the PU-Rx and does not show the distribution characteristic of the primary capacity. Therefore, the CCDF of the primary capacity in the system model is compared with the non-interference, CCR, and interference cases, as shown in Fig. 4.5. These results are obtained under the same condition of Fig. 4.4. The interference metric can protect the primary capacity in the high-capacity region; however, the degradation of the CCDF is not small. In contrast, in the low-capacity region, the CCR metric can maintain the CCDF with a small degradation as compared with the interference metric in any primary capacity.

In a similar way, when utilizing the SIR as a metric, the constraint of the spectrum sharing and the allowable interference are given by

$$\Pr\left[SIR \leq SIR_{\text{th}}\right] \leq \beta, \tag{4.14}$$

$$I_{max,allow,sir} = \frac{P_{\text{rx,pri}} 10^{-\frac{SIR_{\text{th}}}{10}} \beta}{1-\beta}. \tag{4.15}$$

where SIR_{th}[dB] is the allowable minimum SIR.

The SIR-based interference constraint has an advantage when the primary SNR is low. Hence, protection of the PU-Rx with low capacity is required. Here, the requirement to maintain the CDF value of the primary user under the original capacity of 5% of the CDF is approximately 1.32 bps/Hz. Additionally, we set the requirement that the CDF value of 1.2 bps/Hz is maintained at less than 5%. In order to satisfy the requirement, parameter α in the constraint based on the CCR should be set as 0.63, and the SIR_{th} as 3 dB under $\beta = 0.01$.

Figure 4.6 shows the primary average capacity by changing the location of the PU-Rx from the cell center to the cell edge as compared with the non-interference, CCR, and SIR cases. From Fig. 4.6, the SIR metric can protect the primary capacity from 800 m to 1400 m, without a large degradation. However, a large degradation in the cell center area cannot be avoided. In contrast, the CCR metric can avoid a large degradation at each PU-Rx location by using one metric value. Similar to the comparison with the interference metric, we can confirm that the CCR metric can protect the primary user in a wide capacity region.

The CDF of the primary capacity in the system model compared with the non-interference, CCR, and SIR cases is shown in Fig. 4.7. These results are obtained under the same conditions as those shown in Fig. 4.6. From Fig. 4.6, we can confirm that the system using the CCR metric maintains a higher value than the system using the interference metric in common while protecting the high capacity. As a result, the CCR metric can maintain the characteristics of the capacity distribution.

From the four results shown in Figs. 4.4-4.7, spectrum sharing based on the CCR can support a wider capacity region as compared with the other two metrics.

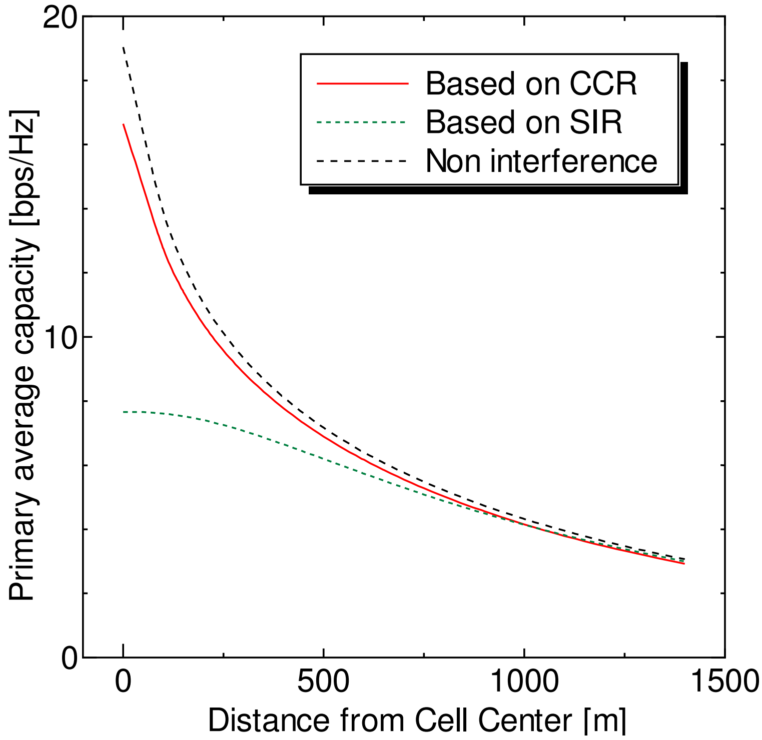


Figure 4.6: Space distribution of the primary average capacity from the cell center to the cell edge as compared with non-interference, CCR, and SIR cases.

When the SNR of the primary user is varied over a wide range, the CCR metric has a beneficial impact on the protection of the primary capacity.

4.4 Simulation Evaluation in Dynamic Model

4.4.1 System Model

The target of our proposed constraint is spectrum sharing in primary system with scheduling transmission within environment that has varying capacities for the PU-Rx attributed to varying locations and SNRs. For example, cellular systems have various types of receivers with high capacity or low capacity owing to a large coverage area. The primary system allocates wireless resources to these users according to the scheduling algorithm. Primary system model, which is utilized for the simulation, is shown in Fig. 4.8. In this model, the primary

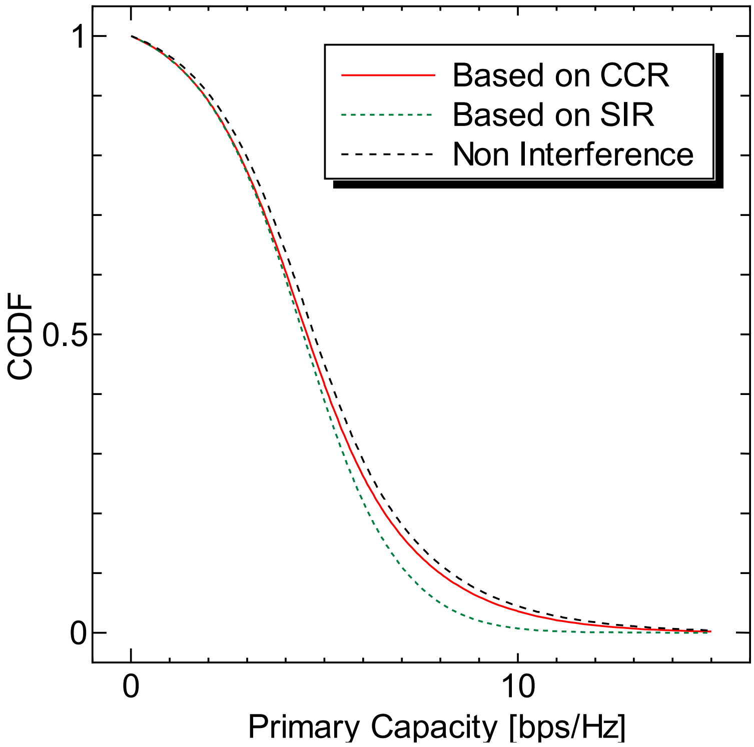


Figure 4.7: CCDF of the primary capacity in the system model compared with the non-interference, CCR, and SIR cases.

system is OFDMA-based system. The PU-Tx allocates the wireless resources in the frequency and time domains to multiple users. The wireless resources is allocated based on proportional fair scheduling.

In the simulation, primary system has circular coverage with a radius of 1732 meters, communicates in the down link on the carrier frequency of 2.5 GHz. The primary parameters are antenna height of 36 meters, total transmit power of 40 dBm, resource block of 1 msec and 180 kHz. The resource assignment of the macro-cell tier is decided based on the PFS algorithm with smoothing factor Tc = 1000, through 10000 slots scheduling term.

In spectrum sharing, the following assumptions are considered. The estimated rates of PU-Rxs are calculated from SNR, and average rates are calculated from SINR interfered by the SU-Tx. The received interferences of PU-Rxs is maximum value which allowed in each interference constraints: the interference power based, SIR based and CCR based constraint.

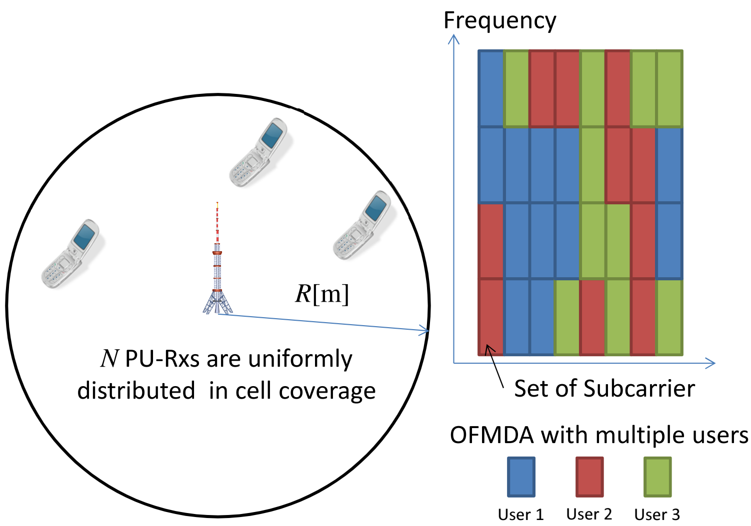


Figure 4.8: Primary System Model for Simulation Evaluation.

4.4.2 The Impact of Interference Constraint

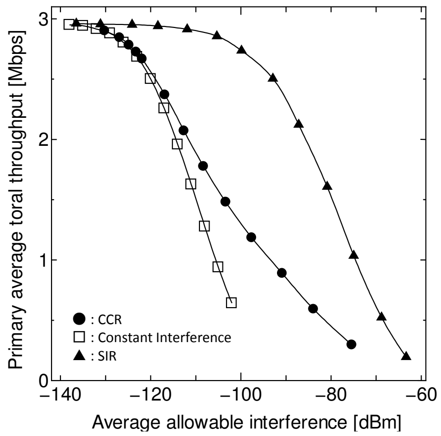
In order to evaluate the performance of scheduling behavior, normalized average rate, average normalized delay of the PU, and fairness of the PU scheduling are used. The fairness is divided into two types which are user rate fairness F_R and the number of allocation resource fairness F_A [49]. F_R indicates fairness of achievable rate among all receivers in scheduling term, and is calculated by the following equation,

$$F_R = \left(\sum_{i=1}^{N} R_i \right)^2 / \left(N \sum_{i=1}^{N} R_i^2 \right), \tag{4.16}$$

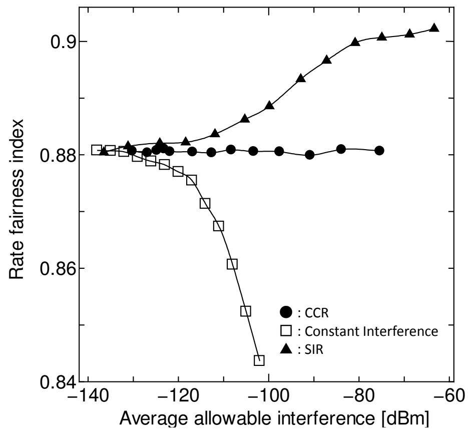
where, R_i is achievable rate of the receiver i in scheduling term, N is the number of the nodes. Besides, F_A indicates fairness of number of assigned resource among all nodes in scheduling term, and is calculated by the following equation,

$$F_R = \left(\sum_{i=1}^{N} A_i \right)^2 / \left(N \sum_{i=1}^{N} A_i^2 \right), \tag{4.17}$$

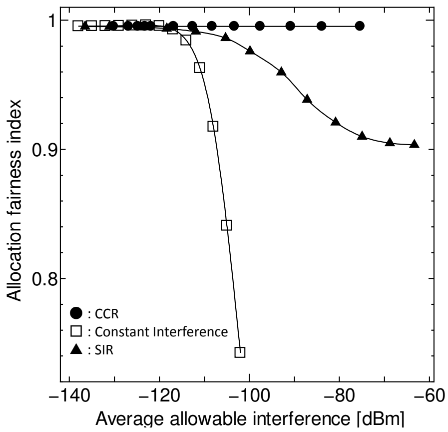
where, A_i is the total number of the assigned resource of node i in the scheduling term. Finally. we describe the definition of delay in this simulation. The duration of consecutive slots in which the number of the assigned resource is zero, is defined as a delay of the receiver.



