# Dynamic Inter-Cell Interference Coordination in Cellular OFDMA Networks

by

**Md Mahmudur Rahman**

A thesis submitted to The Faculty of Graduate and Postdoctoral Affairs

in partial fulfillment of the requirements for the degree of

**Doctor of Philosophy in Electrical Engineering**

Ottawa–Carleton Institute for Electrical and Computer Engineering

Department of Systems and Computer Engineering

Carleton University, Ottawa, Ontario, Canada

The undersigned recommend to The Faculty of Graduate and Postdoctoral Affairs

acceptance of the Thesis

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Chair, Department of Systems and Computer Engineering

Professor Howard M. Schwartz

---

Thesis Supervisor

Professor Halim Yanikomeroglu

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External Examiner

Professor Hossam S. Hassanein

School of Computing & Department of Electrical and Computer Engineering

Queen's University

Carleton University

# Abstract

Inter-cell interference has been traditionally handled by fixed partition based reuse schemes since the beginning of cellular era. Although effective for the then voice oriented networks, it is insufficient for modern day data communications as aggressive reuse is needed to support high data-rates. Due to its potential for spectrum efficiency, studies on dynamic inter-cell interference coordination (ICIC) has gained momentum recently. This thesis presents some of the dynamic inter-cell interference coordination schemes for systems using orthogonal frequency division multiple access (OFDMA) air-interface.

A general sum-utility optimization problem is formulated using integer linear programming for the dynamic interference coordination problem. Due to the size and nature of the problem, a global optimal solution is computationally prohibitive. Therefore, three different sub-optimal approaches have been used to solve the problem:

1. A two-level algorithm with partial central processing,

2. A distributed algorithm with neighboring cell coordination, and

3. A cluster-based fully centralized approach.

All presented schemes are based on the fact that only dominant interferers affect the signal quality of a desired transmission; therefore, coordination locally among a set of neighboring transmitters (called interference cluster) taking into account inter-cluster interference dependency is sufficient to provide avoidance gain.

The solutions reflect different coordination architectures with different levels of avoidance gain and complexity. The performance of these proposed schemes has been compared with those of a number of reference schemes. According to obtained performance results, the proposed schemes always outperform the corresponding reference schemes with significant gain in the cell-edge throughput without impacting the total cell throughput.

# Acknowledgments

It is a pleasure to express my gratitude to many people who directly and indirectly helped and made this thesis possible.

First and foremost, I am greatly indebted to my supervisor, Professor Halim Yanikomeroglu, for his guidance and support with his knowledge and patience whilst allowing me the room to work in my own way. He has provided me with a lifetime opportunity to work in the Wireless World INitiative NEw Radio (WINNER) project which truly enhanced my knowledge through global research exposure. It is never an overstatement to say that one simply could not wish for a better supervisor.

I convey my acknowledgment to my supervisor at Industry Canada, Mr. Adrian Florea, for his support and encouragement without which it would not have been possible for me to write my thesis on-time.

I express my gratitude to the committee members of my thesis proposal whose invaluable comments, suggestions, and insights have enriched the content of this thesis.

I wish to thank all my friends and colleagues at Carleton University, Communications Research Centre, and Industry Canada for their encouragement. I extend special appreciation to the administrative and computing staffs of the department of Systems and Computer Engineering for their continuing support.

Sincere thanks go to my wife and daughter who always stood by me with great patience and good wishes.

I dedicate this thesis to my late parents to whom this thesis would have mattered the most.

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# List of Symbols

| | |
|---|---|
| $\alpha$ | Power amplification factor for the resource blocks in the outer-region in SFR scheme |
| $\beta$ | System bandwidth in PFR scheme |
| $\beta_1$ | Bandwidth for the inner region in PFR scheme |
| $\beta_2$ | Bandwidth for the outer region in PFR scheme |
| $i, j, k$ | Sector index |
| $\psi$ | Dominant interfering sector |
| $\psi_1$ | First dominant interfering sector |
| $\psi_2$ | Second dominant interfering sector |
| $\Psi$ | Set of dominant interfering sectors that are restricted |
| $n$ | Time-frequency resource index |
| $m$ | User index |
| $N$ | Maximum total number of resource units per sector |
| $M$ | Number of user terminals per sector |
| $N_{\mathrm{e}}$ | Number of eligible resource units |
| $N_{\mathrm{r}}$ | Number of restricted resource units |

| | |
|---|---|
| $\rho_i^{(m,n)}$ | Binary indicator showing whether resource $n$ is used by user $m$ in sector $i$ |
| $\gamma_i^{(m,n)}$ | SINR on resource $n$ seen by user $m$ in sector $i$ |
| $r_i^{(m,n)}$ | Rate (bps/Hz) on resource $n$ seen by user $m$ in sector $i$ |
| $r_{i\|\Psi}^{(m,n)}$ | Rate seen on resource unit $n$ by user $m$ of sector $i$, when sectors in set $\Psi$ are restricted for resource $n$ |
| $r_{i\|\Pi}^{(m,n)}$ | Rate seen on resource unit $n$ by user $m$ of sector $i$, when a combination of sectors in $\Pi$ is restricted for resource $n$ |
| $u_i^{(m,n)}$ | Utility of resource $n$ if used by user $m$ in sector $i$ |
| $U$ | Utility matrix |
| $U_{\text{intra}}$ | Utility matrix used for intra-eNB interference avoidance |
| $U_{\text{inter}}$ | Utility matrix used for inter-eNB interference avoidance |
| $\mathcal{H}_{i,x}^{(m,n)}$ | Channel from sector $x$ seen by user $m$ in sector $i$ on resource $n$ (includes path-loss, antenna gains, shadowing, and fading) |
| $d_i^{(m)}$ | Demand factor of user $m$ of sector $i$ |
| $R_i^{(m)}$ | Average time-average throughput of user $m$ of sector $i$ |
| $\bar{R}_i$ | Average time average throughput across all users in sector $i$ |
| $\zeta$ | Attenuation factor for attenuated and truncated Shannon rates |
| $\eta$ | Spectral efficiency |
| $r_p$ | Rate penalty used in intra-eNB interference avoidance |
| $r_m^{TH}$ | Rate threshold used in heuristics to find resource restrictions |
| $\Pi$ | Combination of dominant interfering sectors that are restricted for a given resource unit |
| $I_i^{(n)}$ | Binary indicator showing whether resource $n$ is restricted for sector $i$ |

| | |
|---|---|
| $D$ | Distance between a transmitter and a receiver |
| $L_D$ | Distance dependent path-loss between a transmitter and a receiver in dB |
| $h$ | BS antenna height in meters |
| $f_c$ | Carrier frequency in GHz |
| $\theta_{3\text{dB}}$ | Angle in degrees at which the antenna gain is 3 dB lower than the bore-sight gain |
| $\theta$ | Antenna pattern azimuth angle in degrees |
| $A(\theta)$ | Antenna gain in dB at an horizontal angle of $\theta$ measured from the bore-sight angle |
| $P_t$ | Transmit power per sector antenna |
| $P_c$ | Transmit power per resource unit |
| $P_{TN}$ | Average thermal noise power |
| $c_{y,z}$ | Cost of assigning job $y$ to machine $z$ |
| $a_{y,z}$ | Assignment indicator for job $y$ to machine $z$ |
| $t$ | Time |
| $r_{m,n}(t)$ | User $m$ achievable rate on resource unit $n$ at time $t$ |
| $T_m(t)$ | User $m$ filtered time-averaged rate at time $t$ |
| $R_m(t)$ | User $m$ total rate achieved for all allocated resources at time $t$ |
| $t_c$ | Time constant |

# List of Abbreviations

| | |
|---|---|
| **3G** | $3^{rd}$ Generation |
| **3GPP** | $3^{rd}$ Generation Partnership Project |
| **AMC** | Adaptive Modulation and Coding |
| **ARQ** | Automatic Repeat reQuest |
| **BER** | Bit-Error Rate |
| **B-LDPC** | Block Low-Density Parity-Check |
| **BLER** | Block-Error Rate |
| **BPSK** | Binary Phase Shift Keying |
| **BS** | Base-Station |
| **BSC** | Base-Station Cooperation |
| **CDF** | Cumulative Distribution Function |
| **CoMP** | Coordinated Multi-Point Transmission and Reception |
| **CQI** | Channel Quality Indicator |
| **CR** | Cognitive Radio |
| **CSI** | Channel State Information |
| **E2E** | End-to-End |

| | |
|---|---|
| **eNB** | evolved NodeB |
| **FDD** | Frequency Division Duplex |
| **FFR** | Fractional Frequency Reuse |
| **FH** | Frequency Hopping |
| **GSM** | Global System for Mobile communication |
| **ICIC** | Inter-Cell Interference Coordination |
| **IEEE** | Institute of Electrical and Electronics Engineers |
| **ILP** | Integer Linear Programming |
| **IMS** | IP Multimedia Subsystem |
| **IP** | Internet Protocol |
| **IR** | Inverted Reuse |
| **IRC** | Interference Rejection Combining |
| **ISI** | Inter-Symbol Interference |
| **LOS** | Line of Sight |
| **LP** | Linear Programming |
| **LTE** | Long Term Evolution |
| **LTE-A** | LTE-Advanced |
| **M2M** | Machine-to-Machine |
| **MCS** | Modulation and Coding Scheme |
| **MIMO** | Multiple-In Multiple-Out |
| **MME** | Mobility Management Entity |
| **MRC** | Maximal Ratio Combining |

| | |
|---|---|
| **OFDM** | Orthogonal Frequency Division Multiplexing |
| **OFDMA** | Orthogonal Frequency Division Multiple Access |
| **PF** | Proportional Fair |
| **PFR** | Partial Frequency Reuse |
| **PHY** | Physical |
| **PRB** | Physical Resource Block |
| **QAM** | Quadrature Amplitude Modulation |
| **QoS** | Quality of Service |
| **QPSK** | Quadrature Phase Shift Keying |
| **RAN** | Radio Access Network |
| **RNC** | Radio Network Controller |
| **RRM** | Radio Resource Management |
| **SDR** | Software Defined Radio |
| **SFR** | Soft Frequency Reuse |
| **SINR** | Signal-to-Interference plus Noise Ratio |
| **SISO** | Single-In Single-Out |
| **SNR** | Signal-to-Noise Ratio |
| **SON** | Self Organized Network |
| **TDMA** | Time Division Multiple Access |
| **UE** | User Equipment |
| **UMTS** | Universal Mobile Telecommunications System |
| **UT** | User Terminal |

**UTRAN** UMTS Terrestrial Radio Access Network

**WFQ** Weighted Fair Queuing

**WiFi** Wireless Fidelity

**WiMAX** Worldwide Interoperability for Microwave Access

**WINNER** Wireless World INitiative NEw Radio

**WINNER+** WINNER Plus

**WLAN** Wireless Local Area Network

# Chapter 1

# Introduction

## 1.1 Introduction

In this chapter, the driving factors that motivated the research conducted in this thesis are presented first in Section 1.2. The statement of the problem is outlined briefly in Section 1.3 followed by the contributions of this thesis in Section 1.4. The overview of the obtained results and the organization of this thesis are given in Sections 1.5 and 1.6, respectively.

## 1.2 Motivation

The pace at which the cellular wireless technology has been evolving is probably the fastest compared to any other technology evolution. It is amazing to witness all these evolutions and revolutions, with respect to data speed, service type, applications, hardware, etc., starting from early analog systems to present day digital all-Internet Protocol (IP) systems. As the face of the cellular technology changes, so does its challenges. In the early days, wireless research mainly concentrated on cell capacity, scheduling, antenna design, etc., on which research has matured and we have overcome the underlying issues and challenges over the years. The challenges of cellular technology has now shifted, as we realize that Radio

Resource Management (RRM) is one of the critical functions for the efficiency of future wireless systems. Based on the realization that Radio Access Network (RAN) architecture has a lot to do to squeeze out further capacity from wireless systems, the femto-cell technology has been invented. State-of-art technologies like Cognitive Radio (CR), Software Defined Radio (SDR), Machine-to-Machine (M2M), Self Organized Network (SON) and so on, are emerging with great possibilities and opportunities. However, these opportunities accompany enormous challenges, especially, with respect to interference and related RRM aspects. This thesis focuses on one of such challenges- inter-cell interference.

Orthogonal Frequency Division Multiplexing (OFDM) [1] is being welcomed as a promising air-interface technology for the next generation wireless standards such as for local area Wireless Fidelity (WiFi) [2] networks to wide-area cellular systems like Worldwide Interoperability for Microwave Access (WiMAX) [3], $3^{rd}$ Generation Partnership Project (3GPP) Long Term Evolution (LTE) of Universal Mobile Telecommunications System (UMTS) [4] and LTE-Advanced (LTE-A) [5], and in the forum activities such as WINNER [6] and WINNER Plus (WINNER+) [7] systems. Equipped with OFDM's inherent robustness against frequency selective fading, Orthogonal Frequency Division Multiple Access (OFDMA) offers flexibility for radio resource allocation [8]. The finer resource granularity of the OFDMA allows each resource unit[1] to be allocated and modulated adaptively to obtain frequency as well as multiuser diversity.

In order to meet the high target data-rates in these beyond $3^{rd}$ Generation (3G) and onward cellular systems, dense reuse of frequency is required with the obvious pitfall of high inter-cell interference. Classical approach of interference avoidance through clustering approach may have been good enough for voice services, but it is highly inefficient for systems requiring high data rate for services such as streaming video, video conferenc-

[1] A collection of consecutive sub-carriers over a defined time period, which is regarded as the minimum granularity of the radio resource allocation unit; it is called *chunk* in the WINNER context and *Physical Resource Block (PRB)* in 3GPP LTE and LTE-A studies.

ing, etc. A denser frequency reuse is required to support high data rate with expensive and limited spectrum. Therefore, to obtain the full potential of the OFDMA in a dense reuse environment, appropriate interference mitigation technique(s) is(are) essential. To that end, interference mitigation has been identified as one of the major issues currently being investigated by different standardization bodies and forums focusing on forthcoming cellular systems. Interference mitigation techniques are categorized into three major classes such as interference cancellation through physical layer processing, interference averaging or randomization using frequency hopping, and interference avoidance through network level transmission coordination. The focus of this thesis has been on dynamic inter-cell interference coordination using network layer resource coordination.

## 1.3 Problem Statement

Inter-cell interference avoidance without impacting cell throughput is a challenging task. In this thesis, inter-cell interference problem is addressed using a number of novel dynamic Inter-Cell Interference Coordination (ICIC) schemes.

Interference is an inevitable byproduct of wireless transmissions and it is inherent to any wireless technology. The issue of ICIC using preplanned resource partitioning in a static manner can be traced back to the time when the cellular technology was first invented. However, semi-static or dynamic ICIC techniques, required to support dense spectrum reuse required for current and future high data-rate wireless systems, are fairly recent research interest. The primary objective of such ICIC algorithms is to boost cell-edge performance with a minimal impact on network throughput. To that end, a number of proposals are available through standardization campaigns and scholarly articles. However, most studies consider either static or semi-static approaches, such as the variants of Fractional Frequency Reuse (FFR) schemes, where cell-edge performance can only be enhanced through significant penalty to network throughput. Additionally, such schemes requiring frequency

planning cannot be applied to the emerging femto-cellular networks, as femtocells will be placed at the end user locations in an ad hoc manner making any prior frequency planning difficult. Dynamic coordination schemes, on the other hand, do not require prior frequency planning and operate based on dynamically obtained mutual interference information from surrounding transmitters. Therefore, dynamic schemes are not only effective to avoid interference in macrocell-macrocell scenario, they are also capable of handling interference from macrocells if applied to femtocell or office picocell Base-Station (BS)s. These femto deployments rely on signaling over IP backbone. Future IP communications are expected to be on fast IP Multimedia Subsystem (IMS) core, which will support fast information processing required for dynamic interference coordination schemes. Dynamic inter-cell coordination based schemes can best exploit channel dynamism to achieve maximum interference avoidance gain; however, only a few such studies can be found in the literature.

In this thesis, the interference coordination problem is first formulated using Integer Linear Programming (ILP) approach and then different viable sub-optimal solutions and/or heuristics are explored. The primary focus of these studies is to provide enhanced performance to cell-edge user terminals while keeping the system throughput minimally affected, not affected at all, or even improved. The formulation takes user's achieved throughput status and interference condition into account and finds a set of resource units that are to be restricted in each transmitter in a dynamic manner. Three major different approaches toward the sub-optimality of the solutions are investigated and presented in three main subsequent chapters of the thesis.

## 1.4 Thesis Contributions

A number of low-complexity, viable dynamic ICIC schemes, that show significant gain in cell-edge throughput without impacting cell throughput, have been designed and evaluated in this thesis. The contributions can be summarized as follows:

- The ICIC problem has been formulated using a general optimization framework considering the fact that only neighboring dominant interferers affect transmission quality. We use our previously adopted idea of *interferer group* to form *interference cluster* and model such inter-dependent interference entities. A closed form optimal solution of interference coordination problem that considers a large number of mutually interfering cells is a complex problem due to its large problem size. Therefore, an optimal formulation is devised and different sub-optimal solutions, representing different levels of optimality, complexity, and network architectures, are explored.

- A unique, two-level sub-optimal scheme has been developed, where user-centric resource restrictions are made by a sector-level algorithm that selfishly prepares a list of resources to be restricted in each neighboring dominant interferer sector. The inter-dependency of resource restrictions is handled by another algorithm that resides as a central entity. As the central algorithm only deals with resource restriction conflicts, the overall complexity of the scheme is reduced significantly. We utilize the Hungarian algorithm [9] that works on utility measures (considering users' achieved throughput status) of the resources to prepare the resource restriction request.

- The above scheme has been tailored to a distributed algorithm for the system in which a central entity is not available in the architecture, such as the 3GPP LTE. Interferers have been categorized into intra- and inter-evolved NodeB (eNB)[2] interferers and handled differently due to their signalling and coordination requirements. In particular, as intra-eNB interference mitigation does not require inter-cell signaling, avoidance can be done in each eNB considering mutual interference among its sectors. We devise a novel method for intra-eNB interference avoidance, where Hungarian algorithm has been used in a multi-sector context. To the best of our knowledge, Hungarian algorithm has never been applied to resource scheduling among multiple cells (or sectors).

[2] A BS is called as eNB in LTE terminology.

The inter-eNB interference is handled much like the above scheme; however, resource restriction conflicts are handled by inter-cell signaling using the X2 interface of the LTE system.

- A novel cluster-based sub-optimal scheme has been studied in this thesis, where inter-dependency of resource restriction has been modeled using an ILP approach. Different utility functions have been considered to model different levels of user fairness and the trade-off with system throughput. Also, different cluster sizes representing different computational complexity have been investigated.

- In all investigated solutions, emphasis has been on cell-edge user performance which is a function of channel conditions, mutual interference situation, and users' achieved throughput status.

Some of the research presented in this thesis were conducted under the WINNER project during 2004-2007. In the initial phase of this thesis, an interference avoidance scheme in a relay-based network using Time Division Multiple Access (TDMA) air-interface had been studied. The ideas and/or results of this research were included in WINNER Phase I deliverables [10–13] and presented in [14]. As could be seen from [14] that the initial work on the ICIC problem was done quite early on, much before ICIC became a hot research topic. ICIC schemes considering OFDMA systems that form Chapter 4 of this thesis was first studied in WINNER phase II, where primary emphasis had been on obtaining performance gain due to *dynamic interference coordination*. Results were contributed to WINNER Phase II deliverable [15] and in [16, 17]. An extended version of the work presented in [17] also appeared in [18]. The ideas presented in [16] has been enhanced in [19] in various aspects and a further extended work [20] has been submitted for possible publication.

Besides WINNER, some research were done under industry collaborated research projects in Canada and internationally such as with Communications Research Centre (CRC). Re-

search focus in CRC-Carleton project during 2008-2009 had been on interference avoidance for the 3GPP LTE system. Contributions were made to two CRC-Carleton Year I project deliverables, two Year II deliverables, and presented in [21]. Some ideas of dynamic interference avoidance formed part of a patent [22] filed by Samsung Korea. Contributions were also made to other research projects in the form of in-house research collaborations, which are excluded from this thesis [23–28].

## 1.5 Overview of Results

Cell-edge performance, which is defined as the $5^{th}$ percentile point of the Cumulative Distribution Function (CDF) of the time-average user throughput, is observed. Also, sector throughput for the proposed schemes as well as for the reference schemes is determined. For each investigated scheme, a corresponding reference scheme has been considered for comparison, in which coordination is either not used or used in a static manner. The fairness of the proposed schemes has also been determined using Jain's fairness index [29].

It is observed that the proposed dynamic interference avoidance schemes always provide enhanced performance, with respect to cell-edge throughput and fairness with a minimum impact to sector throughput, compared to that in the reference schemes.

## 1.6 Organization of the Thesis

The remainder of this thesis is organized as follows. A brief literature review is given in Chapter 2. Chapter 3 describes a general optimization framework for the interference coordination problem and gives overview of the three approaches of sub-optimal solutions. Chapters 4, 5, and 6 present details on these approaches along with respective results and discussions. Table 1.1 summarizes major publications that constitute these core chapters of this thesis.

Table 1.1: Major publications constituting the core chapters

| Chapter | Publication |
|---|---|
| Chapter 4 | *VTC2008-Spring* and *TWC2010* |
| Chapter 5 | *WCNC2009* |
| Chapter 6 | *GLOBECOM2006*, *GLOBECOM2007*, *VTC2010-Spring*, and *TVT2011* (submitted) |

It should be mentioned that different proposed dynamic ICIC schemes have been studied in different contexts depending on the requirements of the underlying projects. For example, the two-level algorithm with partial central processing in Chapter 4 has been developed in the context of the WINNER project. On the other hand, the distributed scheme, presented in Chapter 5, considers LTE system due to the requirements of the project. Therefore, the system and simulation parameters of the proposed schemes are different and hence they are described separately in the respective chapters.

Chapter 7 concludes this thesis and outlines a few ideas by which the research presented in this thesis can be extended. Finally, Appendix A presents a list of publications of the author.

## 1.7 Summary

In this chapter, motivation, problem statement, and highlights of the contributions this thesis, a synopsis of the observed results and the organization of this thesis have been provided. The next chapter presents an overview of the current literature on interference avoidance.

# Chapter 2

# Literature Review

## 2.1 Introduction

An overview of the current literature on interference coordination has been provided in this chapter. Multi-cell resource allocation and scheduling techniques are closely related to interference avoidance. Therefore, some notable literatures on multi-cell resource allocation along with brief descriptions of the Hungarian algorithm and proportional fair scheduler, that are used in this thesis, have also been included in this chapter.

## 2.2 Inter-Cell Interference Avoidance

Co-channel interference has always been a challenge which arises due to the reuse of radio resources necessary to cope with the scarcity of radio spectrum. Traditionally, inter-cell co-channel interference is handled by static resource partitioning and frequency planning using the classical clustering technique, first proposed in [30] at the time when the cellular technology was invented. The reuse distance, locations of the BSs in the cell-sites and antenna directivity have been studied rigorously at that time, see [31, 32], for example. In this approach, the higher the cluster size, the lower the interference due to a larger reuse distance.

Such partitioning schemes may have been good enough for early networks focusing primarily on voice service; however, these schemes are inapplicable to future systems envisioned to support ranges of high data-rate applications such as video conference, streaming video, mobile television, etc. Therefore, it is necessary for these systems to employ frequency reuse as dense as possible with necessary protection against inter-cell interference.

Interference mitigation is one of the key issues currently being investigated by researchers in industry and academia of different standardization bodies, forums, and research groups. The techniques used for interference mitigation are generally classified into three major categories such as *interference cancellation* through receiver processing, *interference randomization* by frequency hopping, and *interference avoidance* achieved by imposing restrictions in resource usage in terms of resource partitioning and power allocation [3, 15, 33]. The basic principle of interference cancellation techniques is the receiver signal processing to estimate interference and subtracting it from the desired signal component. Interference averaging techniques such as Frequency Hopping (FH) that ensures User Equipment (UE)s to access a range of channels rather than a narrow set in a specific pattern so that interference effect is averaged out for all UEs in the long term. Finally, the interference avoidance technique focuses on finding an efficient reuse factor often achieved through restrictions on frequency and power allocations that meets network performance goals. The benefits of these techniques are mutually exclusive, and hence, a combination of these approaches is likely to be employed in the system.

UEs at the cell border experience high interference from neighboring transmitters in addition to their high distance dependent attenuation. Scheduling schemes targeting maximized network throughput, such as a maximum-Signal-to-Interference plus Noise Ratio (SINR) type scheduler, will find these UEs with poor channel conditions less attractive as they are not likely to contribute much to the total throughput. Strictly speaking, even a fair scheduler such as a Weighted Fair Queuing (WFQ) scheduler [34], will have a limit to

the extent it can favor the cell-edge users. Consequently, the cell-edge users will suffer from poor throughput. A blunt approach to improve cell-edge UEs' rates could be to assign more resources (e.g., an equal rate sharing approach); however, it would jeopardize the rates of the other UEs in the cell-centre and degrade total cell throughput. Hence, such an approach is highly undesirable. The objective of interference avoidance is, therefore, to improve SINR and provide better services to cell-edge UEs without sacrificing cell-centre throughput. The focus of this thesis is on interference avoidance using dynamic ICIC.

For the sake of organization, the techniques for interference avoidance found in the literature are categorized as follows:

- Interference avoidance using resource partitioning
  - Fractional frequency reuse (FFR)
    - Soft frequency reuse (SFR)
    - Partial frequency reuse (PFR)
  - Inverted reuse (IR)
- Interference avoidance by resource allocation and scheduling
- Interference avoidance using inter-cell handover
- Dynamic inter-cell interference coordination

### 2.2.1 Interference Avoidance using Resource Partitioning

If the available frequency spectrum is reused in each sector without any restriction to frequency resource usage or power allocation, it achieves a reuse factor of 1 (also termed as *universal reuse*), which is the worst inter-cell[1] interference situation.

[1]The terms "sector" and "cell" are used interchangeably in this thesis, and therefore, inter-cell interference refers to interference received by a UE in a sector from any other sector transmitter using the same frequency.

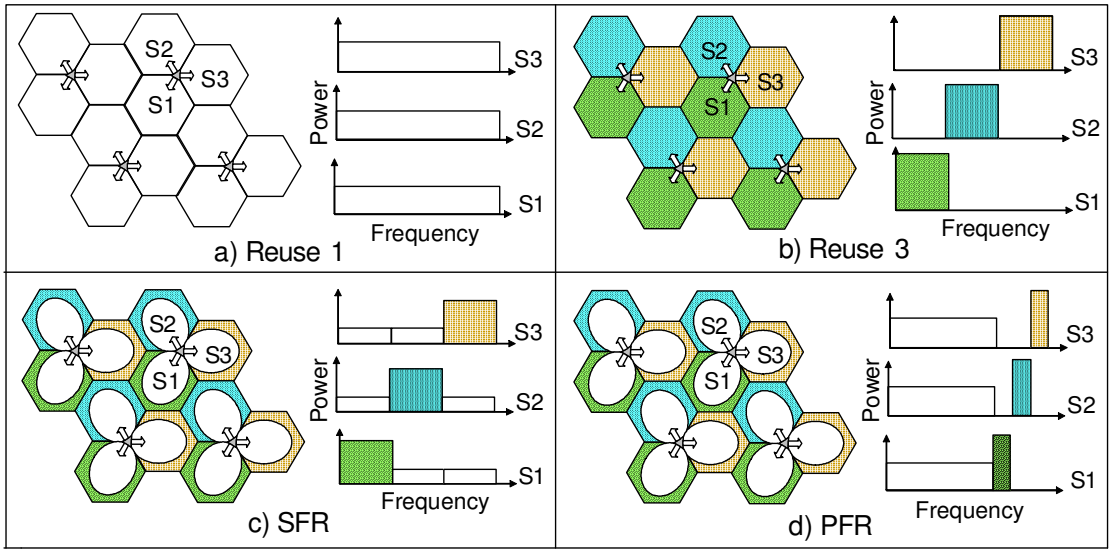


Figure 2.1: Reuse 1 and other static partition based schemes.

On the other hand, if the available frequency spectrum is divided into three sub-bands and each sector is given an orthogonal sub-band among neighboring sectors, then a reuse of 3 can be achieved [30]. This clustering obviously provides improved inter-cell interference, however, it results in a significant resource loss due to partitioning. Figures 2.1.a & 2.1.b show reuse 1 and 3 schemes, respectively, where total transmit power per sector transmitter remains constant in both cases. While reuse 1 does not employ any interference coordination, reuse 3 can be regarded as an extreme case of partition-based static interference coordination. The FFR schemes achieve an effective reuse factor between 1 and 3. Two variations of FFR schemes, namely Soft Frequency Reuse (SFR) and Partial Frequency Reuse (PFR), are shown in Figures 2.1.c & 2.1.d. These schemes are used as some of the reference schemes in this thesis and therefore, are elaborated further in the subsequent sections.

**Fractional Frequency Reuse (FFR)**

Evolved from the classical reuse clustering idea, the FFR scheme was first introduced in [35] for the Global System for Mobile communication (GSM) systems. In the recent years, the FFR scheme has attracted the attention of the researchers in different standardization bodies and forums. It is adopted by the WiMAX forum [3] and 3GPP LTE [33] in the form of different variants. This idea is also explored extensively in the WINNER [15] project. The motivation for proposing the FFR lies in the fact that users in the central area of a cell are robust against interference due to likely weak interference and strong desired signals, and hence they can tolerate reuse of 1 compared to the users at the cell border suffering from high interference as well as high distance dependent attenuations (in desired links). Therefore, it is more effective to use mixed reuse factors, i.e., a higher reuse factor for the UEs in the cell-edge compared to that for the cell-centre areas where reuse of 1 can be supported. A common example of an FFR for a network with trisector BSs is a blend of reuse factor of 1 and 3 in the cell-centre and cell-edge areas, respectively. A simple FFR scheme is shown in Fig. 2.2. Generally, users are classified into cell-edge and cell-centre groups based on the user geometry. Resource is partitioned into inner- and outer-bands (also called minor and major bands), and are allocated to cell-centre and cell-edge users, respectively. Partition of resources into the cell-edge and cell-centre bands determines the effective reuse factor. In most schemes, higher power is allocated to the resources used for the cell-edge UEs. In [36], the effect of power coordination in FFR scheme has been investigated. In that study, a predefined power and frequency planning is applied to show that the power coordinated FFR scheme outperforms a pure FFR scheme where an equal power is applied across the whole band (both the inner and outer sub-bands). PFR [37] and SFR [38] are two variants of the FFR scheme, which are discussed below with a greater details.

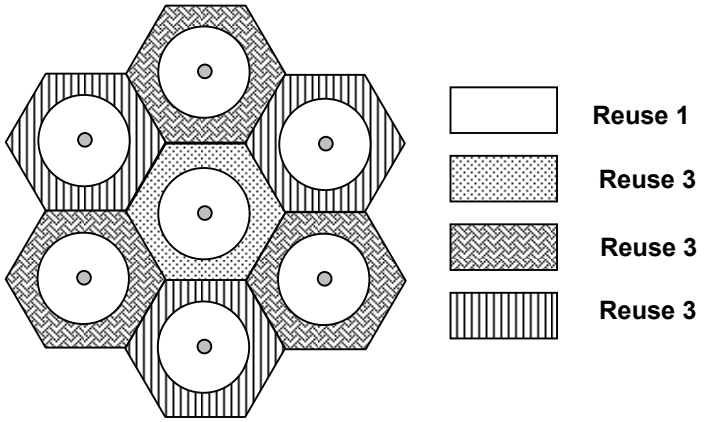


Figure 2.2: Fractional frequency reuse with a reuse factor of 3 in the outer zone.

**Soft Frequency Reuse:** Soft frequency reuse scheme is a variation of FFR, in which a reuse factor of 1 and a factor equal to or greater than 1 are applied in the cell-centre and cell-edge areas, respectively. It was proposed in [38] and [39] under 3GPP LTE framework to provide a higher rate to disadvantaged UEs such as those near the cell boundary.

Fig. 2.1.c shows an example of an SFR scheme for cell sites with sectorization. For 3-sector cell sites, the cell-edge band is usually 1/3 of the available spectrum and is orthogonal to those in the neighboring cells. The cell-edge subcarriers are called major subcarrier group while the cell-centre frequency band is termed as minor subcarrier group. The total transmit power is set fixed and each group is assigned transmission power depending on desired effective reuse factor, which is determined by the ratio of the allocated powers of cell-centre to cell-edge groups.

Transmissions use higher power on the major band as shown in the right side of Fig. 2.1.c. Let us consider that the power per PRB (i.e., time-frequency resource unit) is 1 in the case of reuse of 1 and power per PRB for the cell-edge (major) band is $\alpha$ for the SFR scheme. Then power per PRB in the minor band would be $(3-\alpha)/2$ giving a power ratio of $(3-\alpha)/2\alpha$

for the minor to major band. Minor band is available to cell-centre UEs only and major band can also be used for cell centre areas. Adjusting power ratio from 0 to 1 effectively moves the reuse factor from 3 to 1. Therefore, for a tri-sector cell, the SFR scheme is a tunable compromise between reuse 1 and 3.

The power ratio can be adjusted according to the traffic distribution in the cell. When the traffic load for the cell edge users is high, a relatively small power ratio has to be set. On the other hand, when the traffic is largely concentrated in the central part of the cell, a relatively high power ratio is suggested. In that sense, the effective reuse factor of SFR can be adapted in a static, semi-static, or dynamic depending on the time-scale of the adaptation. In [39], with cell layout without sectorization, simulations are performed for different power ratios in a static manner. Results show that decreasing power ratio provides higher cell-edge throughput with the decrease in throughput for the cell-centre UEs and the cell in general. In [37], simulations are performed with different antenna configurations and receiver combining methods. While the results follow the general trend of increasing cell edge throughput with the decrease in total cell throughput for all simulation combinations, dual antenna Interference Rejection Combining (IRC) receiver provides higher network throughput compared to the single antenna and dual antenna receivers with Maximal Ratio Combining (MRC).

The performance of the semi-static SFR is compared with that of a static in [40] in a network with tri-sector cells. For the static SFR the maximum soft reuse factor is 1/3, i.e., the sub-bands allocated to cell-edge users can be up to 1/3 of the total frequency band. However, in semi-static SFR, the percentage of frequency resources allocated to cell edge users is considered to be equal to the percentage of cell-edge terminals relative to the total number of users which may become larger than 1/3. A single antenna transmitter and dual antenna receiver have been assumed for simulations. It has been shown that the semi-static SFR outperforms the static SFR by providing up to 50% higher cell-edge throughput while

keeping the cell-centre throughput slighly better.

The SFR is also studied extensively in the WINNER project [15, 41] basically in the the context of static partitioning into sub-bands and power allocation. This allocation can be done over the time-scale of days through network planning. The criteria for this allocation could be the average SINR over whole bandwidth. The SFR is evaluated with different reuse factors such as 7/6, 3/2, and 3/1 (a different convention of expressing reuse factor is used here) in the downlink of WINNER system. The reuse factor of 7/6 implies $1/7^{th}$ of the resource will have to use reduced power, for example 10 dB lower as considered here, in each cell. Also, different user speed scenarios have been considered in the simulations. As expected, the performance with 7/6 reuse is shown to be better in terms of cell throughput compared to that in other higher reuse factors. However, comparing with reuse 1 case, it has been shown that only marginal cell-edge throughput performance is observed compared with a large reduction in overall sector throughput. Study also investigates performance with and without receiver diversity, MRC, scheme. The UEs are categorized into cell-edge and cell-centre based on user geometry determined by the received signal power (averaged over multi-path fading) taking into account the large-scale path-loss, shadowing, and antenna gains.

**Partial Frequency Reuse:** Contrary to the SFR, the idea of a PFR scheme is to restrict some resources so that some frequencies are not used in some sectors at all. This concept was first presented in [42]. The effective reuse factor of this scheme depends on the fraction of unused frequency. The PFR and some of its variants are studied in the 3GPP and WINNER projects (see, for example, [37] and [15]). An example of PFR for cell sites with 3 sectors is shown in Fig. 2.1.d. Let us assume that the available system bandwidth is $\beta$ which is divided into inner and outer zones with $\beta_1$ and $\beta_2$, respectively. Usually, $\beta_1$ is used with a reuse factor of 1 and for the tri-sector BSs, the reuse factor for $\beta_2$ is 3 in

the outer zone. In this case, the effective frequency reuse factor is given by $\beta/(\beta_1+(\beta_2/3))$. Therefore, the effective reuse of PFR scheme is always greater than 1. Like SFR scheme, the power used on sub-band for the outer zone is amplified as shown in Fig. 2.1.d.

In [15], the FFR is investigated in the context of WINNER system for various power control and scheduling scenarios. Besides interference avoidance through partitioning and power control, several scheduling approaches have been considered that prioritize the allocation to cell-edge users in different ways. These are as follows:

- Cell-edge UEs are scheduled first, hence, it can take sub-channels from cell-centre band
- Cell-edge UEs can only use cell-edge band
- Cell-edge UEs are scheduled on cell edge band, however, if they require more they take from cell-centre band

The reuse of 3 has been employed for the cell-edge band. Two cases have been considered. In one case, a full-power isolation (defined FFR FI) has been considered, where cells are not permitted to use the cell-edge bands of neighbors. In the other case, cells are allowed these bands but only with reduced power (partial power isolation, FFR PI). For FFR PI scheme, the transmit power on the cell edge band in 1.5 times than the other band. Results show that FFR PI does not bring significant benefit to the cell-edge throughput while keeping minimum impact on the sector throughput. On the other hand FFR FI exhibits significant gain in cell-edge throughput (155%), however, with a significant reduction (up to 15%) in sector throughput.

**Inverted Reuse (IR) Scheme**

The so called *inverted reuse scheme* was proposed within the 3GPP framework for the UMTS Terrestrial Radio Access Network (UTRAN) downlink in [43], and analyzed in [44]

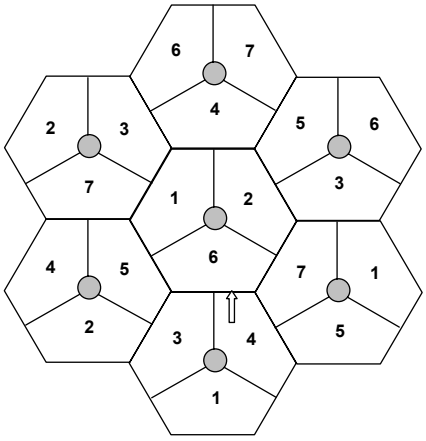


Figure 2.3: Inverted reuse scheme with a reuse of 7/6.

and [45]. The basic idea of this scheme was to divide each sector into zones and available frequency bandwidth into different frequency patterns. For each cell, some frequency patterns could only be used with a reduced power. This scheme is very similar to SFR in that the whole frequency band can be used in each sector. Two possibilities were discussed, where one required network power planning and the other did not. The number of subsets the frequency band partitioned to was 7 or 9.

Figure 2.3 shows the basic concept of this scheme for a reuse factor of 7/6. Here, available frequency band is partitioned into 7 sub-bands. In sector $n$, the $n^{th}$ sub-band can only be used with reduced power. A UE moving from a sector to the direction of another will be assigned resources from the sub-band which is power restricted in the sector of movement direction. For example, as shown by the arrow in the figure, a UE currently served by sector 4 in bottom cell is moving toward sector 6 of the cell. In this case, this user will be allocated resources from sub-band 6. As this sub-band is used in sector 6 with reduced power, this cell-edge user in sector 4 will experience reduced interference power from neighboring sector 6.

### 2.2.2 Comparison Among Partition-based Schemes

While reuse-based schemes such as SFR, PFR, and Inverted Reuse (IR) schemes are studied extensively within the 3GPP LTE project, much of the initiative was in an ad-hoc manner; i.e., a little attempt has been made to compare these schemes in a common frame-work. Also, as static coordination schemes show little to no significant gain in performance [46], there are proposals on using these schemes on semi-static or dynamic time-scales. Which means, the partition of frequency and/or allocation of power should be adapted based on traffic load and/or user terminals data rate requirements.

In [40], a semi-static SFR scheme is evaluated against static SFR. In the semi-static scheme, resource partitioning between cell-centre and cell-edge areas are adapted through semi-static network coordination in cooperation with the Radio Network Controller (RNC) considering the traffic load and data rate requirements of UEs near the edge of each cell. The simulation results in terms of the total, cell interior, and cell-edge throughput are compared with those for the static SFR, where cell-edge partitioning is 1/3 of the available resources. Simulations show that the cell-edge throughput in the semi-static SFR is 10 to 50% higher compared to the static SFR while the cell throughput is marginally better.

Instead of using a fixed power profile in SFR, a dynamically changing power profile has been studied in [47]. The UEs are grouped into high-Signal-to-Noise Ratio (SNR) and cell-edge terminals. This categorization is done based on the observation of long term Channel Quality Indicator (CQI). The idea is to reduce the power for the resources belonging to high-SNR UEs dynamically to obtain a dynamic frequency-power pattern. The algorithm works as follows:

- perform frequency-domain scheduling and initial link adaptation
- for each high-SNR UE, reduce power on a subset of scheduled UEs based on a certain criteria, for example, Bit-Error Rate (BER)

- redistribute saved power across resources belonging to the cell-edge UEs
- estimate interference and channel quality of the cell-edge UEs
- update link adaptation and new rate for the cell-edge UEs

A prediction-based blind power-control algorithm is assumed in order to avoid inter-BS communication. One simple approach is to assume an identical power statistical distribution among cells. Therefore, by monitoring its own power redistribution, A BS predicts the interference distribution and adjust the CQI values for UEs by monitoring its own power redistribution (assuming identical statistical power distribution in the cell). As an example, an exponential-window average of power allocations is suggested to be used to estimate the mean of interference variation. In this sense, the proposed scheme is *statistical interference avoidance* rather than *static interference avoidance* scheme. Compared to the fixed power profile, adaptive power profile (power control) provides no loss to 2% gain in system throughput while improving the cell-edge throughput by 15 to 25%.

SFR and PFR have been compared in terms of theoretical capacity as well as simulations for cell-edge and sector throughput in [48]. It has been shown that SFR is a better candidate than the PFR to enhance cell-edge performance without sacrificing the sector throughput.

### 2.2.3 Interference Avoidance by Fast Cell Selection

In [49], interference avoidance through the use of fast cell selection is investigated. The idea is that each cell-edge UE monitors its interferers as possible candidates for a future handover. By switching to a BS from where it receives the strongest interference, it not only avoids interference but also ensures a strong link for future services. A UE prepares a set of active BSs through measurement to which it can potentially switch to according to certain criteria, for example, instantaneous SINR or achievable rate. The terminal then requests for admission to each of the these cells in the active cell. If the cell cannot afford

to accept the interested UE, the cell becomes a non-primary cell. The accepting cell from the active cells is termed as the primary cell to which a handover takes place. Note that resource is partitioned into common sub-channels (all cells can use) and sub-channels with restrictions determined during active set preparations. The sub-channels in the latter group can be restricted at the non-primary cells. Results are compared with those for conventional handover with and without interference avoidance, and are shown to be better in terms of achieved spectral efficiency.

A similar study is investigated in [50], where the optimal inter- and intra-cell association is discussed considering the network load and inter-cell interference. The PFR has been used as a default partitioning for each cell. The association of UE to a cell either for inner-cell or for outer-cell resources are determined through a network-wide utility maximization problem.

### 2.2.4 Dynamic Inter-Cell Interference Coordination

Most available proposals on FFR rely on static or semi-static coordination among BSs; it is seen in the literature that FFR schemes that use interference coordination in a static or semi-static manner do not provide much overall gain as cell-edge throughput can only be improved with a significant penalty to the system throughput [15]. This is due to the fact that static resource partitioning and/or power allocation on a larger time scale is unable to exploit channel dynamism. An optimal partitioning depends on the distribution of the UEs, arrived traffic, and channel dynamism. Therefore, any static reuse partitioning scheme would be a highly sub-optimal solution. A dynamic partitioning based on UEs' traffic load as well as mutual interference situation may provide balanced improvements for both the cell-edge and cell-centre UEs' rates. Such a dynamic reuse adaptation requires dynamic inter-cell coordination. In addition, schemes requiring frequency planning cannot be applied to the emerging femto-cellular networks [51], as femto-cells will be placed at the end user locations

in an ad hoc manner making any prior frequency planning difficult. Dynamic coordination schemes, on the other hand, do not require prior frequency planning and operate based on dynamic interference information from surrounding transmitters. Therefore, dynamic schemes are not only effective to avoid interference in macrocell-macrocell scenario, they are capable of handling interference from macrocells if applied to femtocell or picocell BSs. There are a few studies in the literature that address interference avoidance between macro- and femtocell deployments [52–54].

Dynamic inter-cell coordination based schemes can best exploit channel dynamism to achieve maximum interference avoidance gain; however, only a few such studies can be found in the literature [16–19, 21, 55–61]. In [55], a dynamic inter-cell coordination scheme is studied in a simplistic scenario and assumptions, where scheme chooses a reuse pattern from four defined patterns with varying degrees of partitioning (e.g., reuse of 1 to reuse of 3). The dynamic FFR scheme, studied in [56], partitions resources dynamically into super-group and regular-group which are allocated to cells and sectors, respectively. The scheme achieves higher system throughput, however, the cell-edge performance degrades as compared to a static FFR scheme.

In [17, 18], a 2-level algorithm has been used to formulate the interference coordination problem. Each sector applies the sector-level algorithm to find a lists of resource units to be restricted in the surrounding dominant interfering sectors as the form of requests. A central optimal algorithm, that maximizes the utility for restrictions, at a central controller has been used to process all requests from all involved sectors. A distributed dynamic interference coordination scheme in the context of LTE system is studied in [21]. Here, interference has been categorized into intra- and inter-eNB interference. Different treatments have been applied to intra- and inter-eNB inter-cell interference. As the central processing is not encouraged in LTE system due to its flat network architecture, inter-cell coordination for inter-eNB interference has been performed over X2 interface (eNB to eNB) [4] through

negotiations.