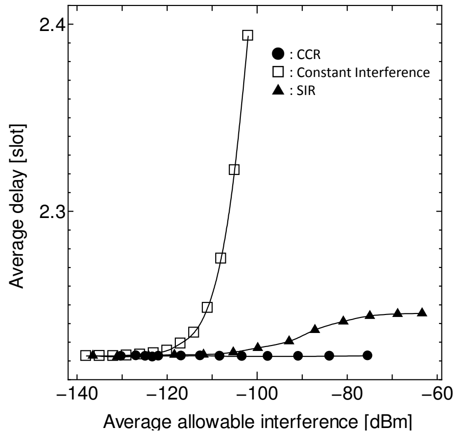
(a) Average throughput of macro-cell tier under three interference constraints.



(b) Data-rate fairness F_R of macro-cell tier under three interference constraints.



(c) Allocation fairness F_A of macro-cell tier under three interference constraints.



(d) Average delay of macro-cell tier under three interference constraints.

Figure 4.9: Performances of macro-cell tier under interference constraints of three metrics.

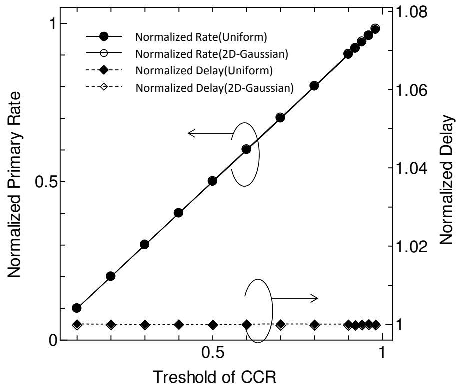
By using four factors, the impact of the interference constraint to the scheduling behavior in the macro-cell tier is evaluated. The simulation results are shown from Fig. 4.9(a) to Fig. 4.9(d). Figure 4.9(a) shows average user throughput of macro-cell tier, interfered by the HeNB with various metric threshold. From

Fig. 4.9(a), we can confirm that the throughput of macro-cell tier is degraded with increasing interference from HeNB over the all constraint. However, degraded throughputs are different among three constraints nevertheless the average interference is the same. This results show that scheduling behavior and most affected users differ depending on the interference constraint.

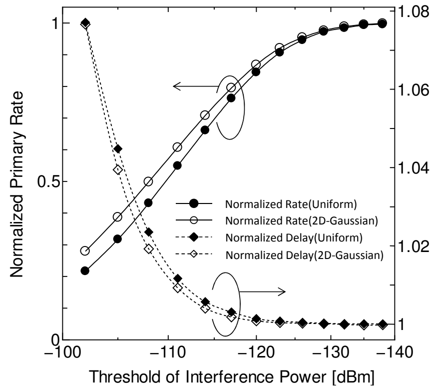
For example, the interference temperature affects the cell-edge user, because throughput of users with lower SNR is more degraded by constant interference power than that with higher SNR. As a result, the average throughput of cell-edge users is decreased and assignment probability of cell-edge users is increased. Therefore, total or average throughput under the interference temperature is reduced. On the other hand, under the SIR constraint, most affected users is changed from cell-edge to cell-center. Hence, the metric of the proportional fair scheduling is increased, because the high estimated rate and low average rate interfered by HeNB. Thereby, the throughput under the SIR constraint is largest over the all interference power compared with other two constraint. In contrast, the CCR constraint keeps the magnitude relationship of average rate among all users, the degradation of the throughput is not noticeable.

Figures 4.9(b) and 4.9(c) show the two fairness results. From two figures, data-rate and allocation fairnesses are largely degraded under the interference temperature. With increasing interference, the data-rate of cell-edge users is sharply dropped. The reasons is the throughput gap between the cell-edge and cell-center becomes large. In the allocation fairness, the fairness is the same degradation as the data-rate fairness, because assigned RBs is concentrated into cell-edge user. By contrast, the data-rate fairness is increased under the SIR constraint in the Fig. 4.9(b). The increase of data-rate fairness caused by reducing gap of throughput between the cell-edge and cell-center due to SIR constraint. However, the allocation fairness is decreased, because of concentrating RBs on cell-center users. Meanwhile, the CCR constraint can keep the same values of two fairness index over all interference region. This is due to characteristic which keeps the magnitude relationship of average rate among all users under the CCR constraint.

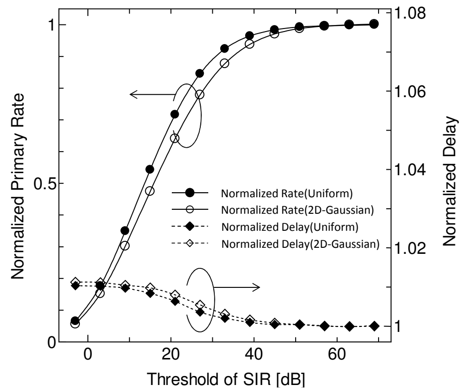
Figure 4.9(d) show the average delay with various interference under three constraint. The interference temperature and SIR constraint cannot maintain



(a) CCR metric



(b) Interference power metric

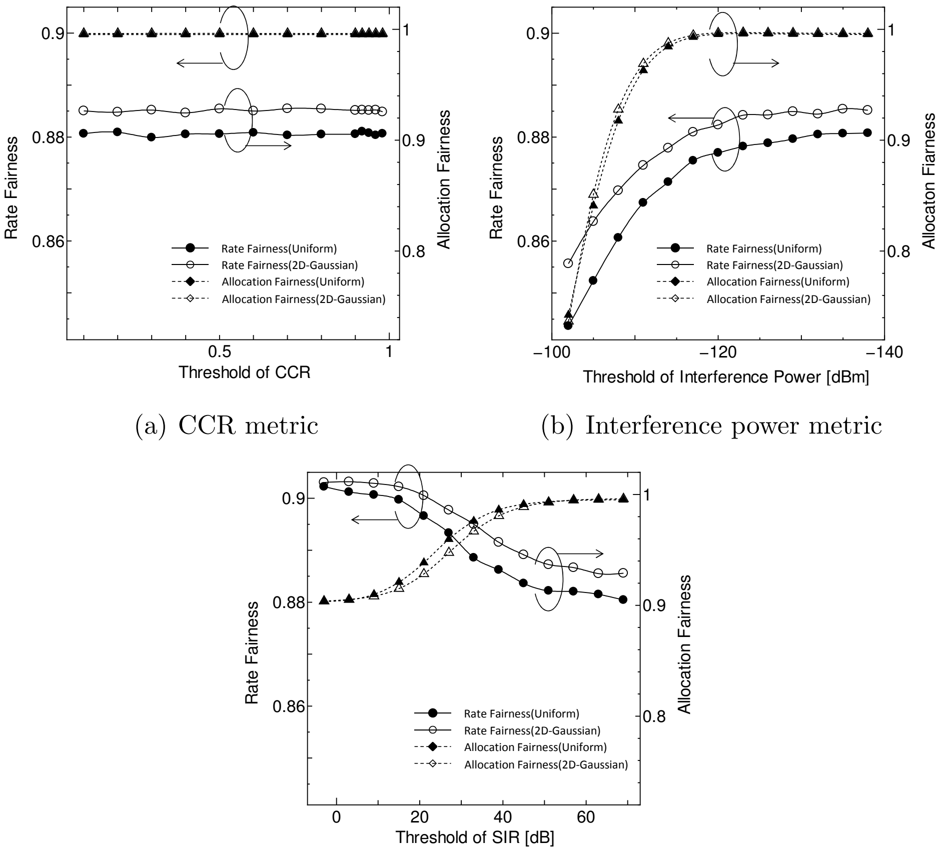


(c) SIR metric

Figure 4.10: Normalized rate and delay of macro-cell tier under interference constraints of three metrics.

the delay with increasing the interference power. The increasing delay is resulted by bias of assignment RBs to cell-ege user or cell-center user. On the other hands, the CCR can keep the same delay over the all interference region. Characteristic which keeps the magnitude relationship of average rate among all users under the CCR constraint enables the same scheduling behavior in existing of strong interference compared with non-interfered case.

Finally, impact on the user distribution in space domain is evaluated. In the spectrum sharing, the threshold value should be decided to applicable value for protection of macro-cell tier (or primary user). From simulation results from



(a) CCR metric

(b) Interference power metric

(c) SIR metric

Figure 4.11: Rate Fairness and Allocation Fairness of macro-cell tier under interference constraints of three metrics.

Fig. 4.9(a) to Fig. 4.9(d), applicable threshold can be decided over three constraints. However, the scheduling performance is depended on the not only propagation curve but also user distribution into cell coverage. Therefore, we evaluate the impact on the user distribution in space domain under three constraints.

Figures 4.10 and 4.11 show the four performances with two user distribution: uniform and 2D-Gaussian distribution. From Fig. 4.10 (a) and Fig. 4.11 (a), the CCR constraint can performances of macro-cell tier independent of user distribution. However, performances of macro-cell tier under interference temperature and SIR constraint are dependent of user distribution. In other words, threshold design of CCR constraint can be decided independent of user distribution. In the cellular networks, the user location does not obey specific pattern. In order to protect the performance of macro-cell tier, interference temperature and SIR constraint should evermore know the user distribution and adapt the threshold along to that.

4.5 Chapter Summary

This chapter presents the interference constraint and two power control schemes based on the CCR. To protect the primary user with various SNRs, we define the CCR as a novel metric. The constraint based on the CCR can protect the PU-Rxs located in different environments with high capacity and low capacity with the same requirement. Two power control schemes, which are the EPCS and the SPCS considering the fading effect, have been proposed. To evaluate the performance of the proposed methods, the average capacities of the primary and secondary users and the CCDF of the primary capacity are analytically derived. As a result, we can confirm that the SPCS has the same performance as the EPCS. Additionally, it is shown that the proposed methods can protect the primary capacity with various SNRs.

Chapter 5

Power Control Scheme Based on CCR

This chapter presents an transmit power control schemes based on the CCR of the secondary user. Previous chapter has proposed the interference constraint based on CCR in order to protect the primary user with widely SNR range. By utilizing the CCR as a metric to protect the primary user, a secondary user can achieve sufficient performance, without a large degradation in the primary capacity. In this chapter, we propose novel power control schemes under interference constraints based on the CCR, with consideration of the fading effect, by using theoretical analysis. There are two types of power control schemes, namely, an exact power control scheme (EPCS) and a simplified power control scheme (SPCS). The EPCS can control the outage probability; however, a numerical analytic approach is necessary to determine the transmit power. In contrast, the SPCS can be used to derive the transmit power from a closed form with an archiving requirement of the constraint. We analytically derive the average capacity of the primary user and the secondary user and the complementary cumulative distribution function of the primary capacity. From these numerical results, we show that the interference constraint based on the CCR achieves better performance in underlay spectrum sharing than the other two interference constraints. Furthermore, the SPCS can achieve a performance equivalent to that of the EPCS, and the SPCS can protect both the low and the high primary capacities under the same constraint.

5.1 Introduction

In the underlay spectrum sharing, the transmit power control of the secondary system is one of key techniques for protecting the primary system. The secondary transmitter should decide the maximum transmit power satisfies the interference constraint before the transmission is started. In the additive white Gaussian noise (AWGN) channel, an element to consider in determining is only the propagation loss between the SU-Tx and PU-Rx.. However, in the fading channel, channel states are randomly fluctuated, as a results the received interference at the PU-Rx is also fluctuated. In order to satisfy the interference constraint, the SU-Tx should decide the transmit power considering the fading effects.

According to the existing researches, the propagation loss can be estimated by using the long term measurement and statistical processing in the database. However, estimated information is only propagation loss without fading behavior, therefore it is difficult to design the fading-adapted transmit power according to database information. In other words, the transmit power control scheme enables to satisfy the fading channel is necessary. In this chapter, we propose two transmit power control schemes through analytical results which are SPCS and EPCS.

Section 5.2 describes two proposed power control methods with exact power control and simplified power control while considering the fading effect. The primary and secondary average capacities are derived by numerical analysis in section 5.4.1 and 5.4.2. In the section 5.5, numerical results for evaluation of the proposed schemes is shown. Finally, chapter summary is concluded in the section 5.6.