A self organizing dynamic FFR scheme is studied in [57], where each sector applies *selfish optimization* to reach to the *Nash Equilibrium* point. The algorithm is tested in a simple scenario to show the proof of concept. The basic idea of the algorithm is that each sector selfishly tries to minimize its total power usage. This results in allocating good sub-bands to cell-edge users with higher power, thereby making these sub-bands poor to the neighboring sectors. The neighboring sectors, as a consequence, will avoid allocating these sub-bands to their cell-edge users; allocation of these sub-bands to their cell-centre users with possibly lower power makes these sub-bands even better for the former sector. The algorithm works iteratively and settles to an equilibrium. This algorithm minimizes sector transmit powers.

Interference coordination is studied using interference graph approach in [58] and [59]. Interference graph is created in [58] based on a predefined SINR. For each node, interfering signals are removed starting from the highest interference until the SINR is above a defined threshold. The interfering nodes that are removed in this process are said to be connected with the node of interest in the interference graph. Resources are allocated in such a way that connected nodes are given orthogonal resource units. The *Tabu Search* algorithm is used in the graph coloring approach in order to allocate resources. In the graph theoretic approach used in [59], ICIC as well as Base-Station Cooperation (BSC) have been studied. The latter is defined as a system architecture, where same data is transmitted from multiple base stations to a particular user on a same time-frequency resource unit.

A joint pattern-based inter-cell interference management and user scheduling scheme, suited for time-division multiple access (TDMA) systems, has been investigated in [60], where a pattern determines whether a particular base station should be turned off at a particular time. Interference coordination using power control has been studied in [61], where power adaptation is performed in an iterative manner by exchanging information

among neighbor base stations.

## 2.3 Multi-Cell OFDMA Resource Allocation using Optimization Framework

A large number of available literature on resource allocation in OFDMA concentrate primarily on various optimization techniques in a single cell context [62–64]. However, in designing practical networks, optimization should be performed in a multi-cell environment taking into account one of the most important performance limiting factors, *inter-cell interference*. To the authors' knowledge, resource optimization in a multi-cell environment has not yet been investigated well and only a few research works on multi-cell allocation can be found in the literature [59, 65–67].

In [65], a Linear Programming (LP) formulation is proposed, where sub-channels are partitioned and assigned fixed reuse factors such that UEs at the cell-edge can only use sub-channels with higher reuse factors. The scheme, based on non-linear integer programming, presented in [66] is interesting from an optimization point, where algorithms residing at the RNC and BSs aim to optimize the total network throughput. However, since the UEs' rate requirements are not considered in the formulation, the scheme is expected to favor UEs that are closer to the BS leading to starvation and unfairness for the cell-edge UEs most affected by interference.

An optimization study that provides optimal resource division between the cell-centre and cell-edge users as well as the optimal distance from the BS beyond which users are defined as cell-edge users has been investigated in [68]. It has been shown that the boundary on cell-centre region is 0.63 Km away from the BS for a cell radius of 1 Km. For the total of 50 resource blocks (in LTE context), the optimal division is as follows: 32 for the cell-centre and 18 for the cell-edge users.

## 2.4 Resource Scheduling Algorithms

A scheduler that is based on only UE rate, such a round-robin or a weighted fair queuing (WFQ) [34], would be able to provide a good level fairness but would result in poor system throughput. On the other hand, an opportunistic scheduler, such as a maximum SINR scheduler, would enhance the cell throughput, however, would severely penalize UEs with poor channel quality resulting a poor level of fairness. Radio resources can be utilized efficiently by using scheduler that takes into account both channel variations and users' achieved data-rate. A comprehensive overview of wireless scheduling along with comparison can be found in [69]. In this thesis, two different scheduling algorithms are used, namely, Hungarian[2] scheduler [9](also known as Kuhn-Munkres algorithm) and proportional fair scheduler [70, 71]. These channel- and fairness- aware schedulers are elaborated as follows.

### 2.4.1 Hungarian Scheduler

Hungarian scheduler is optimal for one-to-one resource allocation; it has been used in wireless communications in a number of studies [64, 72–74]. Hungarian method solves a typical assignment problem as follows:

*minimize*

$$\sum_{y}\sum_{z} c_{y,z}a_{y,z}; \tag{2.1}$$

*subject to*

$$\begin{aligned} &\sum_{y} a_{y,z} = 1, \\ &\sum_{z} a_{y,z} = 1, \\ &a_{y,z} = 0 \text{ or } 1 \end{aligned} \tag{2.2}$$

[2]H. W. Kuhn proposed the Hungarian algorithm in [9]. The work is based on two Hungarian mathematicians, D. König and E. Egerváry, and therefore, named as *Hungarian* to acknowledge their contributions.

where $[c_{y,z}]_{Y\times Z}$ is the cost matrix of the assignment of $Y$ jobs to $Z$ machines and $[a_{y,z}]_{Y\times Z}$ is the assignment matrix. Note that the above minimization formulation can be converted to a maximization problem by replacing $c_{y,z}$ with $-c_{y,z}$.

The Hungarian algorithm works for both balanced ($Y = Z$) or unbalanced ($Y \neq Z$) assignment cases. In the latter, zeros are augmented in the rows or columns, as necessary, to force the working matrix to be balanced. For OFDMA radio resource allocation, the number of resource units are much higher than the number of UE in the system; therefore, the utility matrix (negative of cost matrix) is unbalanced. Iterative Hungarian algorithm works in a repetitive manner, where in each iteration each UE is assigned one resource unit and the process repeats until all resources are exhausted.

An example of a balanced ($Y = Z = 4$) Hungarian assignment is given as follows. Let us consider a cost matrix as

$$C_{4\times 4} = \begin{pmatrix} 14 & 5 & 8 & 7 \\ 2 & 12 & 6 & 5 \\ 7 & 8 & 3 & 9 \\ 2 & 4 & 6 & 10 \end{pmatrix}.$$

The steps of the Hungarian algorithm can be described as follows.

- Step 1: Find the minimum value in each row of the cost matrix:

$$\begin{array}{ll} RW_{min} & \\ 5 & \\ 2 & \\ 3 & \\ 2 & \end{array} \begin{pmatrix} 14 & 5 & 8 & 7 \\ 2 & 12 & 6 & 5 \\ 7 & 8 & 3 & 9 \\ 2 & 4 & 6 & 10 \end{pmatrix}.$$

- Step 2: Subtract $RW_{min}$ from elements in the corresponding row:

$$\begin{pmatrix} 9 & 0 & 3 & 2 \\ 0 & 10 & 4 & 3 \\ 4 & 5 & 0 & 6 \\ 0 & 2 & 4 & 8 \end{pmatrix}.$$

- Step 3: Find the minimum value in each column of the above modified matrix:

$$\begin{matrix} CL_{min} & 0 & 0 & 0 & 2 \\ & \begin{pmatrix} 9 & 0 & 3 & 2 \\ 0 & 10 & 4 & 3 \\ 4 & 5 & 0 & 6 \\ 0 & 2 & 4 & 8 \end{pmatrix} \end{matrix}.$$

- Step 4: Subtract $CL_{min}$ from elements in the corresponding column:

$$\begin{pmatrix} 9 & 0 & 3 & 0 \\ 0 & 10 & 4 & 1 \\ 4 & 5 & 0 & 4 \\ 0 & 2 & 4 & 6 \end{pmatrix}.$$

- Step 5: Use the minimum number of lines to cover all the zeros in the matrix:

$$\begin{pmatrix} \cancel{9} & \cancel{0} & \cancel{3} & \cancel{0} \\ 0 & 10 & 4 & 1 \\ \cancel{4} & \cancel{5} & \cancel{0} & \cancel{4} \\ 0 & 2 & 4 & 6 \end{pmatrix}.$$

- Step 6: Since the number of lines is less than the number of rows[3], we find the minimum value of uncovered numbers which is 1 for this example. We subtract 1 from every uncovered number and add 1 to every number covered with two lines and the modified matrix becomes

$$\begin{pmatrix} 10 & 0 & 3 & 0 \\ 0 & 9 & 3 & 0 \\ 5 & 5 & 0 & 4 \\ 0 & 1 & 3 & 3 \end{pmatrix}.$$

- Step 7: Use the minimum number of lines to cover all the zeros in the matrix again:

$$\begin{pmatrix} \cancel{10} & \cancel{0} & \cancel{3} & \cancel{0} \\ 0 & 9 & 3 & 0 \\ \cancel{5} & \cancel{5} & \cancel{0} & \cancel{4} \\ 0 & 1 & 3 & 3 \end{pmatrix}.$$

- Step 8: In the above, the number of lines to cover all the zeros is equal to the number of rows. Therefore, the assignment can be determined by inspecting the rows as follows. An assignment can be made uniquely when there is only one zero in a row. For example, the third job to the third machine and the fourth job to the first machine. Corresponding rows and columns can be marked as follows:

$$\begin{pmatrix} 10 & 0 & 3 & 0 \\ 0 & 9 & 3 & 0 \\ \cancel{5} & \cancel{5} & \cancel{0} & \cancel{4} \\ \cancel{0} & \cancel{1} & \cancel{3} & \cancel{3} \end{pmatrix}.$$

Inspecting the unassigned rows, it is seen that the second job can be assigned to the 4th machine leaving the first job for the second machine. Therefore, the complete

[3]Go to Step 8 if the number of lines to cover all zeros is equal to the number of rows.

assignment will be $a_{1,2} = 1$, $a_{2,4} = 1$, $a_{3,3} = 1$, and $a_{4,1} = 1$, as follows:

$$\begin{pmatrix} 10 & \textcircled{0} & 3 & 0 \\ 0 & 9 & 3 & \textcircled{0} \\ 5 & 5 & \textcircled{0} & 4 \\ \textcircled{0} & 1 & 3 & 3 \end{pmatrix}.$$

### 2.4.2 Proportional Fair Scheduler

The proportional fair scheduler (PFS) was first presented in the context of code-division multiple access high data-rate (CDMA/HDR) system in [70, 71]. This time-slot based scheduling, in its original form, is not directly applicable to OFDMA system as radio resource is defined in 2-dimensional time-frequency units. If $r_{m,n}(t)$ is the instantaneous data rate for user $m$ and resource unit $n$ at time $t$, then user $m$ will be given transmission opportunity based on the following:

$$\underset{m}{\text{argmax}} = \frac{r_{m,n}(t)}{T_m(t)}, \tag{2.3}$$

where $T_m(t)$ is the filtered average throughput for user $m$ calculated over a time-window of $t_c$. This average throughput is updated after each scheduling interval as follows:

$$T_m(t+1) = \begin{cases} \left(1 - \frac{1}{t_c}\right) T_m(t) + \frac{1}{t_c} R_m(t), & \text{if user } m \text{ is assigned resources in time } t; \\ \left(1 - \frac{1}{t_c}\right) T_m(t), & \text{if user } m \text{ is not assigned resources.} \end{cases} \tag{2.4}$$

Here, $R_m(t) = \sum r_m(t)$ for all resources that are assigned to user $m$ at time $t$. Clearly, time window size $t_c$ has a prominent effect on the trade-off between system throughput and user fairness, and it is the determining factor for the time-scale of the desired fairness which is application specific.

## 2.5 Summary

It is envisaged that spectrum will have to be reused as dense as possible to deliver high data rate to UEs ubiquitously. However, appropriate interference mitigation techniques have to be used in order to realize such a dense reuse. A brief literature review on interference coordination studies, for OFDMA systems available in the literature and standardization communities, is provided in this chapter.

Most of the proposed schemes use static resource partitioning and/or power allocation to improve cell-edge UE data rates. However, these schemes cost overall sector throughput due to partitioning. A dynamic scheme can exploit channel dynamism as well as traffic diversity not only to improve cell-edge throughput, but also to enhance cell throughput. However, the benefit of such dynamic adaptation comes with the cost of overhead signaling and computational complexity. Current literature does not pay much attention to this overhead and benefit trade-off.

# Chapter 3

# A General Optimization Framework for Interference Coordination

## 3.1 Introduction

A general optimization framework for a sum-utility optimization formulation for dynamic interference coordination problem and its sub-optimal solutions are described briefly in this chapter. These sub-optimal approaches are based on different assumptions representing different system configurations, complexities, and interference avoidance gains, which emerge from the common optimization framework.

## 3.2 Common Optimization Framework

Let us consider a network layout which consists of 19 cell-sites as shown in Fig. 3.1. In this layout, each BS has 3 hexagonal sectors each of which is equipped with $120^o$ direc-

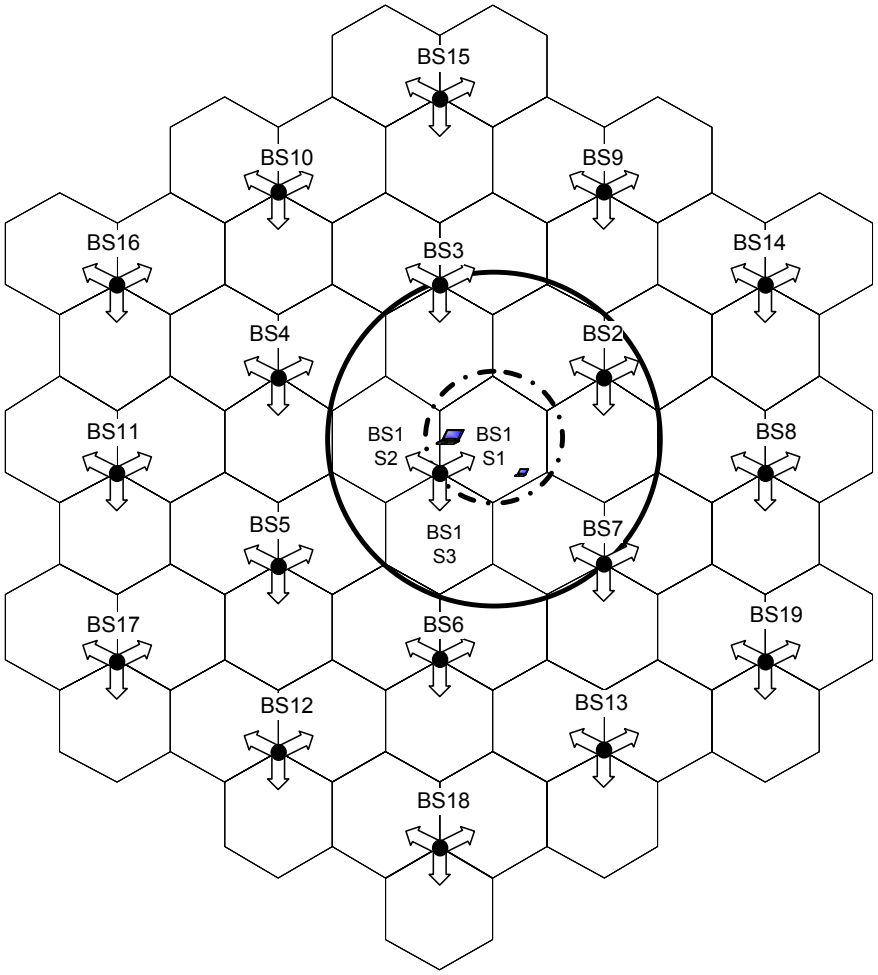


Figure 3.1: Network layout consisting of 3-sector cell sites.

tional transmit antenna. User equipments are assumed to have omni-directional receive antenna. Available frequency spectrum is reused in each sector. This layout is considered in baseline simulations for performance evaluation in the standardization activities in beyond 3G systems such as in LTE [33] and LTE-A [75] from 3GPP, and 802.16j/m [76] standards from Institute of Electrical and Electronics Engineers (IEEE), and forum activities in WINNER [77]. Only downlink interference coordination in this high interference condition, where each sector transmitter is a potential interferer to UEs in other sector, is considered. The sum-utility maximization problem, in which utility is a function of user

throughput and fairness, can be expressed as follows:

*maximize*

$$\sum_{i}\left[\sum_{m=1}^{M}\sum_{n=1}^{N}u_i^{(m,n)}\rho_i^{(m,n)}\right], \tag{3.1}$$

*subject to*

$$\rho_i^{(m,n)} \in \{0,1\}; \forall m \text{ and } \forall n, \tag{3.2}$$

where $u_i^{(m,n)}$ is the achievable utility of resource unit[1] $n$ for user $m$ in sector $i$, which only adds up in (3.1) if $\rho_i^{(m,n)} = 1$, as expressed in (3.2) implying sector $i$ assigns resource $n$ to user $m$. Parameters $M$ and $N$ denote the number of users in each sector and the number of available resource units, respectively. Constraints in (3.2) indicates that the problem is of a binary integer type.

If all available resources are potentially used in all sectors, i.e., reuse of 1 (also called *universal* reuse), high mutual interference will likely degrade the performance of cell-edge users that are not only prone to high inter-cell interference but also to high distance dependent attenuations in the desired links. If the utility depends only on user rate, i.e., $u_i^{(m,n)} = f\left(r_i^{(m,n)}\right)$, where $r_i^{(m,n)}$ is the achieved rate on resource $n$ when allocated to user $m$ in sector $i$, the optimization formulation expressed by (3.1)-(3.2) results in rate maximization problem. This rate maximization is only meaningful for elastic traffic [78]. Resource allocation schemes often have to balance between two competing objectives- system throughput and user fairness [79, 80]. However, scheduling alone may not be sufficient to boost the cell-edge performance or efficient from the system performance point of view. For example, a blunt approach could be to allocate a large number of resource units to each cell-edge user in order to enhance their throughput, which can only be possible with the cost of system throughput as the cell centre UE will be deprived from resources; thus this approach will be highly inefficient. Interference coordination, on the other hand, can

[1] a time-frequency resource unit termed as *chunk* in the WINNER and *PRB* in the LTE studies

improve the SINRs of the cell-edge UE without impacting system throughput. Therefore, interference coordination in the form of resource restriction has been adopted as one of the key features in the future generation system.

In the presented solutions in this thesis, as described in detail in the subsequent chapters, scheduling constraints have been considered; therefore, solutions do not aim to maximize network throughput. Rather, given some scheduling criteria, the proposed schemes aim to maximize sum-utility to boost cell-edge throughput with a minimum impact on the network throughput. It should be noted that all proposed schemes and their corresponding reference schemes use the same scheduling principle and constraints. Therefore, observed performance gain in the proposed schemes is only due to interference coordination.

The interference coordination problem is formulated with the following constraint to the above problem.

$$I_i^{(n)} = \sum_{m=1}^{M} \rho_i^{(m,n)} = \begin{cases} 0; & \text{resource unit } n \text{ is restricted in } i \\ 1; & \text{otherwise.} \end{cases} \tag{3.3}$$

The binary indicator $I_i^{(n)}$ in constraint (3.3) indicates whether a resource unit is restricted in sector $i$ or not; it also implies that if a resource unit is not restricted in $i$, it can only be assigned to one UE. For example, $I_i^{(n)} = 0$ expresses that resource $n$ is restricted in sector $i$, i.e., it would not be used. Note that in one proposed scheme we assume that the restricted resources are used but only with lower power; however, discussions are limited only to the former case in this chapter.

The SINR, $\gamma_i^{(m,n)}$, and the resulting achievable rate, $r_i^{(m,n)}$, depend largely on interference received from the neighboring first-tier sectors. Let us denote $\psi$ and $x$ as the indices of the first-tier dominant and other non-dominant distant inter-cell interferers, respectively, for the UEs in sector $i$. For any resource unit $n$, resource restriction in a sector affects the SINR seen by user $m$ in sector $i$ as follows:

$$\gamma_i^{(m,n)} = \frac{P_c \mathcal{H}_{i,i}^{(m,n)}}{P_c \sum\limits_{x} \mathcal{H}_{i,x}^{(m,n)} \cdot I_x^{(n)} + P_c \sum\limits_{\psi} \mathcal{H}_{i,\psi}^{(m,n)} \cdot I_\psi^{(n)} + P_{TN}}, \tag{3.4}$$

where $P_c$ is the transmit power applied to each resource unit derived from equal power distribution; that is, $P_c = P_t/N$, where $P_t$ is the total transmit power per sector and $N$ is the number of available resources. The parameter $P_{TN}$ is the thermal noise power over the resource bandwidth which includes receiver noise figure. $\mathcal{H}_{i,\psi}^{(m,n)}$ and $\mathcal{H}_{i,x}^{(m,n)}$ are the link gains to the first-tier dominant and other non-dominant interferer sectors. The parameter $\mathcal{H}$ includes large scale path-loss[2], antenna gains and fading. The indicators $I_\psi^{(n)} = \sum\limits_{m=1}^{M} \rho_\psi^{(m,n)}$ and $I_x^{(n)} = \sum\limits_{m=1}^{M} \rho_x^{(m,n)}$ take the value of 0 or 1 depending on whether or not the $n^{th}$ resource unit is restricted in the dominant sector $\psi$ and non-dominant sector $x$, respectively.

Equations (3.1) to (3.4) describe a combinatorial optimization problem which is computationally prohibitive. To illustrate the problem size, let us consider the WINNER system, where there are 144 available resource units. Now, if we consider Fig. 3.1 (i.e., 57 sectors) where each sector has 12 users, the number of 3-dimensional allocation variable, denoted by $\rho$, will be close to 100,000. An integer optimization problem of this size is difficult to solve in reasonable time. However, the second summation in the denominator of (3.4) has the dominant effect on the quality of a resource, i.e., most interference avoidance gain can be achieved by imposing restrictions on these interferers. The focus is to apply interference coordination among a small number of mutually interfering sectors (i.e., $\psi$) with different approaches as described briefly below and in later chapters in details. In other words, $\gamma_i^{(m,n)}$ will not be very sensitive to non-dominant distant interferers and therefore, $I_x^{(n)}$ can

[2]Distance dependent attenuation and shadowing.

be assumed 1; hence (3.4) becomes

$$\gamma_i^{(m,n)} = \frac{P_c \mathcal{H}_{i,i}^{(m,n)}}{P_c \sum\limits_{x} \mathcal{H}_{i,x}^{(m,n)} + P_c \sum\limits_{\psi} \mathcal{H}_{i,\psi}^{(m,n)} \cdot I_{\psi}^{(n)} + P_{TN}}, \tag{3.5}$$

As the number of transmitters in the dominant interferer set is not large, it is possible to calculate a finite set of SINRs given different resource restriction possibilities in the interfering sectors. This facilitates the use of ILP approach to solve the coordination problem.

The utility in (3.1) is defined as a function of rate and user demand, i.e., $u_i^{(m,n)} = f\left(r_i^{(m,n)}, d_i^{(m)}\right)$, where $d_i^{(m)}$ is the demand factor that indicates achieved throughput status of a UE $m$. We define $d_i^{(m)}$ as follows: $d_i^{(m)} = \bar{R}_i/(R_i^{(m)} + \delta)$, where $R_i^{(m)}$ is the average throughput of UE $m$ over a certain time-window, and $\bar{R}_i$ is the average throughput across all UEs and is given by $\bar{R}_i = \left(\sum\limits_{m=1}^{M} R_i^{(m)}\right)/M$. A rate deprived UE, such as one near the cell-edge, will have a higher demand factor. Therefore, the utility will provide advantages to rate deprived UEs to boost their performance. The parameter $\delta$ has a small value that prevents $d_i^{(m)}$ from being $\infty$.

## 3.3 Overview of the Sub-optimal Solutions

Solving the optimization problem defined through (3.1) to (3.4) globally offers a number of challenges- 1) a centralized approach is necessary 2) complete system knowledge at the central controller is required, 3) The resulting combinatorial integer linear problem is similar to a 3-dimensional assignment problem which is NP-complete [81] for a fairly sized problem. In this thesis, different sub-optimal solutions are explored in order to mitigate above difficulties.

The fact which is used in the proposed solutions is that only the dominant interfer-

ers affect the signal quality. As a result, optimization can be applied within a group of neighboring transmitters forming a cluster and this reduces the size of the combinatorial problem significantly. However, in a real network, the relation of interference and its inter-dependency propagates throughout the whole network. To illustrate with an example, let us consider four sectors $A$, $B$, $C$, and $D$; here, let us assume that the transmit antennas belonging to sectors $C$ and $D$ are dominant interferers to UEs in sector $A$, and antennas in sectors $A$ and $C$ are dominant to those in sector $B$. If two clusters are formed as $\{A,C,D\}$ and $\{A,B,C\}$, it would be observed that sectors $A$ and $C$ are common in both clusters. Hence, optimizing each cluster independently may reduce the overall problem size (compared to optimizing $\{A,B,C,D\}$ in a single shot) but it may provide misleading results unless inter-relation among the clusters are captured in the optimization problem. In the solutions, the concept of *interferer group* [14, 16, 82] to form a cluster is used. Algorithm aims to maximize sum-utility within a cluster honoring the inter-cluster dependencies. In particular, three different approaches have been investigated as follows.

### 3.3.1 A Two-Level Algorithm with Partial Central Processing

The functionalities of this algorithm reside at two different levels- sector and central. In essence, the 3-dimensional (3-D) assignment problem defined in Section 3.2 is decomposed to 2 dimensions.

Each sector forms a cluster taking all first-tier sectors as potential dominant interferers. The sector-level algorithm finds a set of resource units for each of its first-tier sectors that are to be restricted from its perspective that heuristically maximizes its the sum-utility in a 2-dimensional sense. However, these clusters are very dependent on each other as a particular sector is a member of different clusters. Therefore, the results from cluster-wise heuristic optimization should be processed in a centralized manner. However, the heuristic optimization (somewhat in a selfish manner) reduces the problem size significantly as it

uses 2-dimensional assignment problem at the sector-level algorithm.

The Hungarian (also known as Khun-Munkres) algorithm [9] is used at the sector-level in an iterative manner. The Hungarian algorithm is a one-to-one optimal solution for an assignment problem, which is polynomial time solvable. However, as this algorithm is used in an iterative manner, the overall assignment becomes rather a good sub-optimal solution. The sector-level algorithm prepares resource restrictions as a form of requests from its perspective. To that end, a central controller is used to process these restriction requests in an optimal manner (the $3^{rd}$ dimension is handled here) and produces a final set of resource restrictions for all sectors. Note that the problem size at the central controller is very tractable as it only works on restriction requests rather than looking into a large combinatorial optimization space. The details of this approach along with performance results are provided in Chapter 4.

### 3.3.2 A Distributed Algorithm with Neighboring Cell Coordination

This is a distributed algorithm where each sector finds a set of restrictions for each of its neighboring dominant sectors as in the previous approach. However, these resource restrictions are negotiated by inter-BS communications. This scheme was developed to study interference coordination problem in LTE [21], where central processing of RRM functionalities is not encouraged due to flat network architecture. In LTE, neighboring BSs (eNBs) communicate with each other using X2 interface [83]. Furthermore, inter-cell interference as intra-eNB and inter-eNB interference are treated differently, as eNB-eNB communication is not required for intra-eNB interference. The Hungarian algorithm is used for intra- and inter-eNB interference avoidance. The scheme is presented elaborately in Chapter 5.

### 3.3.3 A Centralized Approach with Clusters

Compared to the above two, this approach involves more centralized processing. In this scheme, each user in every sector finds two most dominant interferers from the neighboring first-tier sectors with which it forms an *interferer group* (i.e., clusters). The ILP formulation takes dependencies among clusters into consideration by appropriate linear constraints. The problem size is further reduced by assigning a subset of resource units at a time. In summary, a 3-dimensional assignment problem is solved in this scheme, however, with reduced size. A fast commercial solver is used to evaluate the performance of this approach. The scheme along with performance results is provided in Chapter 6. A similar approach in lighter frequency reuse (reuse 3) scenario for a TDMA-based relay network [14] and OFDMA-based conventional network [16] is studied in the early phase of this thesis.

## 3.4 Summary

In this chapter, a general optimization framework for interference coordination problem as formulated in this thesis has been described. The overview of the sub-optimal approaches to the solutions is given briefly. These approaches along with performance results are provided in the subsequent chapters.

# Chapter 4

# A Two-Level Algorithm with Partial Central Processing

## 4.1 Introduction

In this chapter, a novel dynamic interference avoidance scheme is presented which makes use of inter-cell coordination in order to prevent excessive inter-cell interference, especially for cell or sector edge users that are most affected by inter-cell interference, with minimal or no impact on the network throughput. The proposed scheme is comprised of a two-level algorithm - one at the base station level and the other at a central controller to which a group of neighboring base stations are connected. Simulation results show that the proposed scheme outperforms the reference schemes, in which either coordination is not employed (reuse of 1) or employed in a static manner (reuse of 3 and fractional frequency reuse), in terms of cell edge throughput with a minimal impact on the network throughput and with some increase in complexity.

By using inter-cell coordination, the proposed scheme thrives to enhance throughput on allocated resource units considering the throughput status of the cell edge User Terminal

(UT)s[1]. The performance of the proposed schemes is compared to that of some reference schemes, for example, reuse of 1, reuse of 3, and the PFR schemes as described in Chapter 2 and shown in Fig. 2.1. Reuse 1 scheme represents *no coordination* case, and the other two represent static coordination cases.

The work presented in this chapter is an extended version of author's previous work coauthored and presented in [17]. Realistic heuristic methods are used to prepare utility matrix, where two different threshold functions are introduced to provide different degrees of trade-off between throughput and cell-edge performance. An additional scenario in which restricted resource units can also be used with lower transmit power is considered. In addition to the full-buffer traffic assumption, the algorithm is also tested with a traffic model according to Poisson arrival. A number of reference schemes such as Reuse 1, Reuse 3, and PFR are included to which the performance of the proposed schemes is compared. Finally, a Proportional Fair (PF) scheduler [71] along with an iterative Hungarian (IH) scheduler is used.

The remainder of this chapter is organized as follows. The system model is described in Section 4.2. Details of the proposed scheme are presented in Sections 4.3–4.5. Section 4.6 describes system and simulation parameters. Numerical results, obtained through extensive simulations, are discussed in Section 4.7. A hot-spot scenario, where sectors have non-uniform traffic, is presented in Section 4.8. Section 4.9 addresses the implementation complexity issues of the proposed schemes followed by a summary in Section 4.10.

## 4.2 System Model

Let us consider a network layout with 19 BS sites each with 3 hexagonal sectors as shown in Fig. 3.1. Sectors are equipped with $120^o$ directional transmit antennas, while UTs' receive

[1]The terminology to express user equipment is UT in the WINNER project from which the system parameters are taken for this chapter.

antennas are considered to be omni-directional. The antenna gain pattern for the transmit antenna is provided in the following section. As mentioned earlier, this layout represents the baseline simulation test scenario in most studies relating to LTE, WiMAX, and WINNER.

It is assumed that the system uses cell-specific orthogonal reference signals [4]; UTs know the reference signals of neighboring first-tier sectors and are able to determine interference separately. It is evident that for a downlink transmission to a UT in any sector, one of its first-tier sectors is likely to be the most dominant interferer. Let us consider Fig. 3.1 as an example; due to the relative locations and antenna directivity, a cell-edge UT in sector 1 of BS1 may receive the most dominant interference from sector 2 or 3 of BS1 (depending on the UT location), or from sector 2 or 3 of BS2, or from sector 3 of BS3, or from sector 2 of BS7.

## 4.3 Description of the Proposed Scheme

Let us revisit (3.1)-(3.5) and denote $\gamma_{i|\Psi}^{(m,n)}$ as the SINR on resource unit $n$ at UT $m$ given a set of sorted dominant interferers, $\Psi$, are not allowed to use resource unit $n$ (for convenience, the symbols used in this section and onward are listed in Table 4.1). The vector $\Psi$ is sorted by the descending order of interference powers which varies from $\Psi = \{\}$ to $\Psi = \{\psi_1, \psi_2, \cdots, \psi_K\}$, representing no interferer restriction to all first-tier interferer restriction. Therefore, it is evident that $\gamma_{i|\Psi=\{\}}^{(m,n)} < \gamma_{i|\Psi=\{\psi_1\}}^{(m,n)} < \cdots < \gamma_{i|\Psi=\{\psi_1,\psi_2,\cdots,\psi_K\}}^{(m,n)}$ representing the SINR when none, one, two, and so on dominant interferers are restricted to use resource unit $n$ in their sector(s). The restriction can be either in the form that restricted resource units are not used at all (as in (3.1)–(3.5)) or used only with reduced transmit power.

For a target BER, modulation and coding scheme, the above SINRs can be mapped to achievable rates as $r_{i|\Psi=\{\}}^{(m,n)} < r_{i|\Psi=\{\psi_1\}}^{(m,n)} < \cdots < r_{i|\Psi=\{\psi_1,\psi_2,\cdots,\psi_K\}}^{(m,n)}$. Clearly, the minimum and maximum rates can be achieved as $r_{i|\Psi=\{\}}^{(m,n)}$ and $r_{i|\Psi=\{\psi_1,\psi_2,\cdots,\psi_K\}}^{(m,n)}$, respectively; however, the incremental gain from interferer restrictions diminishes as more and more interferers are

Table 4.1: List of Symbols Used

| | |
|---|---|
| $\psi_1$ | the first-tier dominant interfering sectors |
| $\psi_2$ | second first-tier dominant interfering sectors |
| $m$ | UT index |
| $n$ | resource unit index |
| $M$ | number of UTs per sector |
| $N$ | number of available resource units per sector |
| $P_t$ | total power per sector |
| $P_c$ | power per resource unit |
| $P_{TN}$ | average thermal noise power |
| $\mathcal{H}^{(m,n)}$ | channel gain seen by user $m$ on resource unit $n$ |
| $\gamma^{(m,n)}$ | SINR experienced by user $m$ on resource unit $n$ |
| $r^{(m,n)}$ | achievable rate on resource unit $n$ for user $m$ |
| $\Psi$ | set of sorted dominant interferers in descending order that are restricted |
| $d^{(m)}$ | UT demand factor |
| $I^{(n)}$ | indicator to show whether resource unit $n$ is restricted or not |
| $R^{(m)}$ | time average throughput achieved by UT $m$ |
| $\bar{R}$ | average throughput across all UTs |
| $r_{TH}^{(m)}$ | $m^{th}$ UT's rate threshold |

restricted, because $\Psi$ is arranged according to the descending order of interference powers.

As stated in Chapter 3, solving the interference coordination problem network-wide by (3.1)–(3.4) is computationally prohibitive. Therefore, a heuristic approach is resorted to, where each sector locally finds a set of resource units to be restricted, in the form of wish-list, in each surrounding first-tier dominant interferer sector. In other words, each sector selfishly finds resource units for which it prefers $I_{\psi}^{(n)} = 0$ for all $\psi$ (as in (3.3)). This list is prepared based on the inter-cell interference and UTs' demand factors. A utility matrix, $U_{M\times N} = \left[u^{(m,n)}\right]$, is prepared using heuristics based on $I_{\psi}^{(n)}$ values. Then, the Hungarian algorithm (also known as Kuhn-Munkres algorithm) [9] is applied to $U_{M\times N}$ in order to find tentative resource unit-to-UT preferences and resulting restriction wish-list. However, as every sector is a dominant interferer to UTs in some other sectors, it is likely that there will be conflicts in restriction requests. Therefore, a physical or a logical central entity is required to resolve the conflicting requests optimally. This central (or localized central) controller can be a node functionally similar to a RNC in 3G systems or a Mobility

Management Entity (MME) in LTE, or any logical entity residing within a physical node such as an eNB with required connectivity and processing capability. The eNBs having central processing capability can be strategically and sparsely placed in the coverage area. These eNBs can communicate with other regular eNBs using X2 interface.

The proposed inter-cell interference coordination scheme is comprised of two separate algorithms; one is located at the BS level that prepares the resource unit restriction requests and the other resides at the central controller that resolves restriction request conflicts. The working principle of the scheme can be summarized as below:

- UTs send Channel State Information (CSI) including information on two most dominant interference received from their first-tier sectors, to the serving sector.
- Each sector prepares a utility matrix based on the channel states and UTs' demand factors.
- Each sector iteratively applies Hungarian algorithm to the utility matrix to find resource unit restriction requests for each of its dominant interferer neighbors.
- Each sector forwards restriction request list to the central entity.
- The central entity processes requests from all involved sectors and resolve conflicting requests based on the utility values in an optimal manner.
- The central entity then forwards each sector a decided set of resource units that are to be restricted by its scheduler.

The list of restricted resource units remains valid over a long enough time-period but shorter than the channel coherence time. In the following section, the effects of scheduling and dominant interference on throughput and fairness are first discussed. Then investigated algorithms are presented elaborately in the subsequent section.

## 4.4 Effects of Scheduling and Dominant Interference on Throughput and Fairness

Scheduling has a profound effect on the throughput and fairness that can be achieved with a given amount of resources. To show the effect of scheduling on UT throughput, Fig. 4.1 is provided, where different schedulers such as maximum SINR, round-robin, iterative Hungarian, and proportional fair are used. The figure shows instantaneous throughput achieved at each scheduling instant (not averaged over time duration). For the sake of organization, the details of the simulation parameters are deferred until Section 4.6. While maximum SINR scheduling can achieve the highest sector throughput, it severely punishes the cell-edge UTs (lower tail of the CDF). Round-robin scheduler can provide better service to edge UTs, however, it may result in poor sector throughput. The iterative Hungarian and proportional fair schedulers can be seen as schemes that exhibit good compromise between cell-edge and sector throughput. Hungarian algorithm is an efficient, channel aware, and low complexity solution to integer linear programming for one-to-one assignment problem. However, if a UT needs multiple resource units in order for it to achieve the required rate, the iterative Hungarian method rather becomes a good sub-optimal solution. The proportional fair is also a channel aware scheduler, where scheduling priorities are determined by the filtered average UT throughput updated over a certain time window.

In order to have a glimpse of the effect of dominant interference, simulations are used to observe the UT throughput in a sector with different number of interferers restricted. Fig. 4.2 shows the CDF of UT throughput when none, one, two, and three dominant interferers are restricted. Here, full-buffer traffic model and iterative Hungarian scheduler have been considered. It is seen from the figure that most avoidance gain can be achieved by restricting the most dominant interferer and the gain is insignificant beyond $\Psi = \{\psi_1, \psi_2\}$ ($\Psi = \{\psi_1, \psi_2, \psi_3\}$ and onward are not shown in the figure). The inset of Fig. 4.2 shows the

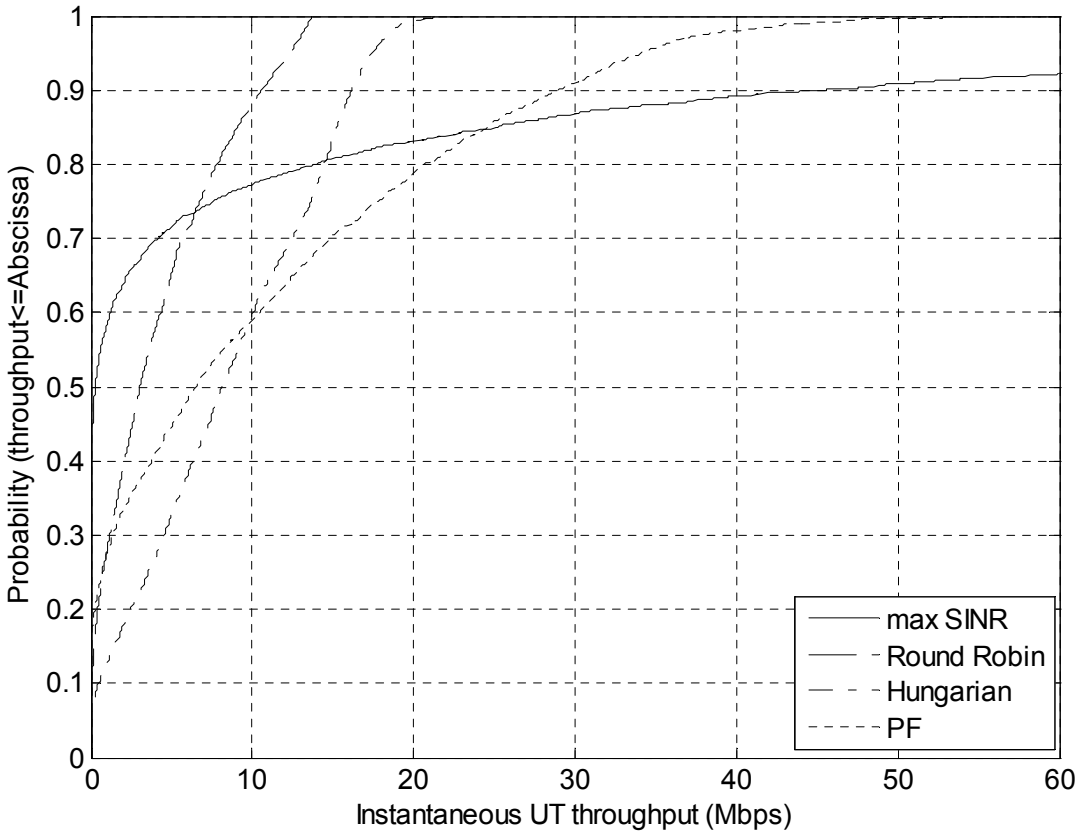


Figure 4.1: Effect of schedulers.

percentage of resource units restricted for $\Psi = \{\psi_1\}$ and $\Psi = \{\psi_1, \psi_2\}$. Note that for each resource unit, interferers are restricted only when there is a rate gain from restriction. For example, if $r^{(m,n)}_{i|\Psi=\{\psi_1\}} < r^{(m,n)}_{i|\Psi=\{\psi_1,\psi_2\}}$, then $\Psi = \{\psi_1, \psi_2\}$, else $\Psi = \{\psi_1\}$ is used. It can also be observed from the figure that on average around 12.5% and 20% of resource units are to be restricted in each surrounding sector in order to obtain the throughput gain observed in the figure. If a sector restricts these many resource units in its surrounding sector, it will also receive similar resource unit restrictions on average from each of its neighbors causing a large number of resource unit restrictions in each sector and resource loss as a consequence. For simplicity, Fig. 4.2 does not consider the resource loss due to restrictions. Detailed results considering resource loss are presented in Section 4.7. It is evident that in order to

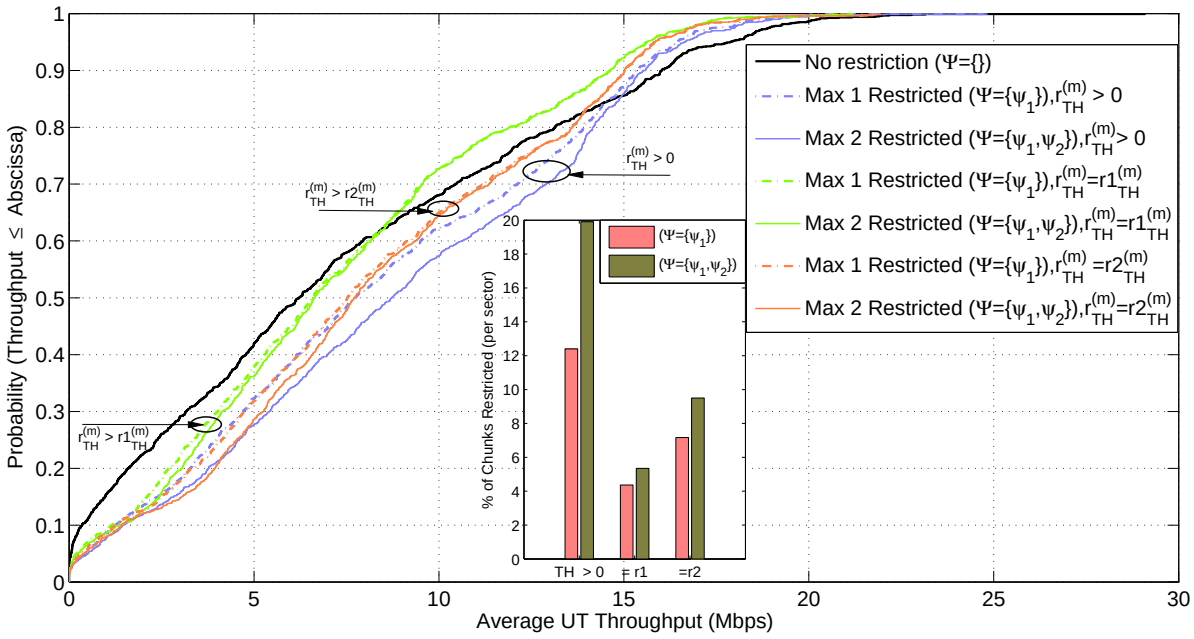


Figure 4.2: Effect of interferer restrictions.

limit the number of restrictions and hence resource loss, only justifiable restrictions should be made. To that end, two cases are presented when resource unit restrictions are made only when significant gains can be obtained considering the service of the UTs. A sector decides on restrictions based on a threshold value $r_{TH}^{(m)}$ given as follows:

$$r1_{TH}^{(m)} = \begin{cases} e^{\left(1-d^{(m)}\right)}; & d^{(m)} \geq 1, \\ \infty; & d^{(m)} < 1, \end{cases} \tag{4.1}$$

and

$$r2_{TH}^{(m)} = \quad e^{\left(1-d^{(m)2}\right)}. \tag{4.2}$$

In (4.1) and (4.2), restrictions are made considering the UTs' current throughput status. In the former, restrictions are made only in favor of those that have received less than

the average service in the sector, while restrictions are made also for the UTs with good throughput status in the latter, given only when a considerable gain can be achieved. That is, if $r_i^{(m,n)}{}_{|\Psi=\{\psi_1\}} \geq r_{i|\Psi=\{\}}^{(m,n)} + r_{TH}^{(m)}$, then the most dominant interferer will be restricted to favor UT $m$ and if $r_{i|\Psi=\{\psi_1,\psi_2\}}^{(m,n)} \geq r_{i|\Psi=\{\psi_1\}}^{(m,n)} + r_{TH}^{(m)}$, then the two most dominant interferers can be restricted. In (4.2), the threshold function is considered steeper in order to impose the fact that restrictions are made in favor of UTs with good service rate only when significant gains are foreseen. The throughput plots for the threshold criteria in (4.1) and (4.2) are shown in Fig. 4.2. The following important observations can be drawn by analyzing Fig. 4.2:

- Higher throughput can be achieved by restricting more and more resource units which implies more penalties to neighboring sectors.
- Substantial gain can be achieved by restricting only the most dominant interferer. Attempts should be made to restrict only this interferer, with the exception for severely rate deprived UTs for which the two most dominant interferers can be restricted.
- The number of restricted resource units and performance can be tuned by choosing an appropriate gain threshold value.
- The performance using the threshold function given by (4.2) is superior compared to that in (4.1) with slight increase in the number of restricted resource units. Both threshold functions are used to derive detailed performance results as presented in Section 4.7.

## 4.5 Interference Avoidance Algorithms

In this section, the sector-level and the central algorithms are described as follows. Sector-level algorithm prepares utility matrix and prepares resource unit restriction requests for each of its first-tier interferers. The central algorithm resolves any conflicting restriction

requests and prepare final restriction list for each sector.