5.2 System Model for Transmit Power Control

In the underlay type based on the proposed constraint, the maximum allowable interference is dependent on the primary capacity. Therefore, the SU-Tx must estimate the primary capacity and determine the transmit power. To support estimation, in this thesis, we assume that the secondary user can obtain the supported information from the spectrum Database (DB). This DB stores information such as the primary user's controlled parameters (e.g., scheduling information and transmit power) and the propagation information, as illustrated in Fig. 5.1. This supported information can be used for estimating the primary capacity and interference toward the PU-Rx.

A specialized DB for the radio environment called the radio environment map (REM) [33],[34] has been attracted as a promising technology for underlay type. The REM stores the geographical spectrum information on the basis of the actual measured values. By employing the DB, the secondary user can obtain the radio environment information, including the temporal white space availability, average signal power of the PU-Rx, and propagation loss. In addition, more advance DB for the underlay type is considered. Moreover, the called Interference Map [35] which means the interference from SU-Tx is generated to spatial information as the geographical map. Furthermore, the spectral DB information is used to spectrum allocation [36] or sensing threshold design [37]. As a result, some primary information is stored in the DB. Since the small cell in HetNet and D2D device is shared the band as the distributed autonomous system so that system complexity is reduced. Nevertheless, calculable values should be used as evaluated metrics with the cooperation of the DB.

In future, the primary users will be able to potentially take a cooperative stance toward spectrum sharing, like the HetNet and/or D2D communication. Hence we assume that the primary user takes a cooperative stance toward spectrum sharing, in which user registers the system parameters and the actual values of the measured parameters in the DB. For example, the carrier frequency, bandwidth, the number of resource blocks, and frame length are stored as system parameters in the DB, without measurement. In addition, the actual transmit power, available locations of the PU-Rx, and employed channel associated with the receiver location are stored as reported values. The primary user avoids registering all personal identifiers of location availability of the PU-Rx in the DB. Hence, the SU-Tx can obtain some parameters and actual information about the primary user through the DB.

The DB equipped with the REM technology, can gather measured data from the radio environment from many cognitive terminals and can provide some kind of radio environment information through statistical processing. Then, the secondary user is able to download the long-term propagation loss and the probability distribution form of the fading variation. When the SU-Tx wishes to transmit the signal, it checks the supported information for controlling the transmit power. In this thesis, the means of acquiring the download channel are not considered.

- Coverage area of the primary user
- Carrier frequency
- Transmit power of the primary user
- Location information of the PU-Rx
- Location information of the primary transmitter
- Propagation information

The SU-Tx obtains its own location information from the global positioning system (GPS). Then, the SU-Tx decides to share the spectrum with one of the primary users. Subsequently, the average signal power of the PU-Rx is estimated by using the DB information. However, we assume that the SU-Tx cannot obtain an instantaneous value of fading variation. By statistical processing on the DB, the average value at each location and the distribution of fading variation can be obtained. However, the instantaneous value of the fading variation cannot be obtained by statistical processing. Then, the SU-Tx needs to decide the transmit power considering the fading effect to maintain the ratio of the capacity without secondary users, C_0, and the capacity with secondary users, C.

5.3 Exact Power Control Scheme (EPCS)

In a Rayleigh fading environment, it is difficult to satisfy the the interference constraint as shown in eq. (4.4). Because of fading variation, the instance value of the received signal power of the PU-Rx and the interference from the SU-Tx cannot be obtained. On the basis of this information, the SU-Tx determines the transmit power through an analytical evaluation of the outage probability. The strategy of the exact power control scheme (EPCS) considers two variations simultaneously on the basis of rigorous calculations. In this thesis, we assume

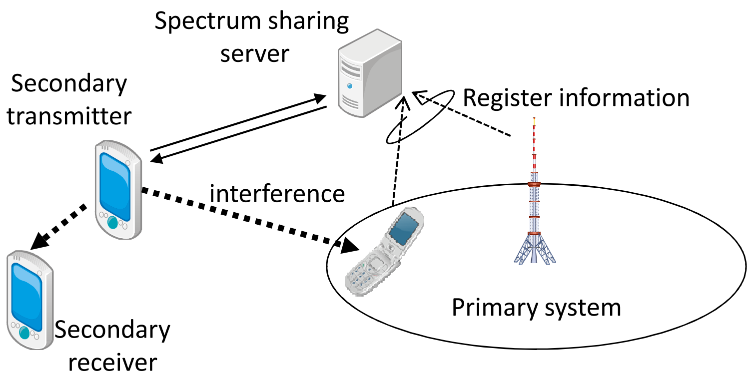


Figure 5.1: Image of power control scheme.

that the distribution of the received signal power in the Rayleigh fading channel is indicated by the following equation:

$$p(P) = \frac{1}{P_{\mathrm{rx,pri}}} \exp\left(-\frac{P}{P_{\mathrm{rx,pri}}}\right). \tag{5.1}$$

The maximum allowable interference is defined by the interference constraint. However, this requirement cannot be used directly for a transmit power design because of the fading variation. The fading effect causes the signal power and the interference power to fluctuate from their average values, causing the transmit power of the SU-Tx based on the maximum allowable interference to lead to excessive interference. In the EPCS, we derive the exact allowable interference $I_{\mathrm{exact,dBm}}$[dBm]. Let $I_{\mathrm{exact,dBm}}$ is recalculated according to the allowable interference power, which is optimized to satisfy eq. (4.4) under the fading channel.

First, the SU-Tx calculates the average received signal power of the PU-Rx, $P_{\mathrm{rx,pri,dBm}}$[dBm], by using the following equation:

$$P_{\mathrm{rx,pri,dBm}} = P_{\mathrm{tx,pri,dBm}} - L_{\mathrm{path,pri}}, \tag{5.2}$$

where $P_{\mathrm{tx,pri,dBm}}$[dBm] is the transmit power of the primary user, and $L_{\mathrm{path,pri}}$[dB] is the estimated path loss between the primary transmitter and the PU-Rx based on their locations. The maximum allowable interference $I_{\mathrm{max,allow}}$[mW], which is defined by the constraint, is calculated for determining I_{exact} and is given as

$$I_{\mathrm{max,allow}}(P, \alpha) = \frac{P}{\left(1 + \frac{P}{N}\right)^{\alpha} - 1} - N, \tag{5.3}$$

where P[mW] is the instantaneous received signal power affected by Rayleigh fading, and N[mW] is the noise power at the primary receiver. However, the secondary user cannot calculate $I_{\text{max,allow}}$ because P is an unknown value.

To determine the transmit power, we calculate the left side in the (4.4), when the average interference I_{ave}[mW] and the average received signal power $P_{\text{tx,pri}}$[mW] are received at the PU-Rx. The signal power variation leads to the allowable interference volume. Excessive interference occurs when the varied interference value exceeds the varied allowable interference. Thus, the calculation requires considering the complementary cumulative distributed probability of the received interference with stochastic variation of the allowable interference.

The left side in eq. (4.4) is a product of the calculated probability of the variation of $P_{\text{rx,pri}}$ and the complementary cumulative probability of I_{ave} exceeding $I_{\text{max,allow}}$. This probability is shown as follows:

$$\Pr\left[\frac{C}{C_0} \leq \alpha\right] = \int_0^{\infty}\int_{I_{\text{max,allow}}(P,\alpha)}^{\infty} \frac{e^{-\frac{P}{P_{\text{rx,pri}}}-\frac{I}{I_{\text{ave}}}}}{P_{\text{rx,pri}} I_{\text{ave}}} dIdP, \tag{5.4}$$

where $I_{\text{max,allow}}$ in I of the integral range is derived by eq. (5.3). $I_{\text{exact,dBm}}$ equals I_{ave}, which satisfies the condition that probability $\Pr = \beta$. Therefore, $I_{\text{exact,dBm}}$ is determined by I_{ave}, which satisfies eq. (5.4). However, $I_{\text{exact,dBm}}$ is not directly calculated from eq. (5.4) because I of the integral range includes eq. (5.4). Equation (5.3) is not an integrable function of P. Therefore, a numerical analysis is required to solve $I_{\text{exact,dBm}}$ because we cannot obtain a closed-form solution for $I_{\text{exact,dBm}}$.

After calculating $I_{\text{exact,dBm}}$, the SU-Tx estimates the average propagation loss between the PU-Rx and itself, $L_{\text{path,pri-sec}}$ using the information of both the locations. Then, the transmit power of the SU-Tx is the sum of the exact interference power and the average propagation loss shown as follows:

$$P_{\text{exact,tx,sec,dBm}} = I_{\text{exact,dBm}} + L_{\text{path,pri-sec}}, \tag{5.5}$$

The transmit power of the SU-Tx, $P_{\text{tx,sec}}$ is determined by selecting the smaller value between the sum of the exact interference power and the average propagation loss, and the constraint value of the maximum transmit power.

$$P_{\text{tx,sec,dBm}} = \min\left(P_{\text{limit,tx,sec,dBm}}, I_{\text{exact,dBm}} + L_{\text{path,pri-sec}}\right), \tag{5.6}$$

where $P_{\text{tx,sec,dBm}}$[dBm] is the eventual allowable transmit power, and $P_{\text{limit,tx,sec,dBm}}$ is the value of the power constraint of the terminal. The SU-Tx controls the transmit power constructed from two values, which are the exact interference power and the average propagation loss, as shown in the following equation:

$$P_{\text{exact,tx,sec,dBm}} = I_{\text{exact,dBm}} + L_{\text{path,pri-sec}}, \tag{5.7}$$

where $P_{\text{exact,tx,sec,dBm}}$[dBm] is the allowable transmit power of the SU-Tx, and $L_{\text{path,pri-sec}}$[dBm] is the estimated average propagation loss between the PU-Rx and the SU-Tx.

Finally, the SU-Tx determines the transmit power considering the power constraint of the terminal.

The EPCS can exactly design the outage probability. Thus, this scheme can achieve stochastic protection of the primary user according under the constraint. However, the realization of perfect stochastic protection requires numerical analysis because the equation for the transmit power is not in the closed form.

5.4 Simplified Power Control Scheme (SPCS)

In order to simply determine the transmit power, it is preferable that the transmit power is obtained by the closed form. However, the EPCS is not convenient because the equation is not the closed form. As a countermeasure, we propose a simplified power control scheme (SPCS) that can determine the appropriate transmit power, with simplicity. The strategy of the SPCS considers two separate factors, which are the primary signal variation and the interference variation. Consequently, we determine the transmit power using underestimated values as two margins.

First, we consider the primary received signal variation. The SU-Tx cannot estimate the instantaneous value of the primary signal power perfectly, because the primary signal power is stochastically variable. Therefore, the SU-Tx requires protecting the primary user stochastically. In order to realize such a requirement, the SU-Tx should underestimate the allowable interference by considering the probabilistic protection based on β.

In a fading environment, overestimation of the primary signal power leads to an increment of the interference power; therefore, we suppress the probability of overestimation of the primary signal power to β. Thus, the SPCS should use the signal value, which has a cumulative probability equal to β. From eq. (5.1), we derive the cumulative distribution function of the primary signal power as follows:

$$\int_0^{P_{\mathrm{und}}} p(P)dP = \beta \Leftrightarrow P_{\mathrm{und}} = P_{\mathrm{rx,pri}} |\ln(1-\beta)|. \tag{5.8}$$

Therefore, $I_{\mathrm{margin,allow}}$ including the margin can be calculated by employing the following equation:

$$I_{\mathrm{margin,allow}}(P_{\mathrm{rx,pri}}, \alpha, \beta) = \frac{|\ln(1-\beta)| P_{\mathrm{rx,pri}}}{\left(1 + \frac{|\ln(1-\beta)| P_{\mathrm{rx,pri}}}{N}\right)^{\alpha} - 1} - N, \tag{5.9}$$

where $|\ln(1-\beta)|$ is the coefficient of the received signal power that has a cumulative probability equal to β.