### 4.5.1 Sector-Level Algorithm

Two major functions are associated with the sector-level algorithm– namely, 1) preparation of a utility matrix using the threshold-based restrictions derived from the channel conditions and UT demands, and 2) Preparation of restriction requests from the tentative resource unit-to-UT allocation by using iterative Hungarian algorithm. The pseudo-codes for the sector level algorithm are presented in Table 4.2.

#### Preparation of the Utility Matrix

In order to construct the utility matrix in sector $i$, the following steps are repeated for each UT $m$ and each resource unit $n$.

- Dominant interferers are sorted in descending order of interference powers into a dominant interferer set.
- The SINRs $\gamma_{i|\Psi=\{\}}^{(m,n)}$, $\gamma_{i|\Psi=\{\psi_1\}}^{(m,n)}$, and $\gamma_{i|\Psi=\{\psi_1,\psi_2\}}^{(m,n)}$, which correspond to restricting none, one, and two most dominant interferers, are calculated from the SINR expression in (3.5).
- The achievable rates for the above SINRs, respectively, $r_{i|\Psi=\{\}}^{(m,n)}$, $r_{i|\Psi=\{\psi_1\}}^{(m,n)}$, and $r_{i|\Psi=\{\psi_1,\psi_2\}}^{(m,n)}$ are determined.
  - If $r_{i|\Psi=\{\psi_1\}}^{(m,n)} \geq r_{i|\Psi=\{\}}^{(m,n)} + r_{TH}^{(m)}$ , sector $\psi_1$ is marked to be restricted if resource unit $n$ is to be assigned to UT $m$.
  - If $r_{i|\Psi=\{\psi_1,\psi_2\}}^{(m,n)} \geq r_{i|\Psi=\{\psi_1\}}^{(m,n)} + r_{TH}^{(m)}$ , sector $\psi_2$ is also marked to be restricted for resource unit $n$.

After finding the inter-cell dominant interferer(s) to be restricted on each resource unit and each UT, achievable rates $r_i^{(m,n)}$ are calculated. Now, the utility of resource unit $n$ for UT

Table 4.2: Sector-Level Algorithm

**%Preparation of the utility matrix**
**for** $m = 1$ to $M$ **do**
  **for** $n = 1$ to $N$ **do**
    $\Psi \leftarrow \{\}$;
    Calculate $\gamma^{(m,n)}_{|\Psi=\{\}}$ and $r^{(m,n)}_{|\Psi=\{\}}$ with $I^{(n)}_{\psi} = 1$; $\forall\psi$;
    $\Psi \leftarrow \{\psi_1\}$;
    Calculate $\gamma^{(m,n)}_{|\Psi=\{\psi_1\}}$ and $r^{(m,n)}_{|\Psi=\{\psi_1\}}$ with $I^{(n)}_{\psi} = 0$ for $\psi \in \Psi$; $I^{(n)}_{\psi} = 1$, otherwise;
    $\Psi \leftarrow \{\psi_1, \psi_2\}$;
    Calculate $\gamma^{(m,n)}_{|\Psi=\{\psi_1,\psi_2\}}$ and $r^{(m,n)}_{|\Psi=\{\psi_1,\psi_2\}}$ with $I^{(n)}_{\psi} = 0$ for $\psi \in \Psi$; $I^{(n)}_{\psi} = 1$, otherwise;
    **if** $r^{(m,n)}_{|\Psi=\{\psi_1\}} \geq r^{(m,n)}_{|\Psi=\{\}} + r^{(m)}_{TH}$ **then**
      resource unit $n$ is marked to be restricted in $\psi_1$
    **end if**
    **if** $r^{(m,n)}_{|\Psi=\{\psi_1,\psi_2\}} \geq r^{(m,n)}_{|\Psi=\{\psi_1\}} + r^{(m)}_{TH}$ **then**
      resource unit $n$ is marked to be restricted in $\psi_2$
    **end if**
  **end for**
**end for**
Fill in corresponding entry of utility matrix $U_{M\times N}$ with $u^{(m,n)} = r^{(m,n)} \cdot d^{(m)}$, considering above restrictions

**%Preparation of resource unit restriction requests**
Initialize $\mathcal{R}_{\psi} = \{\}$; $\forall\psi$;
Initialize $\mathcal{U} = 1 \cdots N$
**while** $\mathcal{U} \neq \{\}$ **do**
  Apply Hungarian algorithm to $U$
  **if** Allocated $n^{th}$ resource unit has a mark for $\psi^{th}$ sector interferer restriction **then**
    Update corresponding entry of restriction request $\mathcal{R}_{\psi}$
  **end if**
  Remove columns of $U$ corresponding to allocated resource units
**end while**

$m$ can be expressed as:

$$u_i^{(m,n)} = r_i^{(m,n)} d_i^{(m)}. \tag{4.3}$$

Each entry of $[U_i]_{M\times N} = [u_i^{(m,n)}]$ is associated with the corresponding interferer(s) to be restricted along with the achieved utility when the resource unit is used by the respective UT.

**Applying Hungarian Algorithm and Finding Restriction Requests**

Hungarian algorithm is iteratively applied to $U_i$ in order to prepare resource unit restriction requests. Resource units are tentatively allocated (as the central controller might override the restriction requests) in order to reserve resource units for each UT with the following steps.

1. Apply Hungarian algorithm to $U_i$. As $M << N$, a maximum of $M$ resource units that yield the maximum sum utility will be allocated to the corresponding $M$ UTs.

2. If any of the above $M$ chosen entries has restriction marked, the corresponding resource unit will be placed in the restriction list for the corresponding interferer.

3. The columns belonging to the chosen entries are deleted from $U_i$. The Hungarian algorithm is applied to the updated $U_i$.

4. Steps 2 and 3 are repeated until all resource units are tentatively allocated to UTs.

Now, each sector has a wish-list of resource units to be restricted for each of its neighboring sectors. These lists are forwarded to the central controller.

### 4.5.2 Central-Level Algorithm

The central controller receives requests from a cluster of BSs and resolves conflicting requests in an optimal manner. For a particular resource unit, Fig. 4.3 shows an example problem to be solved at the central controller using its algorithm. In this figure, arrows with the solid and dashed lines indicate that interference received at the arrow-originating-sector from the arrowhead-sector is acceptable and unacceptable (requested to be restricted), respectively. For example, for a resource unit of interest, sector $B$ can tolerate interference from sector $A$, but the opposite is not true as there is a red (dashed) arrow from sector $A$ toward sector $B$. In this case, either sector $A$ or $B$ has to be restricted for this resource unit. For any

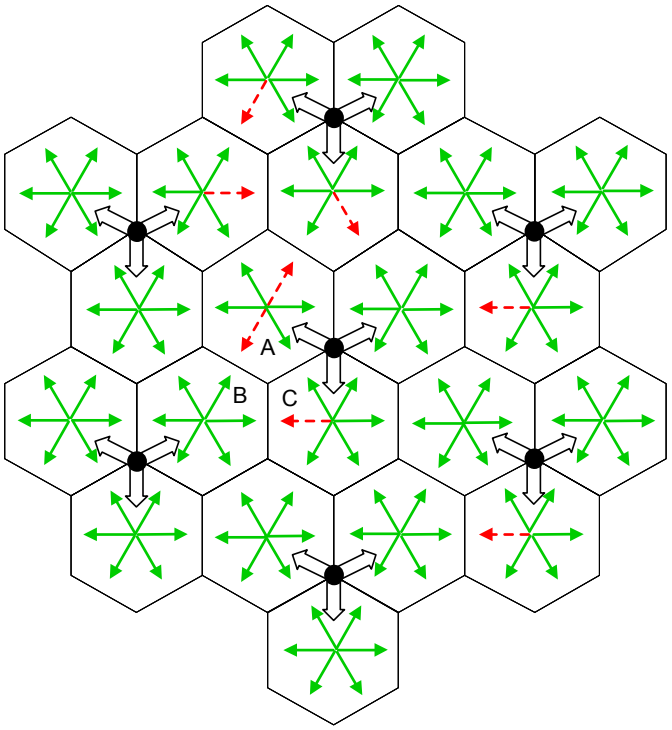


Figure 4.3: Resource unit restriction request for a particular resource unit.

resource unit $n$, the problem at the central controller can be formulated formally as follows:

*maximize*

$$Z = \sum_{i,j \in \Phi} u_i^{(m_i,n)}(1 - x_i^{(n)}) + u_j^{(m_j,n)}(1 - x_j^{(n)}); \tag{4.4}$$

*subject to*

$$x_i^{(n)} + x_j^{(n)} \leq 1; \tag{4.5}$$

where $\Phi$ is the set of sectors in which each sector either requests or is requested for restriction to use resource unit $n$; i.e., $i$ has restriction request to sector $j$ or vice versa or both have restriction requests to each other. $m_i$ and $m_j$ are the candidate UTs for resource unit $n$ in sector $i$ and $j$, respectively. The variables $x_i^{(n)}$ and $x_j^{(n)}$ are binary which represent resource unit restrictions. $x_i^{(n)}$ (or $x_j^{(n)}$) takes the value of 1 if the resource unit is restricted in sector

$i$ (or $j$), otherwise, it is zero. A simple example with reference to Fig. 4.3 (considering only sectors $A$, $B$, and $C$) can be given as follows. Let us assume that for resource unit $n$, sectors $A$, $B$, and $C$ attain utility of 4, 6, and 3, respectively. In this case, the objective function is $Z = 4(1-x_A^{(n)})+6(1-x_B^{(n)})+3(1-x_C^{(n)})$, and the constraints are $x_A^{(n)}+x_B^{(n)} \leq 1$ and $x_B^{(n)} + x_C^{(n)} \leq 1$. Clearly, $x_A^{(n)} = 0$, $x_B^{(n)} = 1$, and $x_C^{(n)} = 0$ provide maximized $Z$, and therefore, sector $B$ has to be restricted for resource unit $n$.

The central controller resolves request conflicts and sends refined restriction lists to all involved BSs.

The proposed restriction processing can be done from time to time as long as the channel coherence time permits. This period is usually much longer than the scheduling interval and shorter than the channel coherence time. Once the resource unit restriction list is available to a sector, the scheduler can perform resource unit scheduling based on its own criteria. In that sense, the above resource unit restriction technique can be considered as independent of scheduling. In this study, the iterative Hungarian and proportional fair scheduling principles are used in both the proposed and the reference schemes. Resource unit restriction processing is performed on 6-resource unit time-interval (i.e., $\sim$2 ms which is much lower than the channel coherence time of $\sim$6 ms considering 20 km/hr user speed and 3.95 GHz frequency band) and scheduling is done at every resource unit time duration. Note that the overhead complexity is proportional to the frequency of the resource restriction cycles. For higher mobility, channel coherence time will be shorter which will require faster restriction updates incurring higher signaling overhead.

It should be mentioned that the proposed scheme also works without the need for a central controller [21], however, with possible degradation in performance as conflict resolution is expected to be suboptimal. In such case, the scheme can take advantage of the inter-BS communications, for instance, using the X2 interface as defined in 3GPP LTE [83]. If two sectors wish to restrict a resource unit to each other, the decision should result in favor of

the sector that foresees higher utilization on that resource unit. The pairwise comparison of utilization results in sub-optimal solution.

Currently, X2 interface supports information exchange between BSs (called evolved NodeB in LTE terminology) primarily for mobility management, load management, and interference coordination, which is controlled by X2AP protocol [84]. With necessary modifications in the protocol message, a BS can pass not only the indices of the resource units to be restricted but also the utilization seen on those resource units.

## 4.6 Simulation Models and Parameters

A total of 19 cell sites (i.e., 57 hexagonal sectors) are considered in the simulations, as shown in Fig. 3.1. The inter-site distance is 1 km. UTs are randomly distributed [85] in the centre 21 shaded sectors within a minimum and maximum radius in each sector. While the sector algorithm is executed in these 21 sectors, other sectors remain as interference contributors only. Performance statistics are collected from the 3 central sectors (i.e. BS1 as marked by the circle in Fig. 3.1).

The available spectrum of 45 MHz in the 3.95 GHz frequency band is available to each sector giving a total of 1152 sub-carriers each of which has a bandwidth of 39.0625 kHz. A resource unit (sub-channel) consists of 8 consecutive sub-carriers. It is a time-frequency resource unit occupying 0.3456 ms and 312.5 KHz, which translates into $8 \times 12$ OFDM symbols [77].

All UTs are assumed to fall in the same service class. Both full-buffer and Poisson traffic models have been considered in this investigation. For the simplicity of simulations, a simple queuing model with Poisson arrival has been assumed for the downlink traffic. The arrival data rate and packet size are considered to be 5 Mbps and 96 bytes, respectively.

Time-frequency-correlated Rayleigh channel samples are generated from the power delay profile for WINNER wide area scenario [85]. The user mobility is assumed to be 20 km/hr.

The following exponential path-loss ($L_D$) model has been used [85],

$$L_D = (44.9 - 6.55\log_{10}(h))\log_{10}(D) + 34.46 + 5.83\log_{10}(h) + 23\log_{10}(f_c/5.0)[\text{dB}], \quad (4.6)$$

where $h$ and $D$ are the BS height and transmitter-receiver separation in meters, respectively, and $f_c$ is the carrier frequency in GHz.

The UT receive antennas are assumed to be omni-directional, while the gain pattern for $120^o$ directional sector transmit antennas is considered to be as follows [77]:

$$A(\theta) = \text{-min}\left[12\left(\frac{\theta}{\theta_{3\text{dB}}}\right)^2, 20\right], \quad (4.7)$$

where the value of $\theta_{3\text{dB}}$ is $70^o$ and $\theta$ varies from $-180^o$ to $180^o$. A Single-In Single-Out (SISO) antenna configuration has been used.

The average thermal noise power is calculated with a noise figure of 7 dB. Independent lognormal random variables with a standard deviation of 8 dB are considered for shadowing. Sector transmit power is assumed to be 39.81 Watts and resource units are assigned powers so that the total used power is constant in all schemes. Retransmission for erroneous data is considered only in simulations with traffic model.

Adaptive modulation with a Block Low-Density Parity-Check (B-LDPC) code is used. The thresholds for Adaptive Modulation and Coding (AMC) modes are determined from a set of water-fall curves produced by the link level simulations [77] and considering 10% Block-Error Rate (BLER). From Binary Phase Shift Keying (BPSK) to 64- Quadrature Amplitude Modulation (QAM) modulation have been used with varying code rates. Eight OFDM symbols (out of 96) distributed within each resource unit are considered to be occupied by the reference signals and control signaling. Therefore, a resource unit using Quadrature Phase Shift Keying (QPSK) with a coding rate of 1/2 can carry 88 information bits.

Note that for the full-buffer case, all available resource units are used in all sectors. Therefore, there is no interference uncertainty due to the unused residual resources. However, in the simulations with traffic model, it is possible that some resources may not be used in some sectors due to empty queues and/or poor channels which may result interference fluctuations; i.e., discrepancies between predicted and actual interference. An approach has been taken in order to minimize the effect of such fluctuations. Interference is estimated based on a probabilistic model. If a resource unit is used at least once in the previous three scheduling instances in an interfering sector, then it is assumed that this particular interfering sector will use that particular resource unit in the upcoming instant. This approach captures the dynamics of a multi-cell simulation more accurately than assuming a fixed allocation in the interfering cells. The statistics are collected based on actual SINR on the scheduled resource units. In this case, if the actual received SINR is less than the predicted one which is used at the transmitter to determine the AMC mode, then the packet is considered to be corrupted. Such retransmissions are scheduled in the next opportunity and given higher priority compared to the new packets.

BS-UT delay performance is observed in the cases with traffic model. This delay is defined as the time difference of the packet arrival at the transmitter queue of the BS and the successful reception of the last byte of the packet at the UT.

In order to solve the binary integer optimization problem at the central controller, YALMIP [86] and LPSOLVE (an ILP solver) [87] have been used along with MATLAB.

## 4.7 Simulation Results

Performance results have been observed for a user density of 12 UTs per sector. Performance of the proposed scheme is compared with that of a number of reference schemes such as reuse 1, reuse 3, and PFR schemes, where the reuse 1 represents a scheme with no coordination and the latter two are the examples of static interference coordination schemes. The reuse 1

scheme copes with the inter-cell interference and maximizes the utility in the presence of the worst-case interference. The reuse 3 and PFR schemes show benefits of static coordination over reuse 1 scheme. While all schemes achieve multiuser diversity, the gain in the proposed scheme is solely due to dynamic interference coordination.

The CDF of the average UT throughput is observed and compared with the $5^{th}$ percentile throughput as a measure of the cell-edge UT performance. The CDF of BS-UT delay for the cases with traffic model is also evaluated. Two different scheduling techniques, such as the iterative Hungarian and proportional fair scheduling principles, are used. Statistics are collected in the central 3 sectors and from 150 simulation drops, where each drop is simulated over a time duration of 100 resource units. In each drop, the throughput of the UT is averaged over this time duration.

The CDFs of UT throughput for the full-buffer case are shown in Fig. 4.4 and Fig. 4.5 when iterative Hungarian and proportional fair schedulers are used, respectively. The lower tail of the CDF is zoomed for the clarity to show the $5^{th}$-percentile points. As expected, reuse 1 scheme performs very poorly with regard to the cell-edge throughput as there is no interference coordination. On the other hand, being a static interference coordination scheme, reuse 3 scheme provides enhanced cell-edge throughput, however, with a significant loss in sector throughput (i.e., around 54%). The PFR scheme attains around 12 times gain in cell-edge throughput compared to the reuse 1 scheme, but with around 30% loss in sector throughput. The proposed dynamic interference coordination scheme attains the most gain in cell-edge performance when the restricted resource units are not used at all. It is also observed that threshold criteria expressed in (4.2) provides a cell-edge throughput equivalent to that of the reuse 3 scheme while keeping sector throughput greater than that in PFR. Also, when restricted resource units are used with 10 dB lower power and the threshold is set to $r2^{TH}$, proposed scheme achieves significantly higher cell-edge throughput without any impact on the sector throughput compared to the PFR scheme. Table 4.3

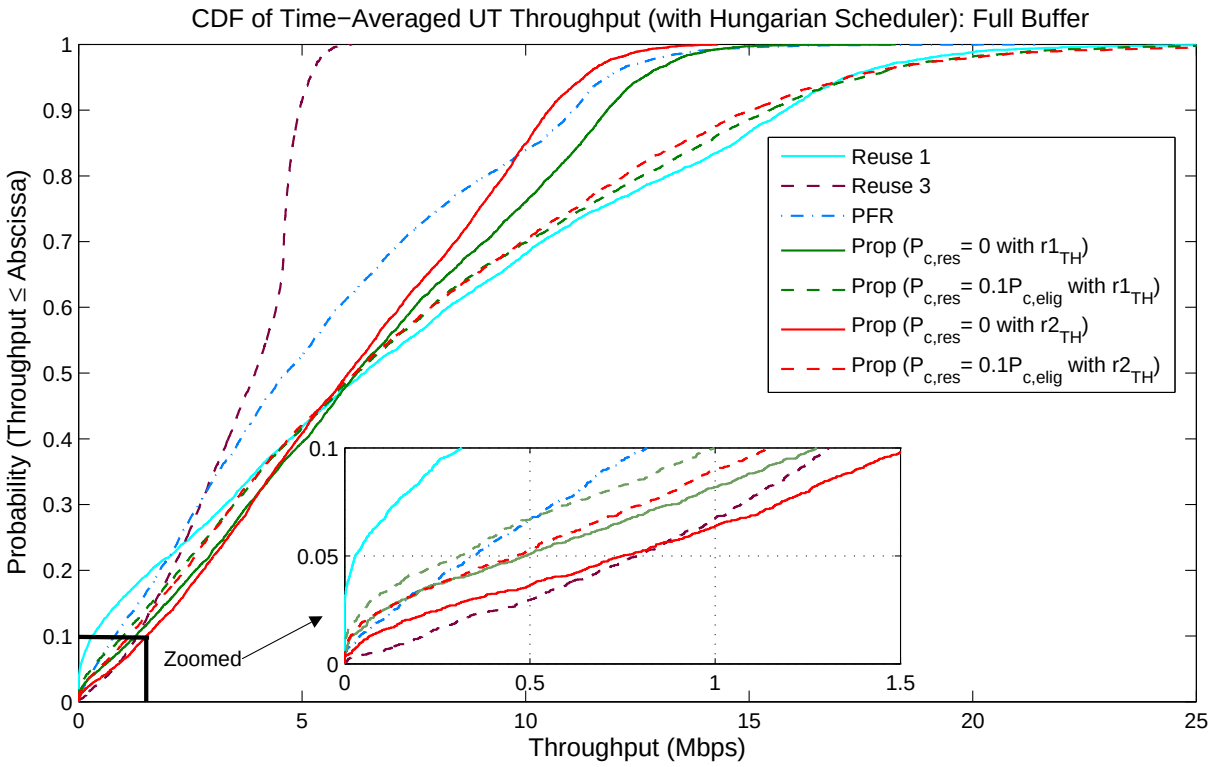


Figure 4.4: CDF of UT throughput (Hungarian scheduler): full-buffer.

summarizes results for the full-buffer and with traffic model (in parenthesis), and compares cell-edge and sector throughputs for the reference and proposed schemes. Prop. 1 and Prop. 2 in the table refer to the scenarios when restricted resource units are not used and used with 10 dB lower power, respectively.

For simulations considering traffic model with Poisson arrival, the CDFs of average UT throughput for the iterative Hungarian and proportional fair schedulers have been illustrated in Fig. 4.6 and Fig. 4.7, respectively. Corresponding BS-UT delay performances are presented in Fig. 4.8 and Fig. 4.9, respectively. Similar to the full-buffer scenario, it is seen that reuse 3 scheme achieves significant gain in cell-edge throughput, but with loss in sector throughput and degraded delay performance compared to the reuse 1 scheme.

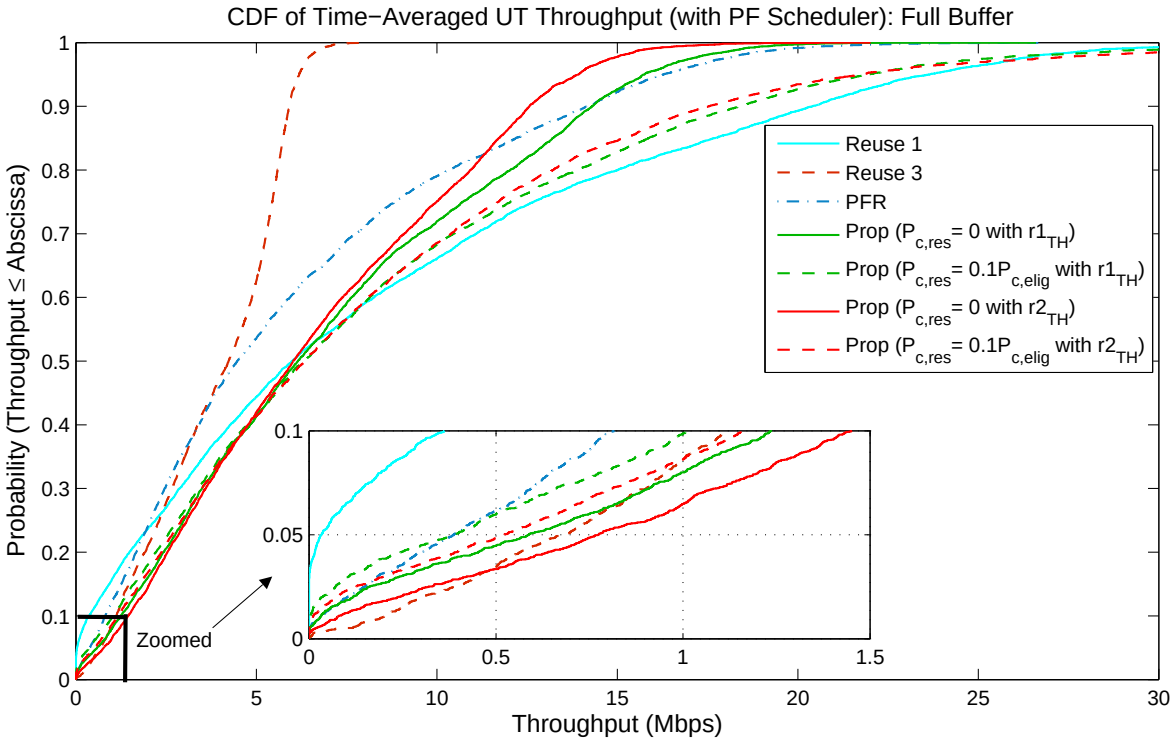


Figure 4.5: CDF of UT throughput (PF scheduler): full-buffer.

The performance of PFR falls between reuse 1 and reuse 3 schemes in terms of cell-edge and sector throughputs, and packet delay. Proposed scheme with $r2^{TH}$ that does not use restricted resource units achieves cell-edge performance comparable to reuse 3 scheme while maintaining the sector throughput and delay performance comparable to reuse 1 scheme. It should be noted that the proposed schemes which use restricted resource units with 10 dB lower power do not bring any additional benefit in the cases with a traffic model as the packet arrival is limited. The numbers in the parenthesis of Table 4.3 compares cell-edge and sector throughputs for all simulated schemes when a traffic model is used.

Table 4.3: Cell-Edge vs Sector Throughput: Full-Buffer and Traffic Model (in parenthesis)

| | Iterative Hungarian | | | Proportional Fair | | |
|---|---|---|---|---|---|---|
| Scheme | $5^{th}$-Perc. (kbps) | $95^{th}$-Perc. (Mbps) | Sector TP (Mbps) | $5^{th}$-Perc. (kbps) | $95^{th}$-Perc. (Mbps) | Sector TP (Mbps) |
| reuse 1 | 29.3 (72.4) | 17.2 (5.42) | 88.6 (46.9) | 33.1 (95.3) | 23.7 (5.40) | 100.2 (46.6) |
| reuse 3 | 795.1 (805.5) | 5.2 (4.89) | 42.0 (41.3) | 674.3 (661.0) | 6.2 (5.27) | 46.0 (42.5) |
| PFR | 347.4 (392.8) | 11.8 (5.35) | 64.3 (45.6) | 386.4 (461.3) | 16.3 (5.40) | 72.5 (46.6) |
| Prop. 1 with $r1^{TH}$ | 486.8 (405.5) | 12.6 (5.40) | 77.8 (48.1) | 586.9 (424.8) | 15.8 (5.40) | 84.7 (47.4) |
| Prop. 2 with $r1^{TH}$ | 310.9 (317.7) | 17.5 (5.41) | 88.6 (47.8) | 391.5 (357.1) | 21.9 (5.40) | 99.0 (47.1) |
| Prop. 1 with $r2^{TH}$ | 750.3 (711.9) | 11.3 (5.35) | 73.1 (47.2) | 773.4 (605.4) | 13.9 (5.37) | 79.5 (46.3) |
| Prop. 2 with $r2^{TH}$ | 464.7 (449.6) | 17.2 (5.39) | 88.0 (47.4) | 520.1 (472.3) | 21.8 (5.39) | 98.4 (46.3) |

## 4.8 Results for Scenario with Sectors Having Non-uniform Traffic

In this section, the results of 2-level algorithm are presented when there are non-uniform traffic in different sectors; this resembles today's real-world real-time traffic, where some sectors may appear to be in the hot-spot areas. The Poisson arrival process is still used, however, with higher generation rates (1.5 times) in these hot-spot sectors.

A layout similar to Fig. 3.1 is considered but identifying the hot-spot sectors (shaded) as shown in Fig. 4.10. It is assumed that the packet size is 96 bytes and average data generation rates for users in the hot-spot sectors are 7.5 Mbps, while the rates for users in the regular sectors are 5 Mbps as before. All other simulation parameters remain unchanged.

The CDF of average user throughput with iterative Hungarian and proportional fair schedulers have been shown in Fig. 4.11 and Fig. 4.12, respectively. The irregularities in the CDF plots arise from the fact that 1/3 of users are having 1.5 times generation rates. In Table 4.4, the cell-edge and sector throughputs for simulations with hot-spot sectors are compared. It is observed that the cell-edge performance for all reference schemes degrade due to the inclusion of hot-spot sectors, while in proposed schemes with threshold function in (4.1), the cell-edge performance is enhanced. However, in proposed schemes with threshold function (4.2), the cell-edge performance slightly degrades. BS-UT delay performance is

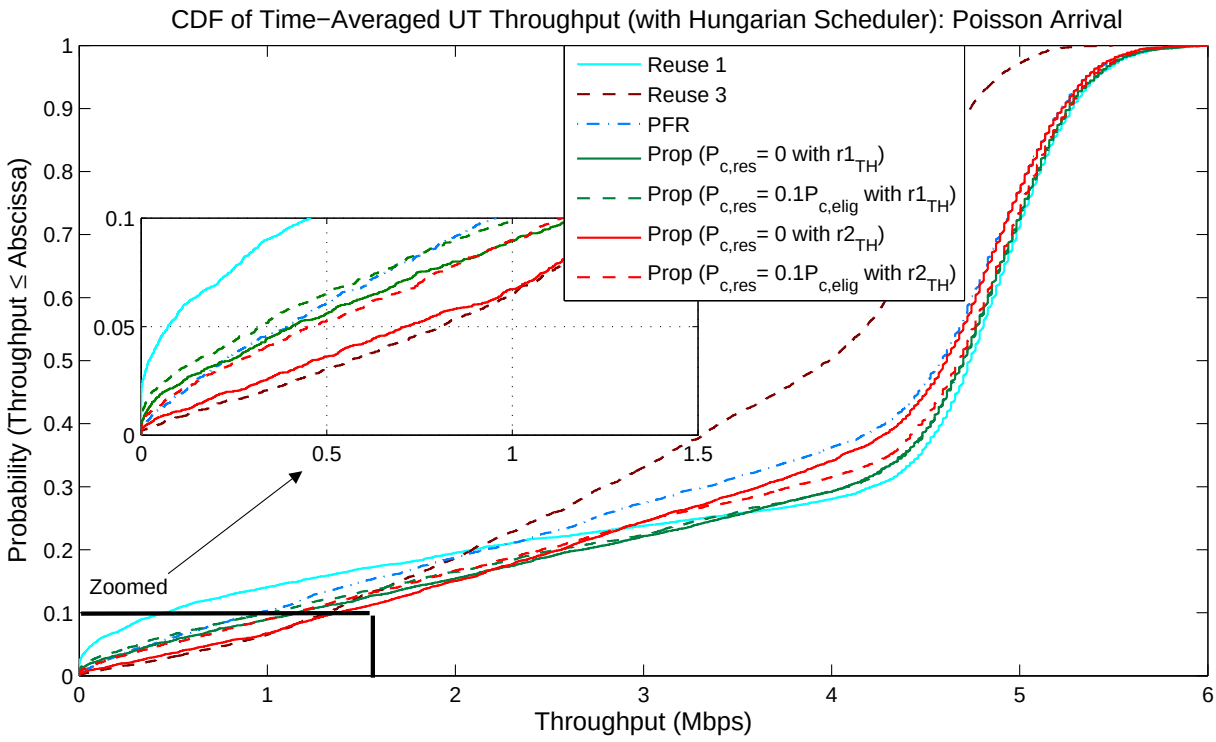


Figure 4.6: CDF of UT throughput (Hungarian scheduler): Poisson arrival.

shown in Fig. 4.13 and Fig. 4.14 for the iterative Hungarian and PF schedulers, respectively. As expected, delay increases for all schemes, however, the relative delay performance remains unchanged.

## 4.9 Implementation Complexity Issues

Two different kinds of complexities are associated with the proposed schemes; the computational complexities of the algorithms and the signaling overhead.

The overall complexity of the sector-level algorithm is dominated by the complexity of the Hungarian algorithm which is upper-bounded by $O(\min^2(M,N)\cdot\max(M,N))$ [88], where $M$ and $N$ are the number of UTs and resource units, respectively. The complexity of

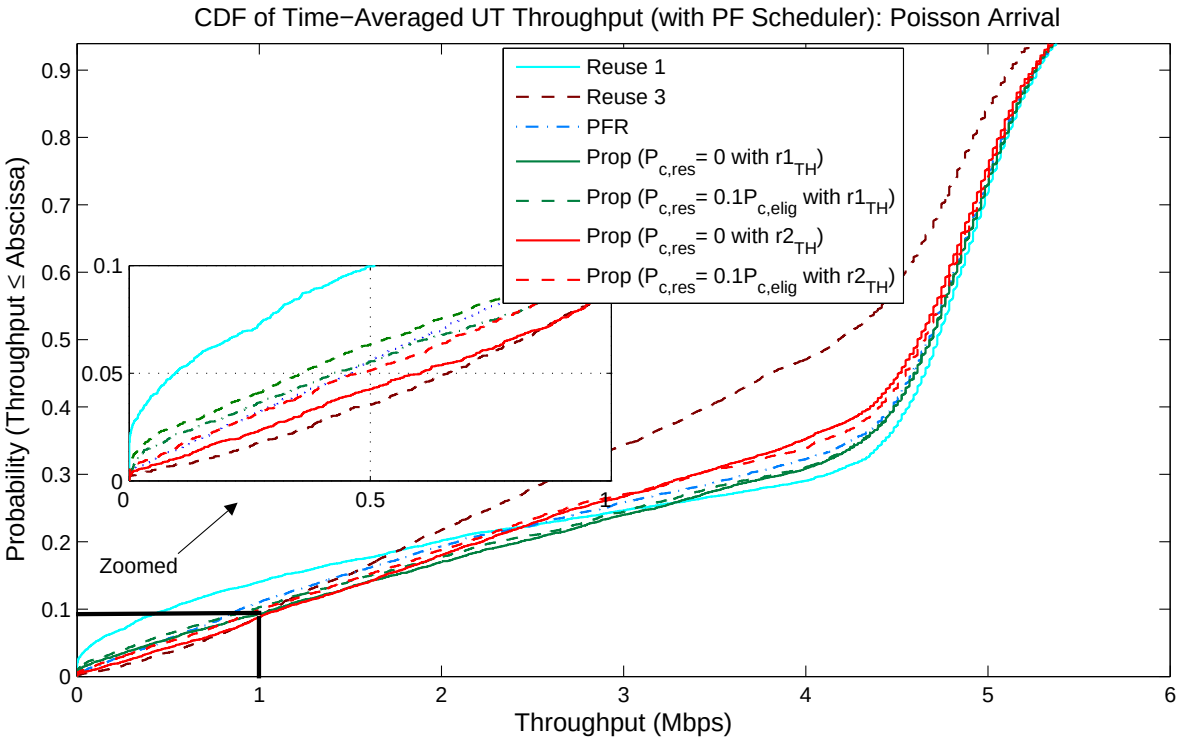


Figure 4.7: CDF of UT throughput (PF scheduler): Poisson arrival.

the algorithm at the central controller depends on the number of sectors that have conflicting restriction requests. This determines the number of variables and constraints in the binary integer problem. For example, if there are 3 pair-wise conflicting requests for a particular resource unit, then the number of binary variables to solve is 6 and the number of constrains is 9.

Systems employing AMC are required to facilitate CSI feedback and are subjected to associated signaling overhead. In the proposed schemes that use threshold function (4.1), only rate deprived UTs are required to send information of two most dominant interference to the serving BS causing additional signaling overhead. All UTs in the proposed schemes with threshold function (4.2) are required to forward such information. Threshold functions

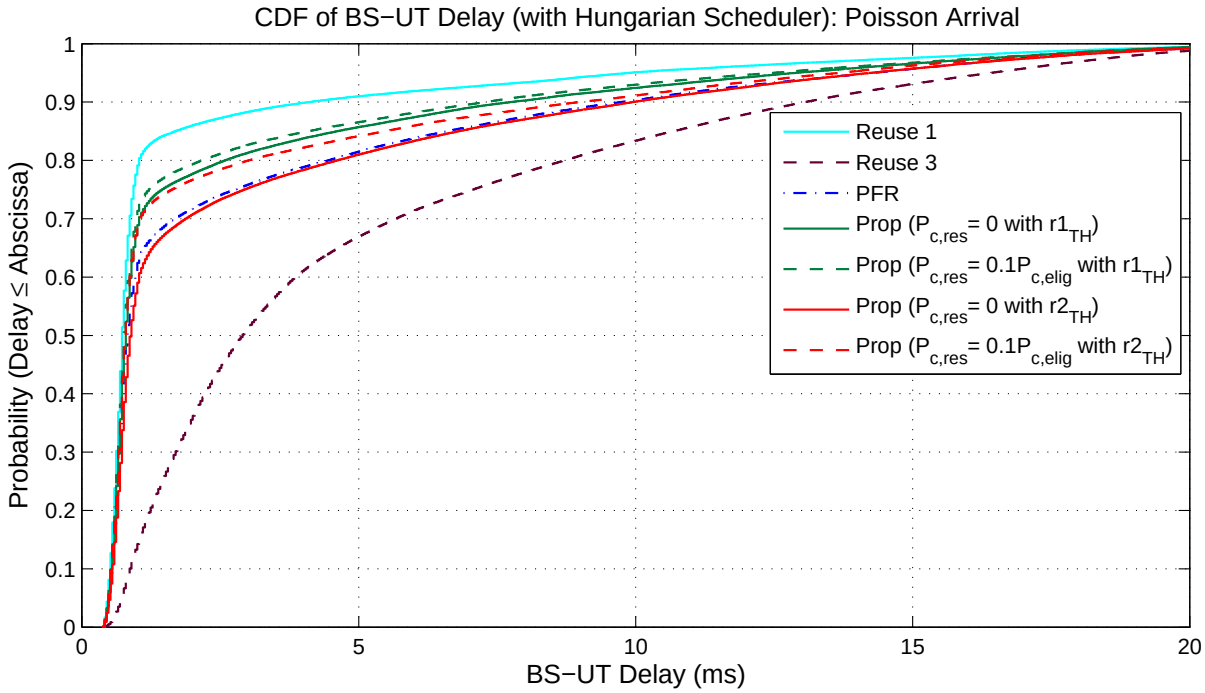


Figure 4.8: CDF of BS-UT delay (Hungarian scheduler): Poisson arrival.

Table 4.4: Cell-Edge vs Sector Throughput: Traffic Model (includes hot-spot sectors)

| Scheme | Iterative Hungarian | | | Proportional Fair | | |
|---|---|---|---|---|---|---|
| | $5^{th}$-Perc. (kbps) | $95^{th}$-Perc. (Mbps) | Sector TP (Mbps) | $5^{th}$-Perc. (kbps) | $95^{th}$-Perc. (Mbps) | Sector TP (Mbps) |
| Reuse-1 | 55.8 | 7.59 | 51.9 | 73.0 | 7.59 | 51.8 |
| Reuse-3 | 802.1 | 4.99 | 41.1 | 648.5 | 5.73 | 43.3 |
| PFR | 389.8 | 7.37 | 48.5 | 454.9 | 7.53 | 50.8 |
| Prop. 1 with $r1^{TH}$ | 536.6 | 7.53 | 52.9 | 541.9 | 7.55 | 52.1 |
| Prop. 2 with $r1^{TH}$ | 395.7 | 7.57 | 52.9 | 438.0 | 7.57 | 52.0 |
| Prop. 1 with $r2^{TH}$ | 697.0 | 7.39 | 50.9 | 578.9 | 7.51 | 50.4 |
| Prop. 2 with $r2^{TH}$ | 433.1 | 7.57 | 52.2 | 458.5 | 7.55 | 50.9 |

in (4.1) and (4.2) can be considered as the trade-off between performance and overhead complexity. However, the rate of required overhead is related to the frequency of the channel reporting and resource allocation operations, which essentially depends on the mobility of the UTs and hence on the resulting channel coherence time. Therefore, a higher signaling overhead would have to be supported for higher mobility UTs. UTs in the reference static

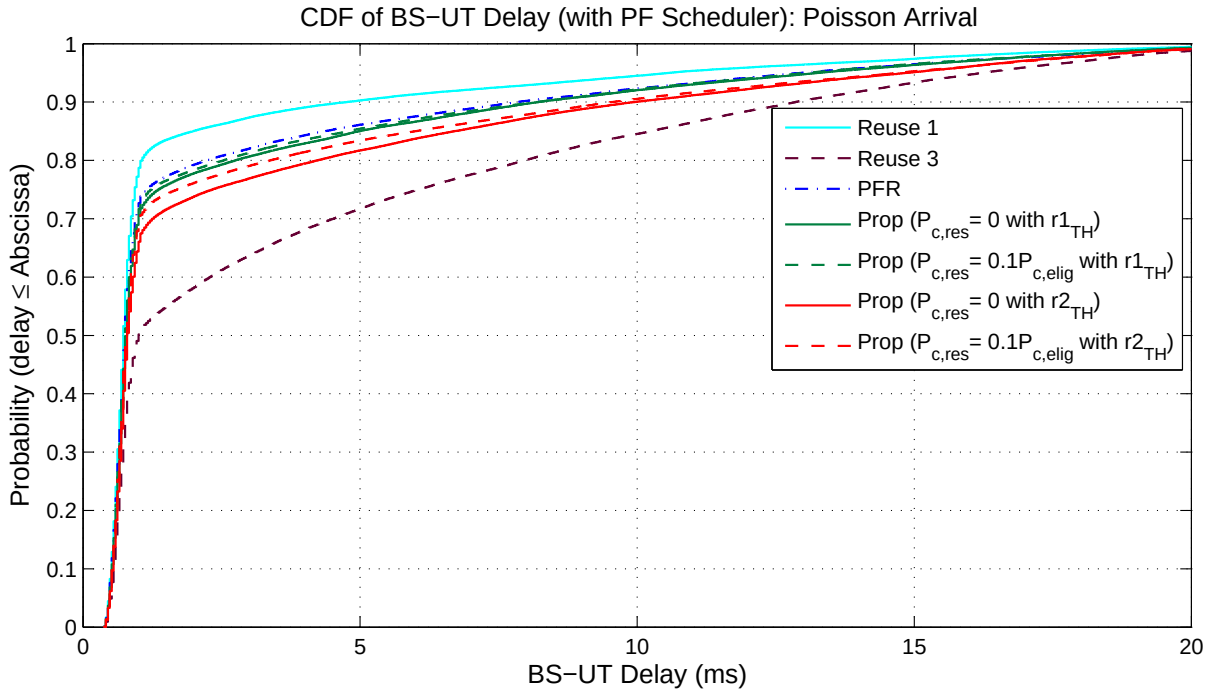


Figure 4.9: CDF of BS-UT delay (PF scheduler): Poisson arrival.

interference coordination schemes do not require to send any additional signaling other than the CSI.

In the proposed schemes, signaling between BS and the central entity is also required which can be performed using high data rate backbone connections such as fiber links and thus it is less of an issue.

## 4.10 Summary

A novel viable interference coordination scheme using downlink multi-cell resource unit allocation with dynamic inter-cell coordination is presented in this chapter. The performance of the proposed schemes is compared with that of a number of static coordination-based reference schemes available in the literature. It is observed from the simulation results that the static coordination schemes achieve enhanced cell-edge throughput only with a significant

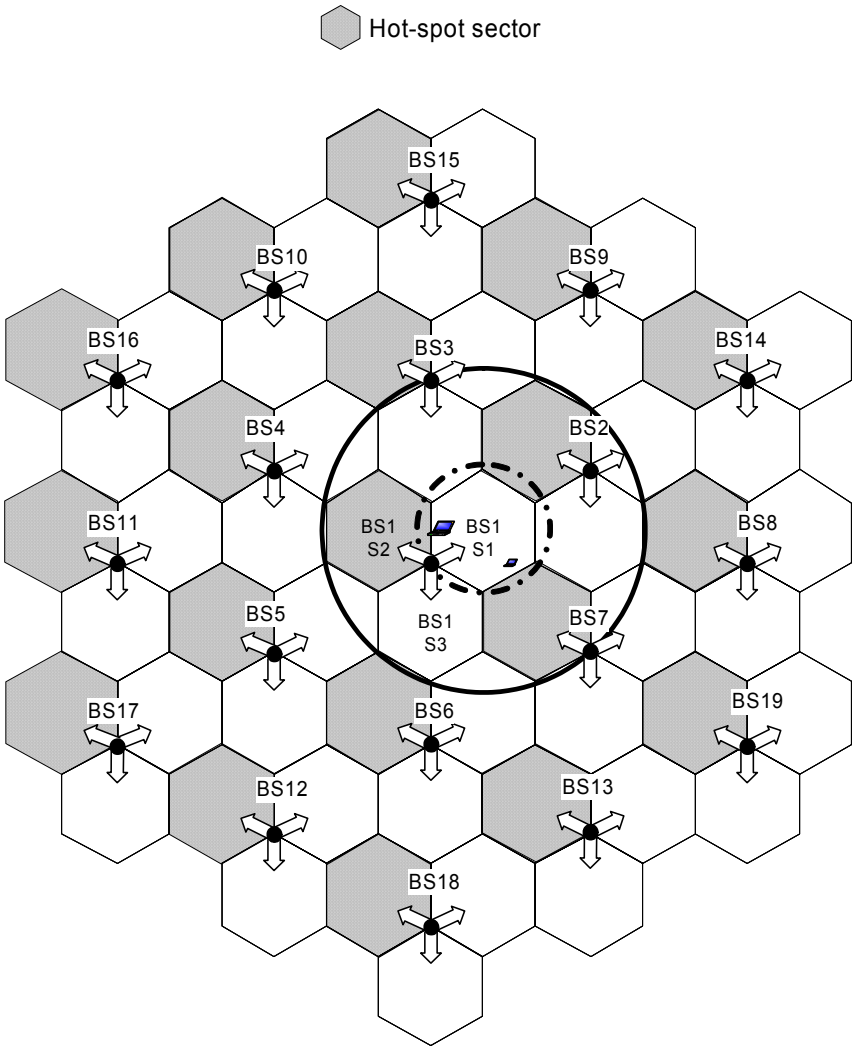


Figure 4.10: Simulation layout with hot-spot sectors

loss in sector throughput. On the other hand, the proposed schemes achieve equivalent or better cell-edge throughput without impacting the sector throughput. All simulated schemes achieve multi-user diversity through the schedulers. Therefore, the observed performance gain in the proposed scheme is solely due to dynamic interference coordination. Enhanced cell edge throughput in the proposed scheme can potentially allow a smaller num-

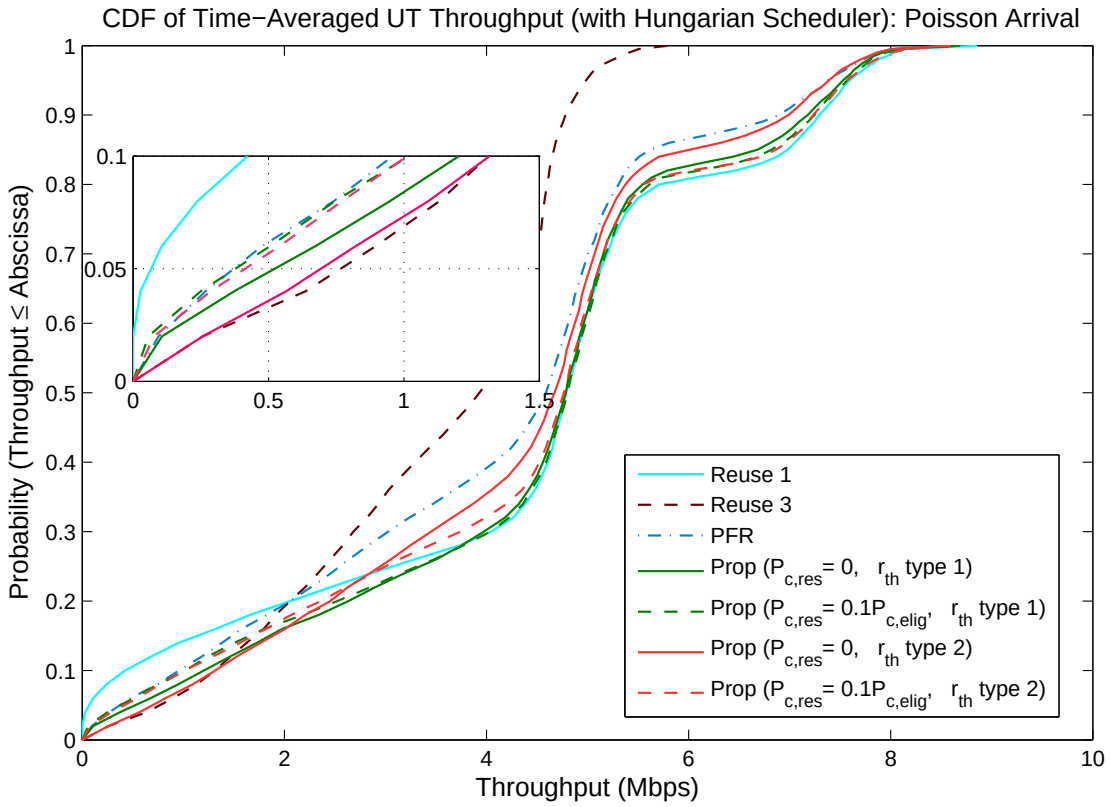


Figure 4.11: CDF of user throughput: iterative Hungarian scheduler (includes hot-spot sectors)

ber of BSs to cover a region yielding substantial savings in the deployment cost. As it does not require any frequency planning, the proposed scheme is not only effective for macrocell environment, it can be applied to future femtocell BSs where user terminals are expected to experience severe interference from neighboring macrocell BSs.