Next, we consider the interference power variation. When the interference increases, there is a high possibility that the received interference exceeds the required interference level. Then, we need to add the margin to estimate the path loss on the basis of their locations. In this thesis, we design the margin as the value that suppresses the probability of the interference exceeding $I_{\mathrm{margin,allow}}$ to β. The margin M_{dB}[dB] is calculated as

$$M_{\mathrm{dB}} = 10 \log_{10} |\ln(\beta)|. \tag{5.10}$$

Thus, the allowable transmit power $P_{\mathrm{simple,tx,sec,dBm}}$[dBm] based on the SPCS is calculated as

$$P_{\mathrm{simple,tx,sec,dBm}} = I_{\mathrm{margin,allow,dBm}} + L_{\mathrm{path,pri\text{-}sec}} - M_{\mathrm{dB}}. \tag{5.11}$$

Then, the transmit power is determined as well as the EPCS.

$$P_{\mathrm{tx,sec,dBm}} = \min\left(P_{\mathrm{limit,tx,sec,dBm}}, P_{\mathrm{simple,tx,sec,dBm}}\right). \tag{5.12}$$

The SU-Tx limits the transmit power below $P_{\mathrm{tx,sec,dBm}}$ and begins transmitting the signal.

5.4.1 Primary Average Capacity

In this subsection, we analyze the primary average capacity. The average received power of the PU-Rx, which is located at a distance of r_{p}[m] from the transmitter, has been driven in eq. (4.6) in previous chapter.

The average interference power is dependent on the transmit power of the secondary user and the average propagation loss between the PU-Rx and the SU-Tx. The transmit power of the secondary user is determined on the basis of the primary capacity, and the average interference power is a function of r_{p} and $r_{\text{p-s}}$. Thus, the received interference from the SU-Tx is determined as follows:

$$I_{\text{pri}}(r_{\text{p}}, r_{\text{p-s}}) = 10^{\frac{P_{\text{tx,sec,dBm}}(r_{\text{p}}, r_{\text{p-s}}) - L_{\text{path}}(r_{\text{p-s}})}{10}}, \tag{5.13}$$

where $r_{\text{p-s}}$ is the distance from the SU-Tx to the PU-Rx. From the previous calculations, the primary fading capacity with r_{p} and $r_{\text{p-s}}$ is calculated by the following equation:

$$C_{\text{pri}}(r_{\text{p}}, r_{\text{p-s}}) = \int_0^{\infty}\int_0^{\infty} \log_2\left(1 + \frac{g_{\text{pri}} P_{\text{rx,pri}}(r_{\text{p}})}{N + g_{\text{p-s}} I_{\text{pri}}(r_{\text{p}}, r_{\text{p-s}})}\right) e^{-(g_{\text{p-s}} + g_{\text{pri}})} dg_{\text{p-s}} dg_{\text{pri}}, \tag{5.14}$$

where g_{pri} is the fading factor between the primary transmitter and the PU-Rx, and $g_{\text{p-s}}$ is the fading factor between the PU-Rx and the SU-Tx. Equation (5.14) is a function of the average fading capacity of the primary user in variables r_{p} and $r_{\text{p-s}}$.

Next, we derive an expression of the primary average capacity in the system model. The primary average capacity is calculated by integrating the product of the primary capacity and the probability density of the capacity.

$$C_{\text{pri,ave}} = \int_0^{R} \int_0^{R + r_{\text{p-s}}} p(r_{\text{p}}, r_{\text{p-s}}) \cdot C_{\text{pri}}(r_{\text{p}}, r_{\text{p-s}}) dr_{\text{p-s}} dr_{\text{p}}, \tag{5.15}$$

where R is the radius of the primary cell, and $p(r_{\text{p}}, r_{\text{p-s}})$ is the probability density of the capacity.

The SINR of the PU-Rx is dependent on the locations of the PU-Rx and the SU-Tx. Therefore, the probability density of the capacity and probability of existence of the PU-Rx and the SU-Tx are equivalent. This probability is a joint probability that consists of the product of the probability of existence of the PU-Rx, $p(r_\mathrm{p})$ and the conditional probability of existence of the SU-Tx, $p(r_\text{p-s}|r_\mathrm{p})$ as follows:

$$p(r_\mathrm{p}, r_\text{p-s}) = \frac{4 r_\mathrm{p} r_\text{p-s} \varphi_\mathrm{b}}{\pi R^4}, \tag{5.16}$$

where φ_b is the maximum value of φ, given r_p and $r_\text{p-s}$. φ is the angle between the line connecting the primary transmitter and the PU-Rx and the line connecting the PU-Rx and the SU-Tx. φ_b is calculated by the following equation:

$$\varphi_\mathrm{b} = \begin{cases} \pi - \cos^{-1}\left(\frac{R^2 - r_\mathrm{p}^2 - r_\text{p-s}^2}{2 r_\mathrm{p} r_\text{p-s}}\right) & \text{where } R - r_\mathrm{p} < r_\text{p-s} \\ \pi & \text{otherwise} \end{cases} \tag{5.17}$$

5.4.2 Secondary Average Capacity

In this subsection, we derive the secondary average capacity. First, we assume that the SU-Tx should be located inside the primary cell, unlike the secondary receiver (SU-Rx). Therefore, the maximum distance between the SU-Tx and the primary transmitter is R[m]. The average signal power of the SU-Rx is calculated from the secondary transmit power and the propagation loss between the SU-Tx and the receiver. The transmit power was a function of r_p and $r_\text{p-s}$; thus, the received signal power at the SU-Rx is shown as follows:

$$P_\text{rx,sec}(r_\mathrm{p}, r_\text{p-s}) = 10^{\frac{P_\text{tx,sec,dBm}(r_\mathrm{p}, r_\text{p-s}) - L_\text{path}(d_\text{sec})}{10}}. \tag{5.18}$$

The interference power from the primary transmitter is determined by distance $r_\text{s-p}$ between the primary transmitter and the SU-Rx. Let $r_\text{s-p}$ is a dependent variable of r_p, $r_\text{p-s}$, φ and θ as shown in Fig. 4.3. Thus, I_sec can be calculated using these four variables in the following formula:

$$I_\text{sec}(r_\mathrm{p}, r_\text{p-s}, \varphi, \theta) = 10^{\frac{P_\text{tx,pri,dBm} - L_\text{path}(r_\text{s-p}(r_\mathrm{p}, r_\text{p-s}, \varphi, \theta))}{10}}. \tag{5.19}$$

Therefore, the secondary fading capacity at the given r_p, $r_\text{p-s}$, φ and θ is calculated as

$$C_\text{sec}(r_\mathrm{p}, r_\text{p-s}, \varphi, \theta) = \int_0^\infty \int_0^\infty \log_2\left(1 + \frac{g_\text{sec} P_\text{rx,sec}(r_\mathrm{p}, r_\text{p-s})}{N + g_\text{s-p} I_\text{sec}(r_\mathrm{p}, r_\text{s-p}, \varphi, \theta)}\right) e^{-(g_\text{s-p} + g_\text{sec})} dg_\text{s-p} dg_\text{sec}, \tag{5.20}$$

where g_{sec} is the fading factor between the SU-Tx and the SU-Rx, and $g_{\text{s-p}}$ is the fading factor between the primary transmitter and the SU-Rx.

The secondary average capacity is calculated by taking the integral of the product of the secondary capacity and the probability density of the capacity. Thus, the secondary average capacity is expressed in the following equation:

$$C_{\text{sec,ave}} = \int_0^R \int_0^{R+r_\text{p}} \int_{-\varphi_\text{b}}^{\varphi_\text{b}} \oint p(r_\text{p}, r_\text{p-s}, \varphi, \theta) \cdot C_{\text{sec}}(r_\text{p}, r_\text{p-s}, \varphi, \theta) d\theta d\varphi dr_\text{p-s} dr_\text{p}, \quad (5.21)$$

where $p(r_\text{p}, r_\text{p-s}, \varphi, \theta)$ is the probability density of the capacity.

The probability density of the capacity and the joint probability density of $r_\text{p-s}$, r_p, φ and θ are equivalent. The joint probability density is given by

$$p(r_\text{p}, r_\text{p-s}, \varphi, \theta) = \frac{r_\text{p} r_\text{p-s}}{\pi^2 R^4}. \quad (5.22)$$

In addition, the average capacity of the primary user and the secondary user using the EPCS, can be analyzed similar to expressions in Sects. 5.4.1 and 5.4.2.

5.5 Numerical Results

5.5.1 System Parameters

The target environment of the proposed two power control schemes is also where the primary SNR is varied due to the differing location of the received terminal. In order to evaluate the performance considering the above environment, the radius of the primary cell is assumed to be $R = 1400$ m. As a result, the difference in the average signal power at the PU-Rx is approximately 50 dB between the terminal located at the cell center and the terminal located at the cell edge. Table 5.1 lists the system parameters used in this evaluation. The parameters of the primary user are determined on the basis of the IEEE 802.16e WiMAX standard [38]. The secondary user is considered to be a femto cell, in which the transmitter is distributed in the primary cell.

Table 5.1: Simulation Parameters.

Channel model		Rayleigh fading
Propagation factor	n	3 (cubic law)
Carrier frequency	f	2.5[GHz]
Noise floor	N_{dBm}	-95.38[dBm]
Radius of primary cell	R	1400[m]
Transmit power of primary	$P_{\mathrm{tx,pri,dBm}}$	40[dBm]
Antenna height of PS-BS	H	32[m]
Communication distance of secondary	d_{sec}	50[m]
Reference distance	d_0	10[m]

5.5.2 Performance Evaluation of Protecting the Primary User

The EPCS computes the probability of the CCR dropping below α on the basis of the exact calculation. The SPCS does not utilize an exact calculation of the interference. Thus, its performance does not archive the probability of the CCR dropping below α.

Here, we evaluate the characteristic of the probability of the CCR dropping below α. The probability using the SPCS is calculated with eq. (5.4) by changing the interference value from I_{ave} to $10^{\frac{I_{\mathrm{margin,allow,dB}}+M_{\mathrm{dB}}}{10}}$. Figure 5.2 shows the evaluation results of the SPCS with $\alpha = 0.9$, 0.95, and 0.98, and $\beta = 0.01$, 0.03, and 0.05. The utilized parameters α and β consider the primary user requirements. If the vertical probability is less than β, we can understand the SPCS achieves the requirement of the constraint. The results show that the SPCS can achieve the constraint for any primary SNR and all combinations of α and β.

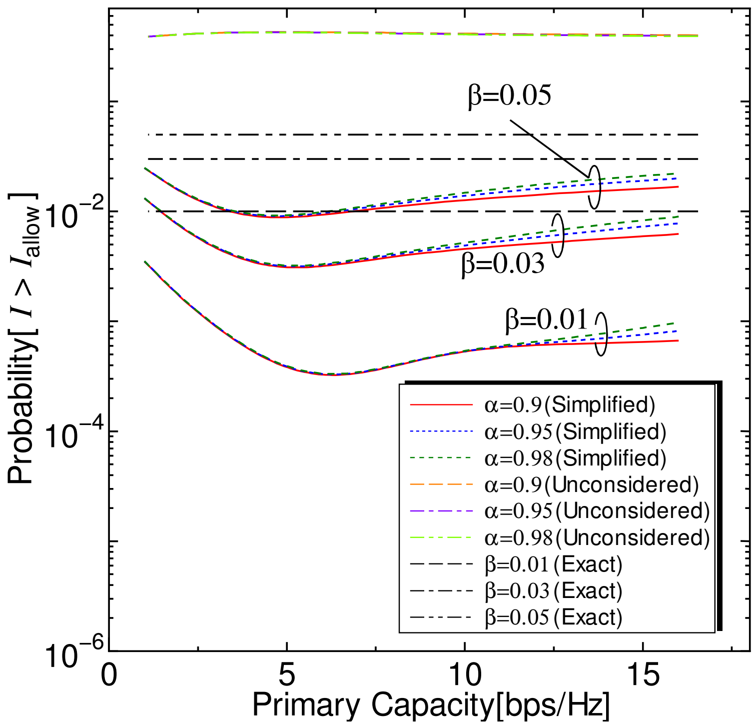


Figure 5.2: Characteristic of the probability of the CCR dropping below α using the SPCS.