Although a central entity for the resolution of the conflicting requests is used, the algorithm can be applied to radio access networks (RANs) without a central controller, for example, 3GPP LTE and LTE-A networks. In this case, resolutions can be performed among neighboring sectors through negotiations using X2 interface that inter-connects BSs.

In the sector algorithm, a simple utility function has been used, where the considered

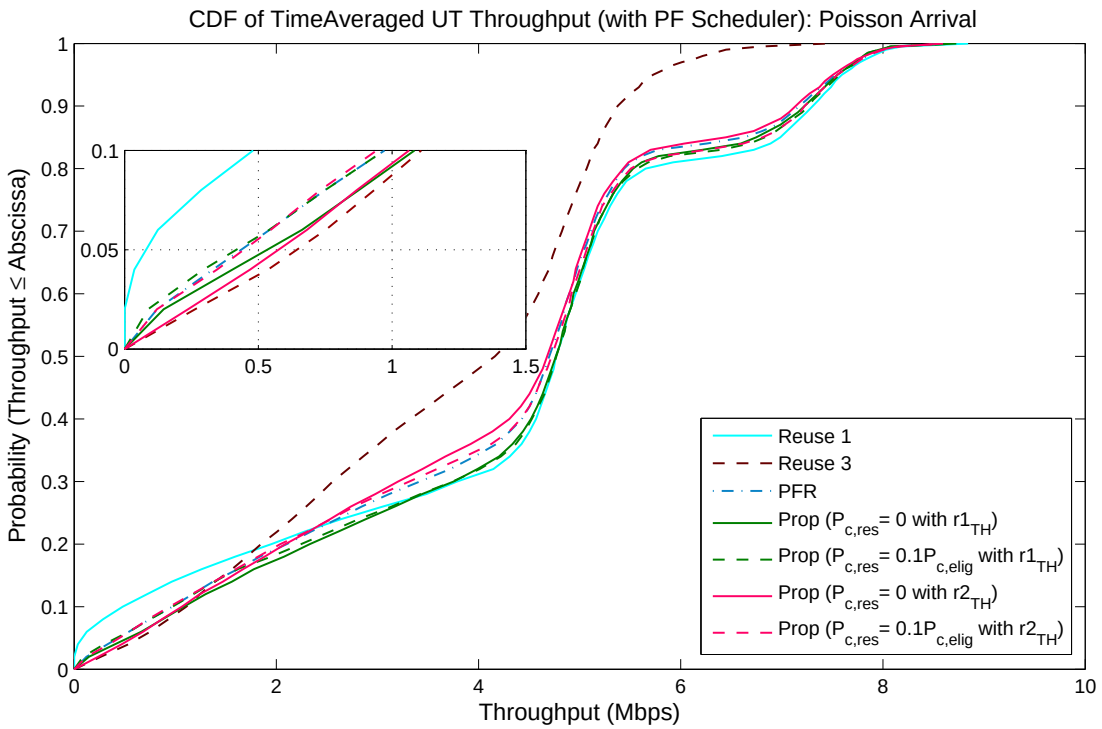


Figure 4.12: CDF of user throughput: proportional fair scheduler (includes hot-spot sectors)

utility is proportional to the achieved rate on the resource unit of interest and UT resource demand at the allocation instant. However, it may be possible to devise a more comprehensive utility function that may consider other critical factors necessary for improved network performance. The presented schemes have, nevertheless, shown the potential of dynamic interference avoidance and highlighted its trade-off between the performance and complexity adjusted through the tunable threshold function.

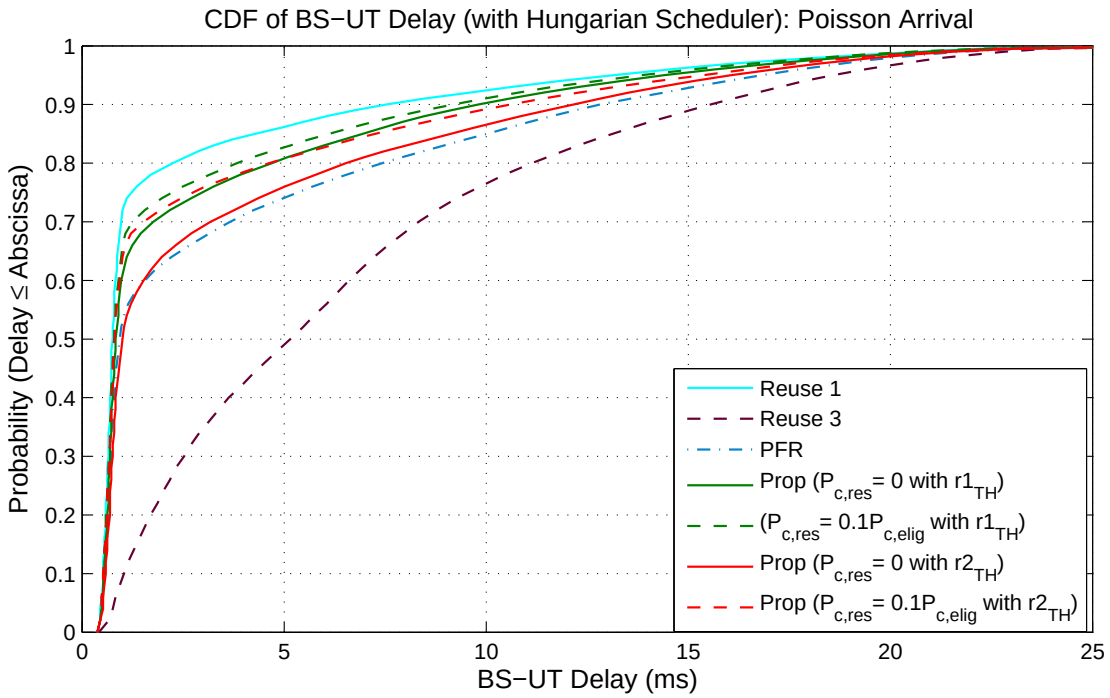


Figure 4.13: CDF of BS-UT delay: iterative Hungarian scheduler (includes hot-spot sectors)

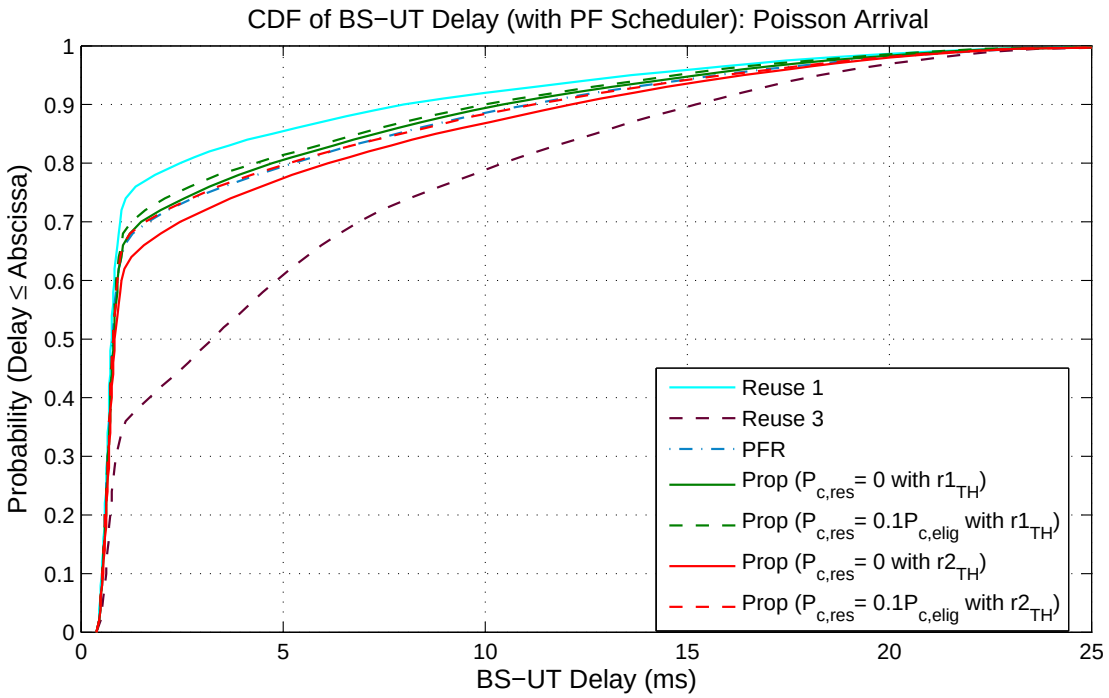


Figure 4.14: CDF of BS-UT delay: proportional fair scheduler (includes hot-spot sectors)

# Chapter 5

# A Distributed Algorithm with Neighboring Cell Coordination

## 5.1 Introduction

In this chapter, an interference avoidance scheme for LTE downlink is presented, which uses dynamic inter-cell coordination facilitated through X2 interface among neighboring UTRAN eNBs. Proposed scheme is evaluated by extensive simulations and compared with a number of reference schemes available in the literature such as reuse 3, a PFR and SFR with different effective reuse factors as discussed in Chapter 2. It has been observed that the proposed scheme attains superior performance in terms of cell-edge and sector throughput compared to those in the reference schemes.

The remainder of this chapter is organized as follows. The proposed scheme is described in Section 5.2. Section 5.3 provides LTE simulation environment and parameters. Simulation results are discussed in Section 5.4 followed by a summary in Section 5.5.

## 5.2 Description of the Proposed Scheme

Let us consider a network layout as shown in Fig. 3.1, with the exception that LTE terminology to denote a base-station, i.e., eNB, is used. Inter-cell interference is categorized into two groups, i.e., intra-eNB and inter-eNB interference as shown in Fig. 5.1. UEs receive dominant interference from the first-tier of interferers: 2 from own-eNB and 4 from cells of other neighboring eNBs, as illustrated in the figure. Based on mutual interference situation and UE rate requirements resource restrictions are prepared using two algorithms, one for intra-eNB and the other for inter-eNB interferers. Interference originated from cells of own eNB should be handled separately as eNB can take appropriate measures itself without the need for inter-eNB communication through $X2$ interface. Both algorithms involve preparation of utility matrix and applying Hungarian algorithm [9] on the utility matrix in an iterative manner in order to find resource units to be restricted in the neighboring cells. Hungarian algorithm is optimal for one-to-one resource unit to UE allocation; however, it becomes sub-optimal when it is used iteratively to assign more than one resource unit to a UE.

The restrictions on the usage of resource units are determined from time-to-time at a time-interval within the channel coherence time, i.e. depending on the speed of the mobile. This interval is denoted as resource restriction refresh interval. Once the resource unit restriction list is available at a sector, the scheduler can perform resource unit scheduling based on its own criteria. Two variations of the proposed scheme have been studied; in one, the restricted resource units are not used at all and in the other, these resource units are used, however, only with reduced power (for example, with 10 dB lower).

### 5.2.1 Intra-eNB Inter-Cell Interference Avoidance

A novel method is used to apply Hungarian algorithm for intra-eNB interference avoidance among three sectors (belonging to the same eNB) as follows. For a particular resource unit,

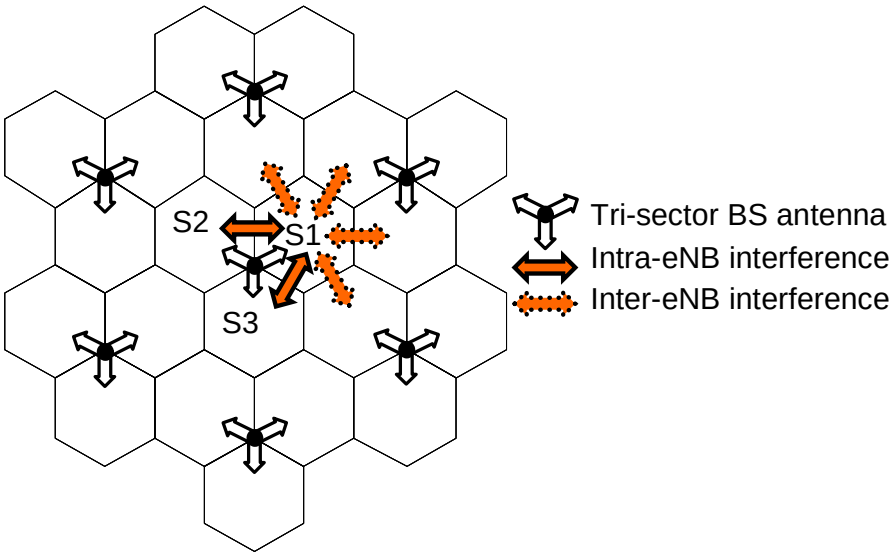


Figure 5.1: Intra and inter-eNB inter-cell interference.

a sector can restrict only one dominant intra-eNB interferer. A utility matrix covering all three sectors of an eNB is constructed as follows.

$$\boldsymbol{U}_{\text{intra}} = \Big[ \overbrace{\boldsymbol{U}_{1|\{\}} \quad \boldsymbol{U}_{2|\{\}} \quad \boldsymbol{U}_{3|\{\}}}^{\text{Sectors 1,2,3 Tx}} \quad \overbrace{\boldsymbol{U}_{1|\{3\}} \quad \boldsymbol{U}_{2|\{3\}} \quad \boldsymbol{0}}^{\text{Sectors 1,2 Tx}} \quad \overbrace{\boldsymbol{U}_{1|\{2\}} \quad \mathbf{0} \quad \boldsymbol{U}_{3|\{2\}}}^{\text{Sectors 1,3 Tx}} \quad \overbrace{\mathbf{0} \quad \boldsymbol{U}_{2|\{1\}} \quad \boldsymbol{U}_{3|\{1\}}}^{\text{Sector 2,3 Tx}} \Big], \tag{5.1}$$

where each element of the above composite matrix is itself a matrix of size $M \times N$; $N$ and $M$ are the number of resource units and the number of UEs per sector, respectively. The first three elements are the utility matrices for sectors 1, 2, and 3 respectively, given all three sectors use the resource concurrently (i.e., no intra-sector restriction). The next set of matrices under the second curly brace are the utilities in Sectors 1, 2, and 3 when Sector 3 is restricted. These utility matrices conditioned on the possible concurrent intra-eNB

inter-cell interferers are of the form below:

$$U_{M\times N} = \begin{pmatrix} u^{(1,1)} & u^{(1,2)} & \dots & u^{(1,N)} \\ u^{(2,1)} & u^{(2,2)} & \dots & u^{(2,N)} \\ u^{(3,1)} & u^{(3,2)} & \dots & u^{(3,N)} \\ \vdots & \vdots & \cdots & \vdots \\ u^{(M,1)} & u^{(M,2)} & \dots & u^{(M,N)}. \end{pmatrix} \tag{5.2}$$

The utility measure $u^{(m,n)}$ is the product of the achievable rate on resource unit $n$ if it is assigned to UE $m$ ($r^{(m,n)}$) and the current demand factor of UE $m$ (i.e., $d^{(m)}$, which is defined as in Section 3.2 of Chapter 3), when both intra-eNB interferers are active. When an intra-eNB sector is restricted, a penalty (in terms of rate) is introduced in the calculation of the utility as below.

$$u^{(m,n)} = \begin{cases} r^{(m,n)} \times d^{(m)}; & \text{all transmit,} \\ (r^{(m,n)} - r_p) \times d^{(m)}; & \text{one restricted,} \end{cases} \tag{5.3}$$

where $r_p$ is the rate penalty considered in the utility measure to account for resource loss due to restriction imposed to one of the intra-eNB sectors. In simulations, $r_p = 1.5$ bps/Hz is considered such that average number resource units restricted by intra-eNB avoidance algorithm is around 10% of the system resource units. It should be noted that in calculating $r^{(m,n)}$, all other inter-eNB interferers are considered active. Entries in $U_{\text{intra}}$ corresponding to UEs having demand factors less than 1 (i.e., rate satisfied in the past) are set to zero so that restrictions are made only for the rate deprived UEs. Then, the Hungarian algorithm is applied to $U_{\text{intra}}$. In each iteration, algorithm selects best resource units for UEs in three different sectors so that the sum of utilities of the chosen resource units is maximized. Note that an entry from a matrix with restriction is chosen only when the rate improvement due to interference suppression exceeds the penalty $r_p$. $U_{\text{intra}}$ is updated after each iteration as

follows.

- If a chosen entry is from the matrix where resource unit restriction is not required, for example $U_{1|\{\}}$, utility entries for the corresponding resource unit for all UEs in $U_{1|\{3\}}$, $U_{2|\{3\}}$, $U_{2|\{1\}}$, $U_{3|\{1\}}$, $U_{3|\{2\}}$, and $U_{1\{2\}}$ in addition to $U_{1|\{\}}$ would have to be replaced by zeros. However, utility entries in $U_{2|\{\}}$ and $U_{3|\{\}}$ remain unchanged in order to allow future iteration to reselect this resource unit.

- If a chosen entry is from the matrix where a resource unit restriction is required, for example $U_{1|\{2\}}$ (sector 2 has restriction on the selected resource unit), following actions are required.

  - Place the resource unit index in restriction list for sector 2
  - Entries corresponding to this resource unit for all UEs in all matrices except $U_{3|\{2\}}$ have to be replaced by zeros. In this case, future iterations will allow resource unit to be used only by a UE in sector 3.

The above steps are repeated until all entries in $U_{\text{intra}}$ are zero. In this process, each sector prepares resource unit restrictions for its intra-eNB neighbors. The number of required iterations varies depending on the number of rate deprived UEs as well the utility values of the matrix.

### 5.2.2 Inter-eNB Inter-Cell Interference Avoidance

Similar to [17, 18] and as in the previous chapter, each sector prepares resource unit restrictions for inter-eNB interferers, based on dominant received interference from four inter-eNB interferers. This algorithm involves preparation of utility matrix $U_{\text{inter}}$ by using heuristics and applying Hungarian assignment algorithm to this matrix. Then, neighboring eNBs are communicated about these resource restrictions over $X2$ interface. The details of this algorithm are discussed below.

**Preparation of Utility Matrix**

Let us consider $r_{i_{(\min)}}^{(m,n)}$ and $r_{i_{(\max)}}^{(m,n)}$ to be the achievable rates for UE $m$ and resource unit $n$ at sector $i$ when none and all $1^{st}$-tier inter-eNB interferers are restricted, respectively. However, moving from $r_{i_{(\min)}}^{(m,n)}$ to $r_{i_{(\max)}}^{(m,n)}$ implies increasing penalty to the interfering sectors, as more and more interferers are to be restricted.

A threshold-based strategy is used to determine which interferers are to be restricted. Based on its demand factor and channel conditions, a UE can restrict two most dominant interferers at most. This limits the number of resulting resource unit restrictions in the neighboring sectors. In order to construct the inter-eNB utility matrix, the following steps are repeated for each UE and resource unit.

- Four inter-eNB dominant interferers are sorted in descending order into a dominant interferer set.
- $r_{i_{(\min)}}^{(m,n)}$ is calculated considering the presence of all inter-cell inter-eNB dominant interferers and taking intra-eNB restrictions into account.
  - If $r_{i_{(\min)}}^{(m,n)} \geq r1_{TH}$, no interferers are to be restricted if resource unit $n$ is assigned to UE $m$ irrespective of its demand factor. In this case, UE $m$ is then either having a strong desired link from serving BS or is experiencing weak interference from all dominant interferers on resource unit $n$. In simulations, $r1_{TH} = 3.5$ bps/Hz is used.
  - Else, calculate the new rate $r_{i_{(\text{new})}}^{(m,n)}$ with the most dominant interferer being restricted.
- If $r_{i_{(\text{new})}}^{(m,n)} - r_{i_{(\min)}}^{(m,n)} \geq r2_{TH}$; i.e., UE $m$ will request this dominant interferer to be restricted irrespective of its demand. $r2_{TH}$=2 bps/Hz has been used in simulations.
- Else if $d_i^{(m)} \geq 1$ (UE $m$ has been rate derived in the past), $r_{i_{(\min)}}^{(m,n)} = 0$, and $r_{i_{(\text{new})}}^{(m,n)} \geq 0$,

the most dominant interferer is to be restricted. In some cases, both $r_{i_{(\min)}}^{(m,n)}$ and $r_{i_{(\text{new})}}^{(m,n)}$ can be zero. If restricting two most dominant interferers provides achievable rate, these will be marked for restriction.