5.5.3 Performance of Average Capacity

Here, we evaluate the performance of the achievable capacities of the primary user and the secondary user. By using the capacity region, we can identify a trend in the spectrum sharing performance attributed to the changing parameters of the constraint. The capacity region is obtained by the results of analysis explained in Secs. 5.4.1 and 5.4.2. Figure 5.3 shows the capacity region using the EPCS and SPCS. In Fig. 5.3, the performance curve is drawn by changing α from 0 to 1.0 and maintaining $\beta = 0.01$. In this evaluation, $P_{\text{limit,tx,sec,dBm}}$ was set to 40 dBm. Additionally, the results are plotted every 0.1 from $\alpha = 0$ to $\alpha = 1.0$. The point when $\alpha = 1$ is on the line defined by secondary average capacity $C_{\text{ave,sec}} = 0$.

The capacity region of the SPCS has a property similar to that of the EPCS from the results. The curve of the capacity region meets another curve on both ends of the capacity region. When $\alpha = 0$, the SU-Tx is not subject to the limitation of the spectrum sharing constraint; thus, the restriction is only defined

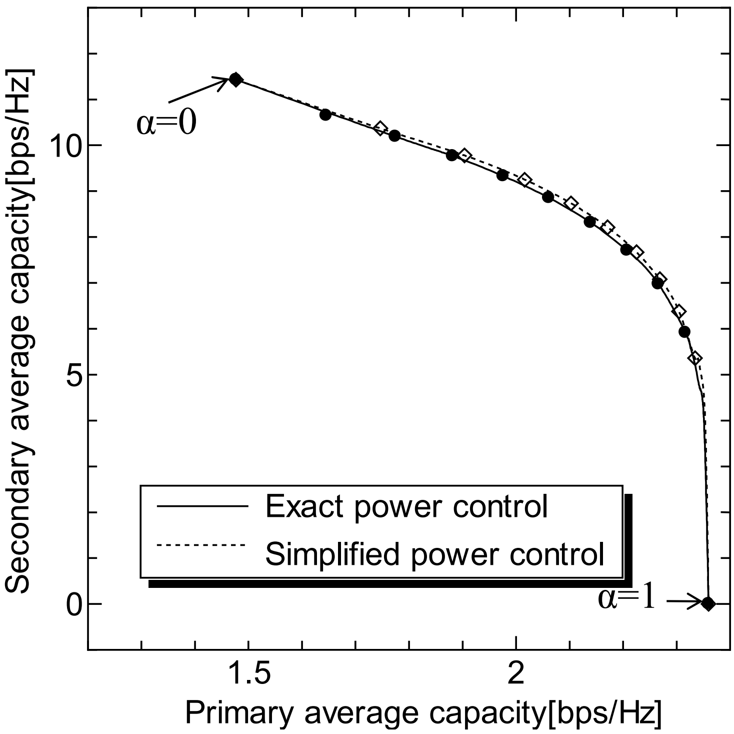


Figure 5.3: Capacity region using the exact and the SPCS.

by the maximum transmit power of each SU-Tx. As a result, the transmit power of the SPCS and that of the EPCS are identical. At the other end of the curve, when $\alpha = 1.0$, a secondary transmission is not allowed in order to limit the CCR at 1.0. As a result, two curves achieve the same secondary average capacity $C_{\text{ave,sec}} = 0$.

There are gaps between two power control schemes when parameter α is set to the same value because of different designs of the margin. The SPCS obtains a larger margin than that of the EPCS. As a result, the average primary capacity increases when the SPCS is applied. However, the two proposed schemes show a similar curve; therefore, we only use the SPCS to evaluate the performance as compared with the other power control schemes.

5.6 Chapter Summary

This chapter presents two power control schemes based on the CCR. To protect the primary user with various SNRs, we define the CCR as a novel metric. Two power control schemes, which are the EPCS and the SPCS considering the fading effect, have been proposed. To evaluate the performance of the proposed methods, the average capacities of the primary and secondary users and the CCDF of the primary capacity are analytically derived. As a result, we can confirm that the SPCS has the same performance as the EPCS.

Chapter 6

Resource Allocation under Interference Constraint

A Heterogeneous Network (HetNet) is the mixture network consisted of pico cell, femto cell and relay network in addition to macro cell. A home eNodeB (HeNB) overlays smaller coverage to the macro cell coverage in order to support the local high traffic of Macro eNodeB (MeNB) by off-loading the traffic to the HeNB. In the view point of the spectral efficiency, the frequency band of the HeNB is designed using the same band of the MeNB. However, the inter-cell interference between the MeNB and the HeNB gives harmful effects to both communication qualities of two cells. The performance degradation of the MeNB communication can be avoided by the transmit power control of the HeNB under the interference constraint at Macro User Equipments (MUEs). On the other hand, it is difficult to improve the communication quality of the Home User Equipment (HUE) by the transmit power control or the power allocation, since the transmit power of the HeNB is restricted according to the interference constraint. However, conventional interference constraints does not considers scheduling behavior in cellular system, therefore this paper propose the interference constraint for protection of scheduling behavior at MeNB. In addition, the HeNB and the HUE should communicate in the interference environment. Hence, HeNB has to achieve the efficient spectrum access by scheduling without the transmit power control. Therefore, we propose an adaptive interference scheduling for small cell in the HetNet without increasing the feedback information compared with the

Proportional Fair Scheduling. Through the computer simulation, we show the effectiveness of the proposed scheduling under the interference constraint.

6.1 Introduction

The variety of new generation devices (netbooks, smart phones, tablet and other mobile internet devices) cause a significant increase in the traffic of the broadband communications. Based on the forecast data by Cisco, mobile traffic increases 66 times with an annual growth rate of 131% between 2008 and 2013[1]. In addition, the number of wireless devices is also increased, hence the spectral efficiency should be improved in high-dense node environment. The cellular networks face with demand of communication quality improvement under two above problems. In order to satisfy the increasing demands on wireless mobile networks with higher throughputs, orthogonal frequency-division multiple access(OFDMA)-based networks are being developed as Long Term Evolution (LTE). In the OFDMA, the spectrum is orthogonally divided into time-frequency resource blocks (RBs), which increases flexibility in resource allocation, thereby allowing high spectral efficiency. Exploiting all RBs simultaneously to achieve so-called universal frequency reuse becomes a key objective toward deployment of future cellular networks such as the LTE and the LTE-Advanced (LTE-A).

In the LTE-A, one of two-tier networks so called Heterogeneous Network (HetNet) is employed [2, 3]. The HetNet consisted of the mixture networks of multiple cells with different coverage size, is supported in order to offload the local high traffic in the macro cell coverage. Usually, most of the high traffic is generated in an indoor environment or a small local area, hence it is difficult to support the traffic by only the Macro eNodeB (MeNB). The survive of the macro coverage essentially has a coverage holes in specific area (e.g., indoor environment), then low-power and small-coverage local nodes called Home eNodeB (HeNB) such as pico, femto, and relay nodes deployed at coverage holes. The advantage of using the HeNBs that are located inside buildings is significant since 50% of voice calls and more than 70% of data traffic originate indoors [4]. The HetNet aims to improve the system capacity by using the HeNB overlaid to the MeNB coverage.

HetNet characteristically has existence of MeNB-HeNB back-haul coordination, allowing modifications of existing macro-cells for HetNet deployment. However, interference mitigation in two-tier networks faces practical challenges: random deployment of femto-tier cells, restricted/closed access, no coordination among macro- and femto-tiers and backward compatibility [6]. In these challenges, the cognitive radio (CR) is the most promising solution for interference mitigation. The MeNB and CR-enabled HeNB are analogous to primary and secondary users in the CR model, respectively. This means not necessary to operate the MeNB and the CR-enabled HeNB (CR-HeNB) by the same operator. In other words, CR-HeNB has to protect the MeNB communication for universal frequency reuse among different operators.

In this case, it should be noted that two points; how to design the metric for the MeNB protection, because HeNBs plays the role of the lower such as the secondary user. Other one is efficient resource allocation problem in the CR-enabled HeNB, the HUEs probably receive strong interferences, since MeNB transmits signals with higher power and random distribution indicates the possible presence multiple neighboring HeNBs. In the other words, HeNB should efficiently design resource allocation under applicable interference constraint for dynamic primary system. As a related works in cognitive radio, some constraints with various metrics for protection of the primary user(s), have been proposed [40, 41, 42].

The CR-enabled HeNB should efficiently use the user diversity to improve the performance under existence of the inter-tier and intra-tire interference and interference constraint. Then, the scheduling algorithm becomes important in order to achieve the efficient utilization of the wireless resource. The efficient scheduling is required to be aware the channel state at the receiver, but the feedback of the channel state information (CSI) from the HUE decreases the spectral efficiency due to the overhead. Then, this chapter focuses on the issue for avoiding the degradation of the scheduling performance caused by the CSI error in the interference channel.

Here, we consider utilizing the weight obtained by the relationship between the historical information and current information from the feedback, approximates a CSI adjustment factor. In this chapter, we improve two important factors of the cellular networks; the cell throughput and the fairness among the users are increased by the adaptive weight. Then, two kinds of interference-adapted scheduling weight without increasing the amount of feedback from the Proportional Fair Scheduling (PFS) algorithm[47] are proposed in order to design the multipurpose weight.

The rest of this chapter is organized as follows. Section 6.2 describes the our scenario and system model. Section 6.3 presents the proposed interference constraint in detail. The novel interference-adapted weighted Scheduling is presented in Sec. 6.4. Simulation results and comparisons are given in Section 6.5. Finally, conclusions are provided in Section 4.5.

6.2 System Model: Cognitive Two-Tier Heterogeneous Network

HetNet in the 3GPP release characteristically has existence of MeNB-HeNB backhaul coordination, allowing modifications of existing macro-cells for HetNet deployment. In the view point of the spectral efficiency, the frequency band of the overlaid HeNB is designed using the same band of the MeNB with assistance of above condition. Accordingly, the cross-tier interference between HeNB/MeNB and Macro User Equipment(MUE)/Home UE (HUE) became more critical issue in the HetNet due to short distance in cross-tier interference channel. In other words, the benefit is realized only when cross-tier interference is well managed. Therefore, cross-tier interference mitigation is most important topic in the HetNet. In 3GPP Release 10, enhanced inter-cell interference coordination (eICIC) which the MeNB sets almost blank subframes (ABS) to reserve some subframes for the HeNB, is introduced [5]. As a related study, controlling the HeNB coverage called the Range Expansion [39] by setting ABS at the MeNB through the eICIC scheme has been studied. These schemes are considered on the assumption of the existence of modifications of existing macro-cells.

Although, the structure of HetNet can be extended to coexistence between macro-cellular and spot wireless systems. The concept extension leads efficient solution for shortage of spectrum resource in including, without limitation to cellular system. This motivation is similar to the spectrum sharing by using CR technology. In other words, applying the CR technology permits development of HetNet's potential according to the information acquired by CR technology. In other words, channel-aware behavior of CR-HeNB mitigative complexity of system design for realization of HetNet benefit. The impact of applying CR technology allows the coexistence of macro cell and standalone femto cells, i.e. a macro/femto network is regarded as a two-tier network where the femto cell plays the role of the lower tier that compensates and facilitates the transmission of the higher macro cell tier.

As one of radio environment awareness, utilization of database has been attracted in current cognitive radio. In the spectrum sharing based on the FCC's rule, the cognitive device (White Space Device: WSD) has to access the spectrum database which stores the available channels as a geographical data, and downloads the available channels in WSD position, when the WSD accesses the TV-licensed band. Another database for spectrum sharing is also considered, one of them is called Radio Environment Map (REP) shown in [43]. This database stores the radio environment information such as, the spatial distribution of signal power from PU transmitter, PU's system parameters and so on. The secondary user can set the optimal or appropriate parameters for overlay and/or underlay spectrum sharing.

In this chapter, HetNet structure is considered as two-tire cellular networks with CR-HeNB assisted by support equipment such as spectrum database and/or support manager. The CR-HeNB can obtain the necessary information to protect the macro-cell communication, such as geographical information of spectrum (or channels), location of the MUE, scheduling results at MeNB, through the support manager as shown in Fig. 6.1. The CR-HeNB can control the resource allocation under satisfactory the cross-tier interference constraint. In this scenario, the MeNB registers own information: scheduling information, location information of MUEs and so on. Meanwhile, the HeNB only downloads the information of the MeNB without the registration of own information. Therefore, inter-tier interference mitigation should be achieved without the support manager.

In the cognitive two-tier HetNet the MeNB located upper tier does not facilitate the femto-tier communication when the MeNB decides the resource assignment, and communicates to the MUE. In our assumption, the pilot signals of the

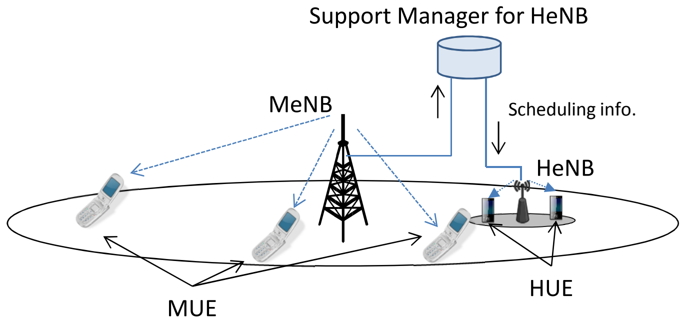


Figure 6.1: HetNet with support manager for HeNB

Resource Block from the MeNB and the HeNB are inserted into the sub-carrier without overlaps between the MeNB and the HeNB. Therefore, the MeNB can obtain only the CSI of the MUE. For these reasons, the MeNB can be considered as a general cellular system with OFDMA scheduling in the LTE or the LTE-A standard. The scheduling algorithm of the MeNB is assumed as the PFS algorithm without controlling the transmit power or spatial resource pattern as well as the FFR (Fractional Frequency Reuse) [44].

In the OFDMA using the PFS algorithm, the assigned user of channel j , k_{tj} is decided from MUE $i = 1, 2, \cdots, N_M$, based on the following equation,

$$k_{tj} = \arg\max_{1 \le i \le N_M} \frac{D_{ij}(t)}{R_i(t-1)}, \tag{6.1}$$

where $D_{ij}(t)$ is the estimated rate of channel $j = 1, 2, \cdots, M$ at MUE i in slot t and $R_i(t)$ is the average rate at MUE i until slot t. Since the PFS algorithm uses moving average method, the average rate $R_i(t)$ is updated from $R_i(t-1)$ by using the following equation,

$$R_i(t) = (1 - T_c^{-1}) R_i(t-1) + T_c^{-1} \sum_{j=1}^{M} D_{ij}(t) I_{ij}(t), \tag{6.2}$$

where T_c is the smoothing coefficient which decides how many historical rate is used for averaging. $I_{ij}(t)$ is the indicator function which shows the assign state of each user, as shown in the following equation,

$$I_{ij}(t) = \begin{cases} 1 & k_{tj} = i \\ 0 & k_{tj} \neq i \end{cases}. \tag{6.3}$$

According to the our assumption, the estimated rate from CSI, $D_{i,j}(t)$ in eq. (6.1) is driven from SNR without the interference from HeNBs. However, $D_{i,j}(t)$ for updating the $R_i(t)$ in eq. (6.2) is actual rate with interference from HeNBs, because $D_{i,j}(t)$ is actual rate in the HetNet environment. Since, actual rate is degraded from estimated rate at a maximum SINR allowed by the interference constraint. This difference has impact on the scheduling behavior in the HeNB, therefore design of the interference constrain dictates cellular performances of the HeNB cell (e.g., cell and cell-edge throughputs, fairness, latency and so on).

6.3 Transmit Power Constraint of HeNB under Interference Constraint

Small-cell tier is regarded as a secondary system in two-tier network where the small-cell plays the role of the lower tier that compensates and facilitates the transmission of the higher macro-cell tier. Since the HeNB communicates to HUE over the same band of the MeNB, the communication channel can be modeled at a channel i as the simple interference channel as shown in Fig. 6.2. Under the constraint of the received interference at the MUE, the HeNB decides the maximum transmit power according to the constraint metric. In this chapter, the HeNB can perfectly control the transmit power to satisfy the interference constraint, because it is assumed that necessary information for control are fully obtained at the HeNB.

According to analysis shown in [45], assignment probability through the proportional fair scheduling is along to the distribution of instantaneous rate value, and magnitude relationship of mean rate, among the primary users. Therefore, to protect the scheduling behavior on the primary system is required to keep the magnitude relationship of mean rate into the spectrum sharing. When the HeNB decides the maximum transmit power, metric of the requirement performance at

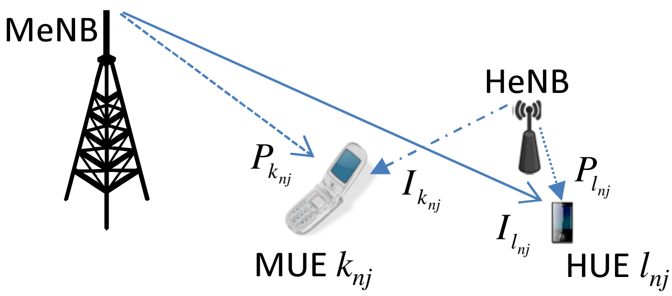


Figure 6.2: Interference channel among MeNB, HeNB, MUE and HUE

the MUE should be formulated as the equation of the interference power. In other words, metric of the interference constraint should be designed considering above requirement in order to protect scheduling behavior in the Macro-cell tier.

In this chapter, the Capacity Conservation Ratio (CCR) which has been proposed for the interference constraint in the spectrum sharing in our previous work[46], is used as the metric of the interference constraint. The CCR is defined that the ratio of the original capacity without the interference to the degraded capacity with the interference. In the case where keeping the CCR of the MUE is required, the degradation ratio of the MUE capacity due to the interference from the HeNB can be kept independent on the strength of the received signal power at the MUE. Therefore, the degrading capacity is small against the MUE at the low SNR, and the degrading capacity is large against the MUE at the high SNR, in the CCR constraint.

Altogether, interference constraint has to linearly degrade rate of HUEs from original rate of them. Figure 6.3 shows the relationship of original capacity and interfered capacity under three constraints. The interference temperature and SIR constraint lead non-linearity relationship, then two constraints cannot linearly keep the magnitude relationship of mean interfered rate among primary users as shown in Fig. 6.3. In contrast, the CCR constraint can keep the magnitude relationship, therefore it is promising that the CCR can protect the scheduling behavior of the primary user.

Therefore, we employ the CCR constraint in order to protect the scheduling

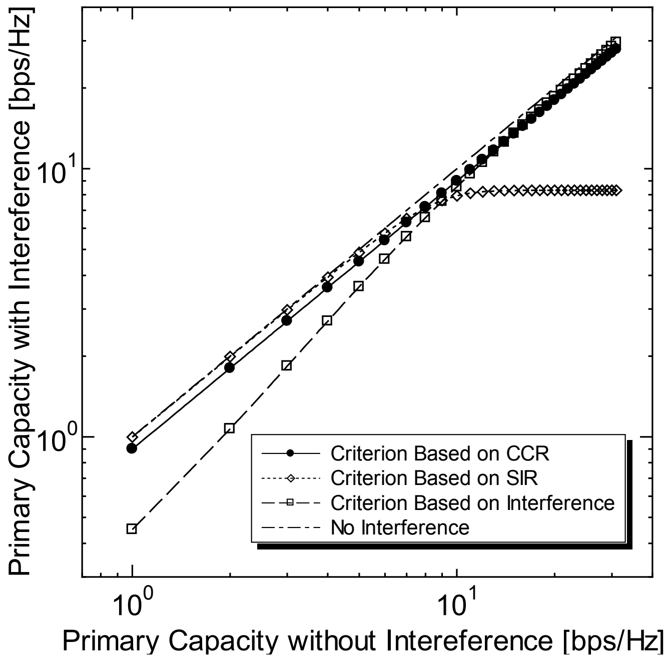


Figure 6.3: Relationship of original capacity and interfered capacity under tree constraint: Interference temperature, SIR constraint and CCR constraint.

behavior of macro-cell tier. The constraint equation of CCR is written by,

$$\frac{C}{C_0} = \frac{\log_2\left(1 + \frac{P_{k_{tj}}}{N_{k_{tj}}}\right)}{\log_2\left(1 + \frac{P_{k_{tj}}}{I_{tj}+N_{k_{tj}}}\right)} \geq \alpha_{ccr}, \tag{6.4}$$

where, C is degraded capacity of the primary user caused by interference from secondary user, C_0 is original capacity without interference and α_{ccr} is constraint threshold.

This chapter considers the channel capacity calculated by Shannon's theorem as a throughput. Thereby, inequality interference constraint is shown by following equation,

$$I_{tj} \leq \frac{P_{k_{tj}}}{\left(1 + \frac{P_{k_{tj}}}{N_{k_{tj}}}\right)^{\alpha_{ccr}} - 1} - N_{k_{tj}}, \tag{6.5}$$

where $P_{k_{tj}}$ is the received signal power at the MUE and $N_{k_{tj}}$ is the noise power of the MUE. Let α_{ccr} affects the both capacities of the MUE and the HUE, since when α_{ccr} is increased, the transmit power of the HeNB is decreased and the capacity of the MUE is increased.

In the case that the HeNB has to satisfy the interference constraints, the HeNB decides the transmit power $P_{tj,\mathrm{dBm}}$, under substituting right-hand side in eq.(6.5), to the maximum allowable interference $I_{tj,\max}$ in the following equation,

$$P_{tj,\mathrm{dBm}} = I_{tj,\max,\mathrm{dBm}} + L_{path,\mathrm{dB}}, \tag{6.6}$$

where $I_{tj,\max,\mathrm{dBm}}$ is dBm unit of the maximum allowable interference, and $L_{path,\mathrm{dB}}$ is propagation loss between the HeNB and the MUE.

6.4 Interference-Adapted Weight for Scheduling

In the cognitive two-tier HetNet, the inter-tier interference between the MeNB and the HeNB leads the large degradation of the communication performances at both the MeNB and the HeNB. The issue of only the MeNB can be avoided by the transmit power control at the HeNB as indicated in subsection 6.3. However, the performance degradation of the HeNB communication is insoluble due to hierarchical network structure in the considered scenario. In addition, it is difficult to achieve the high SNR at the HUE, because the power control is effectively applied not to improve the HUE performance, because the maximum transmit power per channel is limited by the interference constraint. Therefore, the HeNB should achieve the high performance by using the only scheduling algorithm.

However, the scheduling behavior does not work as required, if actual SINR of the HUE and SINR estimated from pilot signal are different due to the received interference from the MeNB. The scheduling performance can be improved by feedback including the signal and interference strength, although the increasing overhead results in a degradation of the communication efficiency. In order to solve this problem, adaptive scheduling metric should be designed. This chapter approaches the design of adaptive scheduling weight without more feedback compared to the PFS.

In the PFS algorithm, the receiver feeds back to the estimated rate for assignment decision in the next slot and actual rate in current assigned slot. An equivalent feedback of the PFS is given in the HeNB communication in this chapter, the HeNB can obtain the ratio of the actual rate degraded by the interference and the estimated rate ignored by the interference, is approximative CCR. The HeNB can estimate the actual CSI by the estimated rate multiplied by this ratio. This ratio $\delta_{lj}(t)$ of the HUE $l = 1, 2, \cdots, M_H$ at the channel j, is calculated by the following equation,

$$\delta_{lj}(t) = \delta_0 + \sum_{s=1}^{t-1} \left(I_{lj}(t) \frac{D_{\mathrm{r},lj}(t)}{D_{\mathrm{e},lj}(t)} \right) / \sum_{s=1}^{t-1} I_{lj}(t), \tag{6.7}$$

where δ_0 is the initial value of the CCR, $D_{\mathrm{r},lj}(t)$ is the actual rate of channel j at the HUE l in slot t, $D_{\mathrm{e},lj}$ is the estimated rate from the pilot signal and $I_{lj}(t)$ is the indicator function of the assignment of jth channel in the slot t. The numerator in eq. (6.7) means summation value calculated by using the actual rate only when HUE l is assigned to the channel j. The denominator in eq. (6.7) means the number of the assignment channel until slot t.

The HeNB is able to approximates the estimated rate to the actual rate from the product of $\delta_{lj}(t)$ and the estimated rate, then we use the $\delta_{lj}(t)$ as the scheduling weight. Let $w_{\max}$ is shown as,

$$w_{\max,lj}(t) = \delta_{lj}(t). \tag{6.8}$$

By using $w_{\max,lj}(t)$, the HeNB can obtain the approximative actual rate without more feedback, since the scheduling weighted by $w_{\max,lj}(t)$ supports the interference channel environment. The metrics of MAX-CIR [48] and PFS includes the estimated rate, since this weight can be applied to two scheduling metrics.

The scheduling metric weighted by $w_{\max,lj}(t)$ allows for increasing the assignment probability of the HUE with high CCR; however, the fairness among HUEs is degraded due to decreasing the assignment probability of the HUE with low CCR. Then, time-varying CCR $\varepsilon_l(t)$ depending on scheduling results is proposed. Let $\varepsilon_l(t)$ is combination of two averaging value: An exponential moving average of the CCR in time domain, and an arithmetic mean of the CCR in frequency domain. Therefore, $\varepsilon_l(t)$ of the HUE l is calculated by,

$$\varepsilon_l(t)=(1-T_H^{-1})\varepsilon_l(t-1)+T_H^{-1}\sum_{j=1}^{M}I_{lj}(t)\frac{D_{\mathrm{r},lj}(t)}{D_{\mathrm{e},lj}(t)}, \tag{6.9}$$

where T_H is the smoothing coefficient.

Let $\varepsilon_l(t)$ is reduced when the HUE l receives the strong interference, and is also assigned no channel. In other words, the inverse of $\varepsilon_l(t)$ is large at the HUE l under unfavorable conditions. Accordingly, we proposed second weight $w_{\mathrm{pf},lj}(t)$, which is product of $\delta_{lj}(t)$ and inverse of $\varepsilon_l(t)$. Let $w_{\mathrm{pf},lj}(t)$ is expressed in the following equation,

$$w_{\mathrm{pf},lj}(t) = \frac{\delta_{lj}(t)}{\varepsilon_l(t)}. \tag{6.10}$$

This weight is expected to keep the fairness among the HUEs, because characteristics of $\delta_{lj}(t)$ and $\varepsilon_l(t)$ increase the assignment probabilities of both high and low CCR HUE.

6.5 Simulation Evaluation

In this section, two performances are evaluated: the scheduling behavior of macro-cell tier and performances of small-cell tier, under the interference constraint. Firstly, the impact of interference constraint to the scheduling behavior of macro-cell tier is evaluated. After that, performances of small-cell tier in the environment of random distribution HeNBs is derived through the computer simulation.

The number of resource blocks with 1 msec and 180 kHz are 25. The resource assignment of the macro-cell tier is decided based on the PFS algorithm with Tc = 1000, through 10000 slots scheduling term.

The propagation loss is calculated as following equation,

$$L_{path,dB}(d) = -20\log_{10}\left(\frac{\lambda}{4\pi d_0}\right) + 10n_{pl}\log_{10}\left(\frac{d}{d_0}\right), \tag{6.11}$$

where, d_0=10 meters is free space propagation distance, n_{pl}=4.0 is propagation factor, λ is the wave length of the carrier frequency, and d is distance between

Table 6.1: Simulation Parameters.

Channel model		Propagation loss Log-normal shadowing Rayleigh fading
Derivation of shadowing		8[dB]
Propagation factor	n_{pl}	4.0
Carrier frequency	f	2.5[GHz]
Noise floor	N	-174.0[dBm/Hz]
Radius of primary cell	R	1732[m]
Transmit power of primary	$P_{\mathrm{tx,pri,dBm}}$	43[dBm]
Antenna height of PS-BS	H	36[m]
Reference distance	d_0	10[m]

the MeNB and MUE. The standard variation of the log-normal shadowing is set to 8.0 in this simulation. This shadowing is assumed that the shadowing gain is uncorrelated in the space domain, and is fixed during the scheduling term. To calculate the SIR, the SINR or the channel capacity of the MUE, the noise power of the PU receiver is set to -174[dBm/Hz].

Firstly, proposed scheduling algorithms are evaluated in the single HeNB environment simulation. Second, multiple HeNBs randomly distributed environment is used for evaluation proposed scheduling algorithms.

6.5.1 Performance of small-cell tier with single HeNB

We show figures: characteristic of the cell throughput and fairness of the HeNB, with changing the distance between the HUE and the MUE, and the number of HUEs in shown from Fig. 6.4 to Fig. 6.7, respectively.

From Fig. 6.4 and Fig. 6.5, the throughput of the MAX-CIR weighted by $w_{\max}$ is achieves the higher than that of normal MAX-CIR. This is resulted that the metric of the MAX-CIR weighted by $w_{\max}$ shows the approximate SINR without

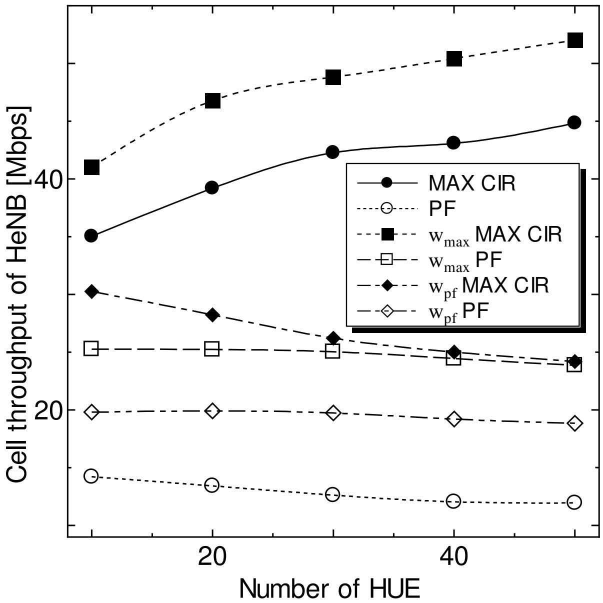


Figure 6.4: Average cell throughput of HeNB at distance between the HUE and MUE is 800m.

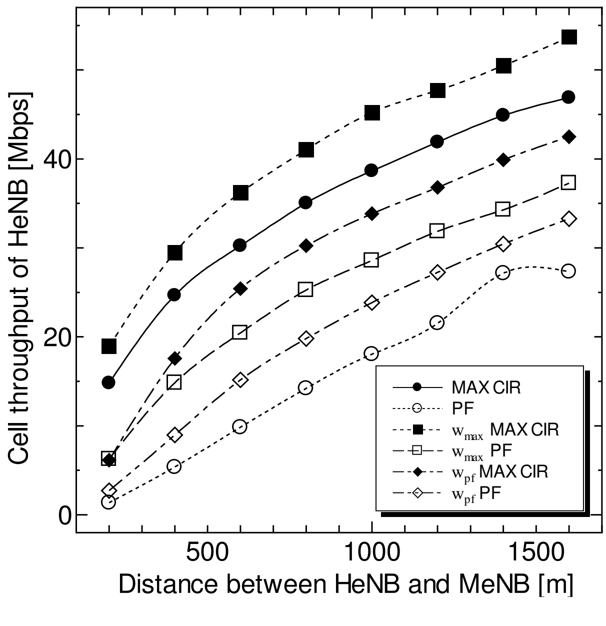


Figure 6.5: Average cell throughput of HeNB in number of HUEs is 10.

the feedback of the interference information from the HUE. Thus, the MAX-CIR weighted by $w_{\max}$ can select the HUE with high throughput and high efficiency.

In addition, the MAX-CIR weighted by w_{max} shows higher fairness than the normal MAX-CIR in shown Fig. 6.6 and Fig. 6.7. The fluctuation of the scheduling metrics in the MAX-CIR is caused by on only one fading variation of the signal channel. However, the actual SINR at the HUE is depended on two fading variations of the signal channel and the interference channel. For these reasons, the metric of the MAX-CIR weighted by w_{max} is close to the actual SINR.

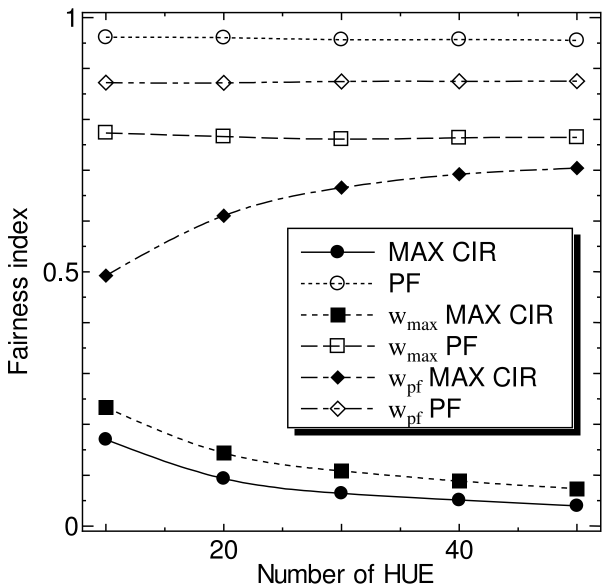


Figure 6.6: Fairness index among HUEs at distance between the HUE and MUE is 800m.

In addition, other three weighted scheduling methods achieve higher throughput compared with the PFS. From Fig. 6.4 and Fig. 6.5, we can confirm the PFS weighted by w_{max} and MAX-CIR weighted by w_{pf} is more than a little different from the high user density or the strong interference environment. In the view point of the metric, difference between two scheduling is only denominator. From Fig. 6.6, the difference of the fairness becomes small with increasing the number of the HUE. By contrast, the difference of the fairness becomes large with increasing the distance as shown in Fig. 6.7. Accordingly, the exponential moving average CCR, $\varepsilon_l(t)$ in the MAX-CIR weighted by w_{pf} shows similar characteristic to the exponential moving average rate in the PFS metric. In other words, the temporal averaging has larger impact than the spectral averaging in $\varepsilon_l(t)$ in high

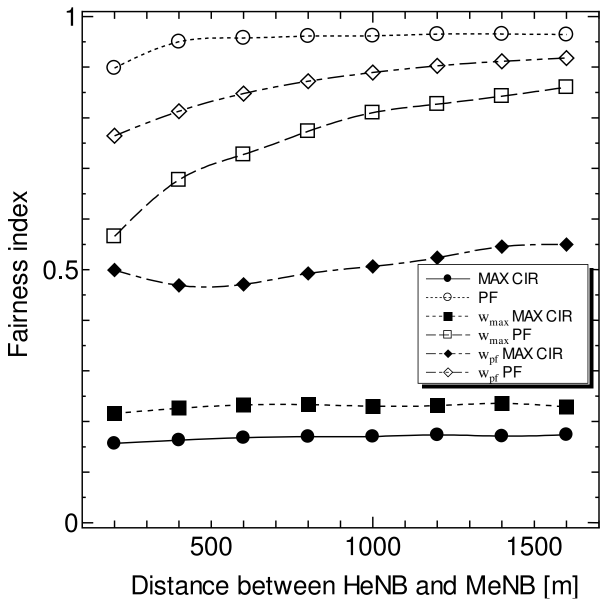


Figure 6.7: Fairness index among HUEs in number of the HUEs is 10.

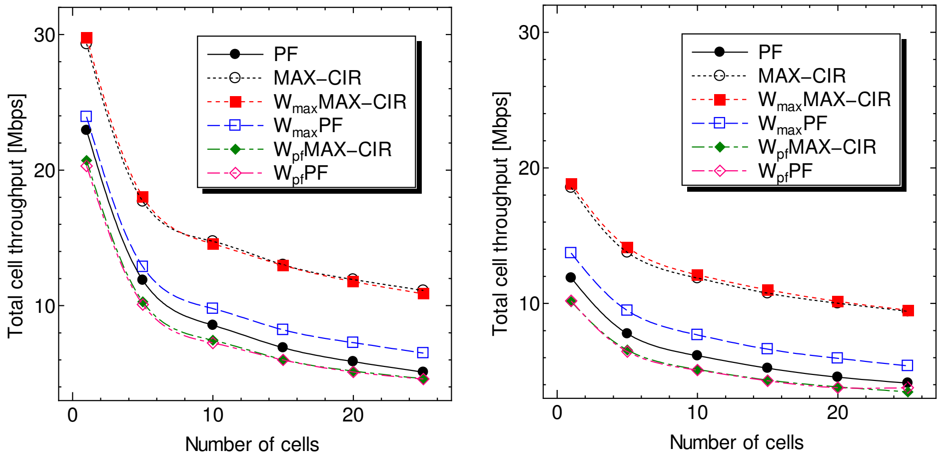
user density, because the assignment probability per HUE is small. Meanwhile, in the strong interference or low user density environment, $\varepsilon_l(t)$ has the effect of the increasing rate.

Therefore, high performance of the throughput and/or the fairness can be achieved by designing the scheduling metric and weight according to the surrounding environment of the HeNB. In particular, if the throughput is emphasis, it is better to select the MAX-CIR weighted by $w_{\max}$. The PFS weighted by w_{pf} and the PFS weighted by $w_{\max}$ show the good balance of the throughput and fairness.

6.5.2 Performance of small-cell tier with Multiple HeNBs

In this subsection, we show simulation results in multiple HeNBs environment. In this environment, the performance of HeNBs is reduced, because the maximum interference is divided by the number of HeNB cells and mutual interferences among HeNBs occur. Especially, decreasing of maximum transmit power in each RBs is big factor of performance degradation due to reducing degree of freedom in the resource allocation. Then, the scheduling algorithm becomes important role. In this subsection, the total cell throughput and user fairness of each cells and CCDF of the user throughput is used for performance evaluation.

We show the eight figures as results from Fig. 6.8 to Fig. 6.11.

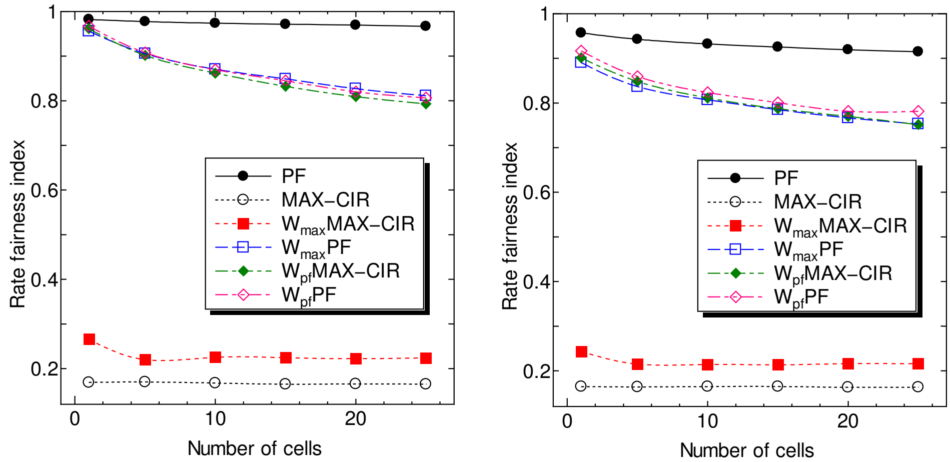


(a) Interference constraint with α=0.1. (b) Interference constraint with α=0.9.

Figure 6.8: Total throughput of each HeNBs.

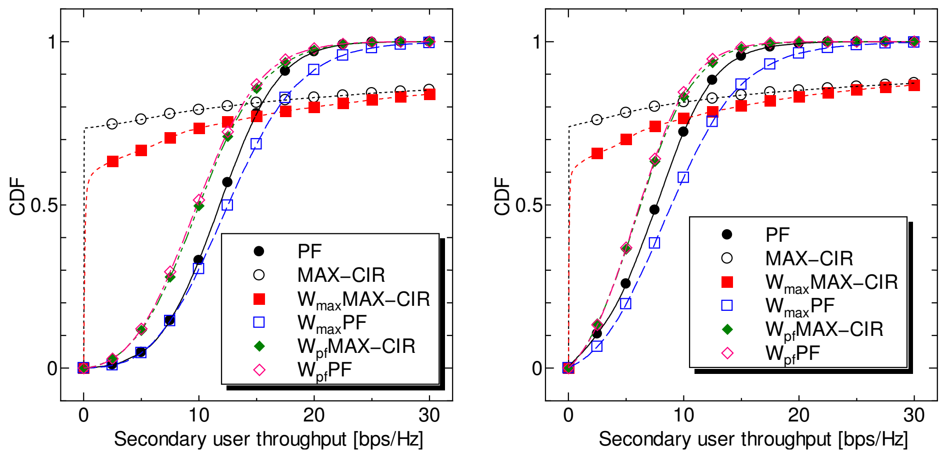
From Fig. 6.8, we can confirm the weighted scheduling W_{max}MAX-CIR achieves the higher or equal throughput of MAX-CIR over the all number of cells. Other three proposed scheduling algorithm W_{max}PF achieves higher throughput than the PFS algorithm. The weigh W_{max} is effective in improving the throughput. However, other proposed weight W_{pf} is no effective in improving the throughput in the multiple HeNBs environment differently from single HeNB environment. In addition, relative relation of each algorithms is no changed with changing the constraint parameter α.

Figure 6.9 shows the performance of rate fairness among users. Differently from throughput results, the performance of PF, W_{max}PF, W_{pf}MAX-CIR and W_{pf}PF is changed with changing parameter α. The most of scheduling algorithms reduce the fairness performance with increasing the α. However, W_{pf}MAX-CIR keeps approximately-same value from $\alpha = 0.1$ to $\alpha = 0.9$. It is noteworthy that difference between the PF and W_{pf}MAX-CIR is reduced with increasing the α and number of cells. W_{pf}MAX-CIR has potential of keeping high performance in the harsh environment such as the high density environment of HeNBs.



(a) Interference constraint with α=0.1. (b) Interference constraint with α=0.9.

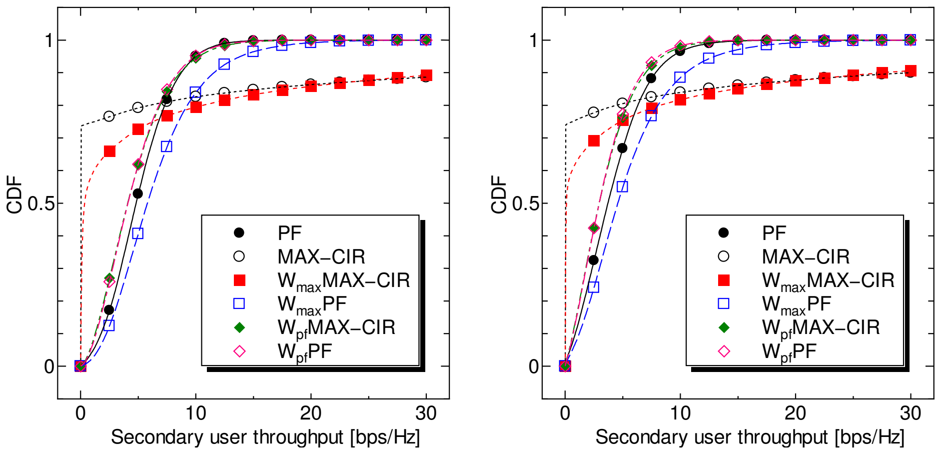
Figure 6.9: Rate fairness index of each HeNBs.



(a) Interference constraint with α=0.1. (b) Interference constraint with α=0.9.

Figure 6.10: CCDF of SU throughput with 5 cells.

The potential of W_{pf}MAX-CIR can be confirmed from Figs. 6.10 and 6.11. In the view point of CDF property in the throughput, W_{pf}MAX-CIR achieves the higher 95% CDF throughput with non-zero 5% CDF throughput in four results. Moreover, in the harsh environment (e.g., large number of cells and near-one α), the performances of 95% and 5% CDF throughputs are improved thatn the PFS.



(a) Interference constraint with α=0.1. (b) Interference constraint with α=0.9.

Figure 6.11: CCDF of SU throughput with 25 cells.

6.6 Chapter Summary

In this chapter, we initially discussed importance of the scheduling in the HeNB in the HetNet. We then proposed two novel scheduling weights based on the CCR for high spectral efficiency. Two proposed weights are no necessary increasing feedback information compared with the PFS. However, in our simulation results, we can confirm that four weighted schedulings achieve satisfactory performance of the throughput and/or the fairness in comparison with the normal PFS and the normal MAX-CIR.

Chapter 7

Conclusion

This chapter concludes our research work base on the study of Resource Allocation for Spectrum Sharing considering Interference Constraint of Primary System, which is consisted of the power allocation based on proposed interference constraint and environment aware scheduling for CR-enabled HeNB in the Heterogeneous networks. First, we described the interference constraint and power control schemes, their advantages and contributions. Secondary, we surmised the interference aware scheduling, and benefit points and contributions. Finally, we discussed about the potential future research direction.

7.1 Contribution and Advantages of the Proposed Resource Allocation

The cellular networks face paradigm shift in order to satisfy the demand of the performance improvement. The heterogeneous networks is new approach in a different way of peer-to-peer communication. Different networks is mixed in overlay environment, and assign of the same frequency to all networks in HetNet is allowed. The aggressive frequency reuse, so called *universal frequency reuse* is considered as the important key technique for performance improvement of cellular networks. This network has great potential in the view point of the spectral efficiency, cell capacity and throughput of cell-edge user. However, the HetNet is required the precise network design with a gain of the mixture network by controlling the same operator. However, currently researches focus on more general HetNet as multi-tier networks, which is allowing no modified of existing macro bases station, no backhaul network between macro- and femto-tier networks for coordination and random distribution of femto-tier cells. It means availability of coexistence different networks operated by different operators like as the spectrum sharing in the cognitive radio. Meanwhile, the femto-tier cell faces the problem of protection of macro-tier cell without the strong cooperation to macro-tier. The HeNB in femto-tire has to provide cognitive capability in order to protect the macto-tier communication.

Since the macro-tier protection lead to the MeNB and HeNB are analogous to primary and secondary users in the CR model. The first challenges are the design of metric in the interference constraint and transmit power control schemes for satisfying the constraint. In the absence of the interference constraint which is supportable wide range of SNR in the primary user, the either large degradation of the primary performance or heavy restriction to the secondary user is caused. Therefore, novel metric of the interference constrain, called CCR was proposed. The interference constraint based on CCR can maintain the small degradation over the wide SNR region, therefore it can be applied to protect the macro-cell in heterogeneous network. However, this constraint requires varied information for setting the transmit power control. Then, we make power control scheme more realistic through the analytical result. Two power control schemes are derived; the exact power control scheme written non-closed form can set the outage probability and the simplified power control shown closed form can protect the primary system with larger margin than exact power control scheme.

These results is applied to the HeNB in HetNet environment, an efficient scheduling algorithm was studied as our next research. Under the interference constraint, the femto-tier cell faces the problem of how to decide resource assign in the cross- and intra-interference channel. Firstly, we focus on the scheduling over only existing cross-interference in simple HetNet model. This scheduling uses the relationship between estimated rate and historical rate for adaption of interference strength in each HUEs. In the simple model, we confirm that the performances which are throughput and fairness can be improved compared with the traditional scheduling, without increasing overhead. In the proportional fair scheduling , the estimation rate and historical rate is reported to base station as feedback information. The proposed algorithm requires only same information of the proportional fair scheduling. After that, we evaluated the performance in the extend model which is random distribution of femto-tier cells. In this model, more interferences are arisen; the HUE receives the cross- and intra-interferences. The proposed scheduling algorithm show the better performance in the view points of the throughput and/or fairness.

7.2 Future Research Work

Our research works focus on two-tier wireless networks, i.e. there is not difference among multiple secondary (or lower priority) systems in the view point of the priority. However, in th future wireless networks, system of varied types (e.g. peer-to-peer, vehicular, cellular network) share the spectrum resource with different QoS. For example, the one of the system requires the robustness communication, other one is balance of throughput and fairness. Coexistence of valid systems requires complex design in order to satisfy the all QoS, and this design is inflexible. For adaptive resource allocation with valid systems, we believe multi-level priority among the secondary systems is necessary. The wireless resources should be allocated along to each priority along QoS of each systems in time, space and frequency domain. As for future work, coexistence among the primary system and multiple secondary systems by multi-tier system is an interesting research topic to achieve the better performances for all shared systems.

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List of Publications Directly Related to The Dissertation

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