Note that the above threshold values are chosen such that the number of resource units restricted by inter-eNB algorithm is on average around 15-20% of the available system bandwidth. After finding the inter-eNB dominant interferer(s) to be restricted on each resource unit and each UE, achievable rates $r_i^{(m,n)}$ are calculated. Now, the utility of resource unit $n$ for UE $m$ can be expressed as:

$$u_{m,n}^{(i)} = r_{m,n}^{(i)} d_i^{(m)}. \tag{5.4}$$

The utility matrix is given by $\left[U_{i(\text{inter})}\right]_{M\times N} = \left[u_i^{(m,n)}\right]$. Each entry of $U_{i(\text{inter})}$ is associated with corresponding interferer(s) to be restricted in addition to the achievable rate and demand when resource unit $n$ is used by UE $m$.

**Applying Hungarian Algorithm to Utility Matrix**

Hungarian algorithm is applied to in an iterative manner as earlier. In each sector, steps given below are followed to prepare inter-eNB resource units restrictions.

- Apply Hungarian algorithm to $U_{i(\text{inter})}$. If any selected utility entry has a corresponding interferer restriction, the restriction list will be updated with the marked interferer for the resource unit.
- Update the columns of the utility matrix corresponding to assigned resource units with zeros. Now, apply the Hungarian algorithm to the updated utility matrix.
- Repeat above steps until all entries of the utility matrix are zero. The number of required iterations is bounded by $\lceil N/M \rceil$.

**Inter-eNB Communication using X2 Interface**

For a particular resource unit, Fig. 5.2 shows an example scenario of inter-eNB inter-cell restrictions. In this figure, the green (solid line) and red (dashed line) arrows indicate that inter-eNB inter-cell interference received at the arrow-originating-sector from the arrowhead-sector is acceptable and unacceptable (to be restricted), respectively. For example, for a resource unit of interest, sector $B$ can tolerate interference from sector $A$, but the opposite is not true as there is a red (dashed) arrow from sector $A$ toward $B$. In this case, either sector $A$ or $B$ has to be restricted for this resource unit. In this case, eNB corresponding to sector $A$ communicates with the eNB corresponding to sector $B$ using $X2$ interface [83] about restricting the resource unit.

It is expected that a pair of sectors will have restrictions for the same resource unit in some cases (i.e., red arrows to each other). In such cases, the sector that achieves higher utility survives. The negotiation of resolution of this type of conflicting restrictions is also carried over $X2$ interface.

Currently, X2 interface supports information exchange between eNBs primarily for mobility management, load management, and interference coordination, which is controlled by X2AP protocol [84]. Protocol message LOAD INFORMATION is used to indicate UL interference power in three levels (low, medium, and high). In order for the proposed scheme to work with X2 interface, X2AP message has to be modified so that a requesting eNB is not only able to pass the index of the resource units requested to be restricted but also the utilities it estimates on those resource units. If two eNBs wish to restrict a resource unit to each other, the decision should result in favor of the eNB foresees higher utilization on that resource unit. In the current message format, instead of passing the interference information eNB can pass utility information. However, 3 levels (i.e., 2-bits) will probably be too course for the utilities to be meaningfully compared. A higher quantization level such as 16-levels (i.e.,4-bits) utility information may be required which would require increased

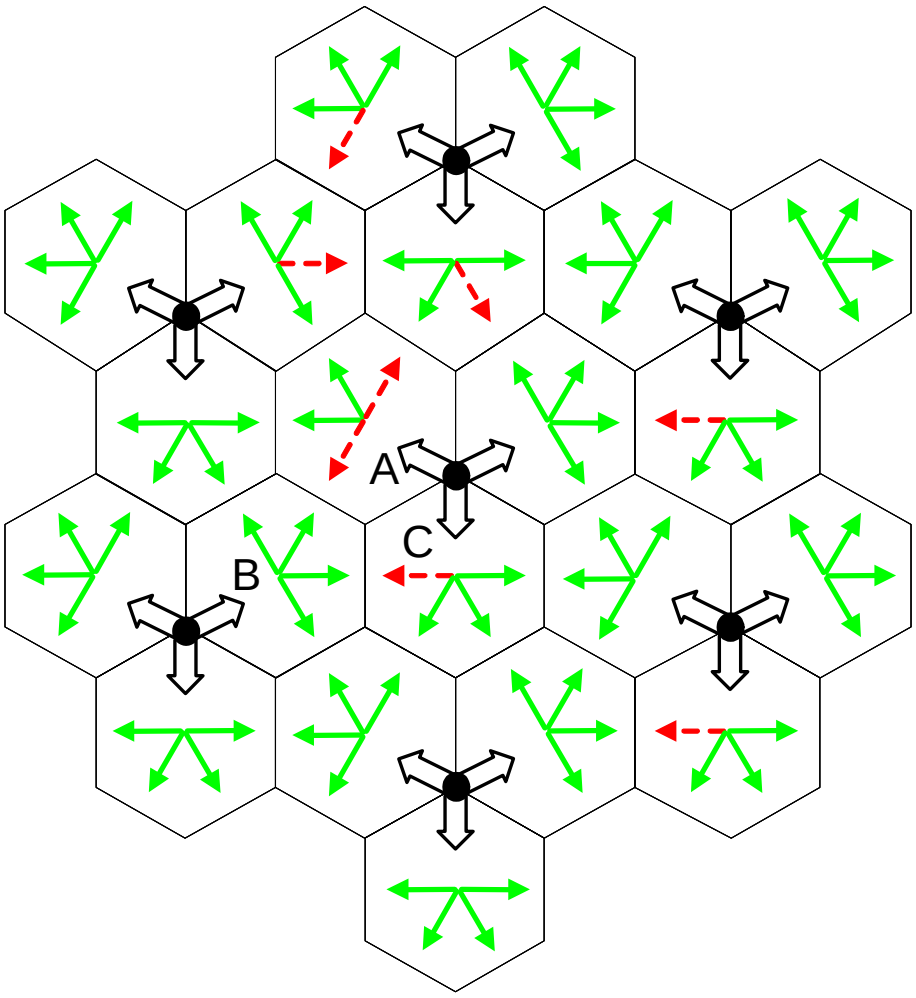


Figure 5.2: Graphical representation of inter-eNB PRB restriction.

rate for eNB-eNB signaling.

## 5.3 Simulation System and Parameters

Considered simulation and system parameters are taken mostly from [33] and [89] as summarized in Table 5.1. Time-frequency correlated 6-taps extended spatial channel model (SCME) with power delay profile as defined in [90] is considered. Independent lognormal shadow fading with a standard deviation of 8 dB has been assumed. 20 MHz system band-

Table 5.1: System and Simulation Parameters

| **Parameter** | **Assumption** |
|---|---|
| Cellular Layout | Hexagonal grid, 19 cell sites, 3 sectors per site |
| Inter-site Distance | 500 m |
| Path-loss | $L_D$=128.1 + 37.6 $\log_{10}(D)$, $D$ in km |
| Shadowing | Independent Log-normal std. 8 dB |
| Penetration Loss | 10 dB |
| Antenna Pattern | A($\theta$) = -min $\left[12\left(\frac{\theta}{\theta_{3\text{dB}}}\right)^2, 20\right]$,$\theta_{3\text{dB}} = 70^o$ |
| Carrier / Bandwidth | 2.0 GHz/20MHz |
| Channel model | 6-Tap SCME |
| UE speeds of interest | 30 km/hr |
| Sector TX power | 46 dBm |
| Minimum UE Distance | $\geq$ 35 m |

width constitutes 100 resource units. A resource unit consists of 12 subcarriers (each of 15 kHz) in frequency and 7 OFDM symbols in the time dimension. Four and three OFDM symbols per resource unit are used for downlink reference and control signals, respectively, giving 77 OFDM symbols per resource unit for data traffic. Therefore, a resource unit can carry 77 information bits with QPSK rate 1/2 Modulation and Coding Scheme (MCS).

AMC is used with various MCS modes with QPSK, 16-, and 64-QAM, and coding rates ranging from 1/8 to 4/5. Link adaptation is performed using attenuated and truncated form of Shannon bound, matched to link level performance curves with above mentioned modulation level and coding rates, as follows [91].

$$\eta = \begin{cases} 0; & \gamma < \gamma_{\min}, \\ \zeta S(\gamma); & \gamma_{\min} < \gamma < \gamma_{\max}, \\ \eta_{\max}; & \gamma \geq \gamma_{\max} \end{cases} \tag{5.5}$$

where $\eta$ is the spectral efficiency in bps/Hz, $\gamma$ is the SINR seen on resource unit and $\zeta$ (0.75 used in simulation) is the attenuation factor applied to the Shannon bound given by $S(\gamma) = \log_2(1+\gamma)$ which achieves $\eta_{\max}$ (4.8 bps/Hz) at $\gamma_{\max}$ (19.2 dB) or beyond and 0 at $\gamma_{\min}$ (-6.5 dB) or lower. Automatic Repeat reQuest (ARQ) has not been considered

Table 5.2: Power Allocation to Physical Resource Blocks

| **Scheme** | **Allocated power / resource unit** |
|---|---|
| Reuse 1 | $P_t/N$ |
| Reuse 3 | $3P_t/N$ |
| PFR 1.3 | outer resource: $2.25P_t/N$; inner resource: $1.13P_t/N$ |
| SFR 1.5 | outer resource: $1.5P_t/N$; inner resource: $0.75P_t/N$ |
| SFR 2.0 | outer resource: $2.0P_t/N$; inner resource: $0.5P_t/N$ |
| SFR 2.5 | outer resource: $2.5P_t/N$; inner resource: $0.25P_t/N$ |
| SFR 2.75 | outer resource: $2.75P_t/N$; inner resource: $0.13P_t/N$ |
| Proposed 1 | eligible resource: $P_t/(N - N_\mathrm{r})$; restricted resource: 0 |
| Proposed 2 | eligible resource: $10P_t/(10N_\mathrm{e} + N_\mathrm{r})$; restricted resource: $P_t/(10N_\mathrm{e} + N_\mathrm{r})$ |

in simulations. For fair comparison, total transmit power per sector is kept constant in all schemes, which is $\approx P_t$. Accordingly, power allocated to resource units for different schemes are shown in Table 5.2. In the table, $P_t$ (46 dBm), $N$ (100), $N_\mathrm{r}$, and $N_\mathrm{e}$ are the total power per sector, system bandwidth in terms of number of resource units, and the number of restricted (from intra and inter-eNB), and unrestricted resource units, respectively. As shown in the table, restricted resource units are unused in proposed scheme 1 and used with 10 dB lower power in proposed scheme 2.

## 5.4 Simulation Results and Discussions

The performance of the proposed interference avoidance scheme is compared to that of the reference schemes in terms of cell-edge and average sector throughput. Cell-edge throughput is defined as the $5^{th}$ percentile point of CDF of UE throughput. The reference schemes simulated are reuse 1, reuse 3, SFR (with effective reuse of 1.5, 2.0, 2.5, and 2.75), and PFR (effective reuse of 1.3).

Statistics are collected from a total of 300 drops. In each drop, UEs are uniformly distributed according to a density of 12 UEs/sector. Simulation time span is 25 ms (50 resource unit time) in each drop. Resource restriction refreshment interval considered is 6 resource unit durations This time is 3 ms (i.e., a time-slot of 0.5 ms corresponds to a

resource time duration in LTE standards) which is within the channel coherence time of ∼8 ms for the UE speed of 30 km/hr and the operating frequency of 2.0 GHz.

The UEs are placed in the central 21 sectors among the total 57 sectors of 19 sites. For the proposed scheme, allocation algorithms are run in these 21 sectors. Statistics are collected from the central eNB (3 sectors) only. Interference is calculated using central cell approach.

Fig. 5.3 shows CDF of UE throughput for the proposed as well as reference schemes. The lower tail of CDF is zoomed in Fig. 5.4 in order to view the cell-edge throughput clearly. Fig. 5.5 compares cell-edge and average sector throughput among all simulated schemes with reference to reuse 1 scheme. It is observed that while reuse 3 scheme achieves 168.4% improvement in cell-edge throughput compared to reuse 1 scheme, it suffers from sector throughput degradation by 49.2%. The PFR scheme improves cell-edge throughput by 149.7%, however, with 26% reduction in sector throughput. SFR schemes with effective reuse of 2.0, 2.5, and 2.75 show cell-edge throughput improvement by 21.4%, 69.4%, and 114.7% with degradation of sector throughput by 4.3%, 8.6%, and 26.1%, respectively. SFR scheme with effective reuse of 1.5 neither improves cell-edge nor sector throughput compared to reuse 1 scheme. Comparing with reuse 1 scheme, proposed scheme 1 improves cell-edge throughput by 266.1% with an improvement in sector throughput by 3.9%. Proposed scheme 2 shows inferior cell-edge and superior sector throughput compared to those in proposed scheme 1 as restricted resource units are used with reduced power, which favors cell-centre UEs while harms those at the cell-edge. However, compared to reuse 1 scheme, proposed scheme 2 obtains 171.3% improvement in cell-edge throughput while improving the sector throughput by 7.2%.

The performance gain in the proposed scheme is achieved with the cost of increased overhead required for UE-BS feedback as well as eNB-eNB communication over $X2$ interface.

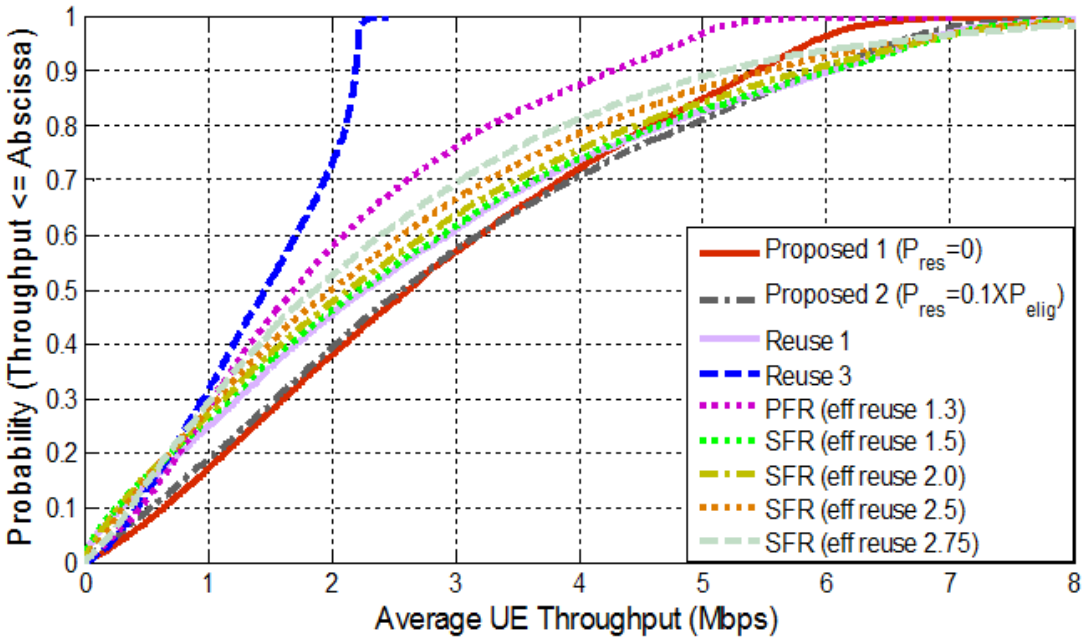


Figure 5.3: CDF of UE throughput.

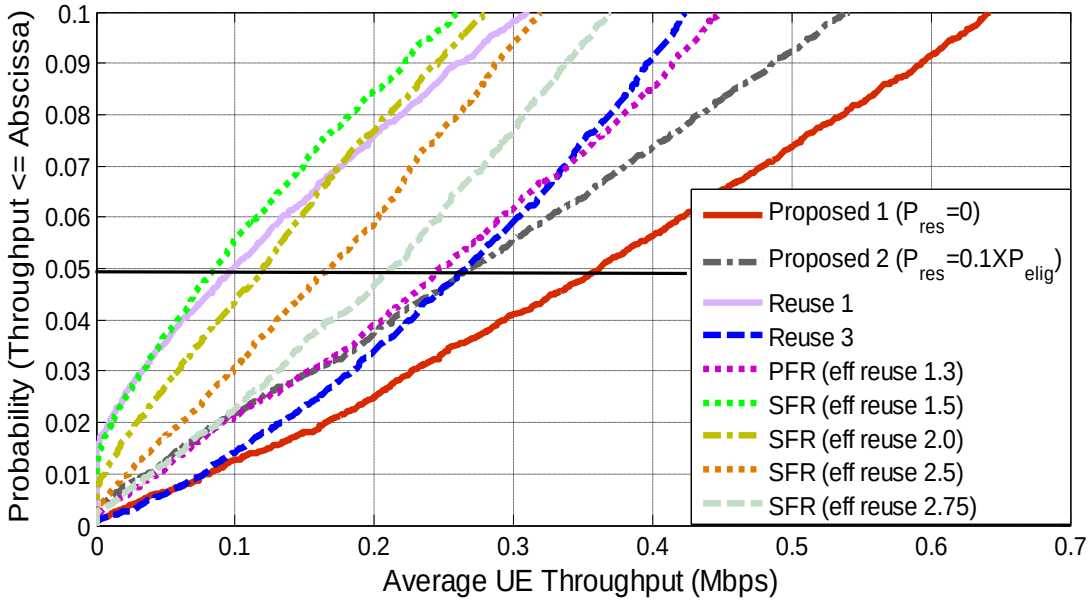


Figure 5.4: CDF of UE throughput (zoomed to show cell-edge throughput).

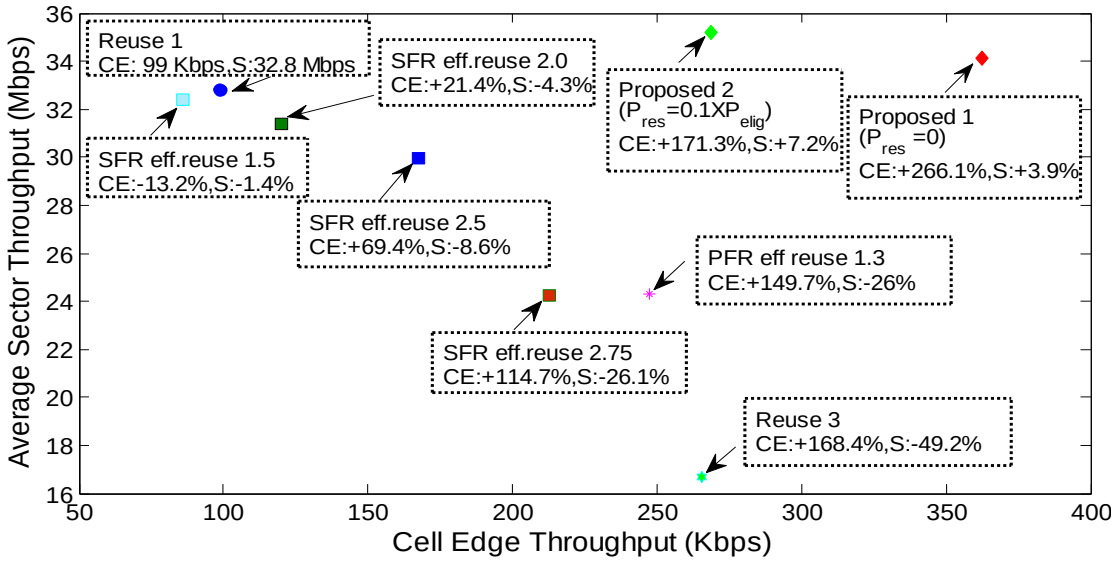


Figure 5.5: Cell-edge vs. average sector throughput.

## 5.5 Summary

An interference avoidance scheme for downlink LTE system that uses dynamic inter-cell coordination supported by $X2$ interface is presented. Two variations of the proposed scheme have been compared with the reference reuse 1 scheme as well as the static partition based interference avoidance schemes in the literature. It has been observed that although static schemes achieve improved cell-edge throughput, they suffer seriously in terms of sector throughput. On the other hand, the proposed schemes not only achieve higher cell-edge throughput but also show improvement in average sector throughput compared to those in any static schemes.

# Chapter 6

# A Cluster-Based Centralized Approach

## 6.1 Introduction

In this chapter, the performance of a novel cluster-based dynamic inter-cell interference coordination scheme using binary integer linear programming optimization technique has been investigated that aims to maximize a throughput- and fairness-based utility. The inter-dependency of inter-cell interference among the clusters is modeled in the constrained optimization formulation. Different utility functions for two different coordination cluster sizes, representing varying computational complexities, have been considered to compare the performance. The cell-edge and sector throughput values as well as user fairness levels of the proposed schemes are compared with those obtained from the uncoordinated interference scenario. To the best of our knowledge a cluster-based dynamic interference coordination taking inter-cluster interference dependency, scheduling, user throughput status, etc., into account in an ILP optimization formulation has not been studied yet. The primary objective of this study is to quantify achievable gain of dynamic interference coordination considering

neighboring interference clusters of different sizes.

The interference coordination problem stated in (3.1)-(3.5) is reformulated as a cluster-based approach. The author studied a cluster-based integer programming approach to interference coordination problem in a simplistic network scenario first in [16] and later in a larger network in [19]. Based on these previous work, this chapter considers a reduced coordination cluster size that results in less computational complexity. A detailed complexity comparison among the presented schemes is also provided. The ideas presented in this chapter are closely related to the coordinated fast scheduling part of the coordinated multi-point transmission and reception (CoMP) concept of the LTE-Advanced technology [92].

The rest of this chapter is organized as follows. Section 6.2 describes the system layout considered. The formulation of the algorithm is presented in Section 6.3. The simulation and system parameters are described in Section 6.4. Performance results are discussed in Section 6.5. The complexity comparison among the schemes is provided in Section 6.6 followed by a brief summary in Section 6.7.

## 6.2 System Model

This study has also been conducted in the context of LTE; therefore, a network layout as in Chapter 5 that consists 19 cell sites each with 3 hexagonal sectors. Directional transmit antennas with $120^o$ beamwidth (3 dB beamwidth of $70^o$) at each sector and omni-directional receive antennas at user equipments (UEs) are considered. The antenna gain pattern is as provided in Chapters 4 and 5.

The system uses cell-specific orthogonal reference signals [4] as assumed in previous chapters and UEs know the reference signals of the neighboring first-tier sectors; therefore, UEs can estimate interference from the first-tier sectors separately. For a downlink transmission to a UE in any sector, one of its first-tier sectors is likely to be the most dominant interferer. If Fig. 3.1 is taken as an example again, it will be seen that a cell-edge UE in

Table 6.1: List of Symbols Used

| | |
|---|---|
| $\psi_1$ | the first dominant interfering sector |
| $\psi_2$ | second dominant interfering sector |
| $m$ | UE index |
| $n$ | RB index |
| $M$ | number of UEs per sector |
| $N$ | number of available RBs per sector |
| $P_c$ | power per RB |
| $P_{TN}$ | average thermal noise power |
| $\mathcal{H}^{(m,n)}$ | channel gain seen by UE $m$ on RB $n$ |
| $\gamma^{(m,n)}$ | SINR experienced by UE $m$ on RB $n$ |
| $r^{(m,n)}$ | achievable rate seen by UE $m$ on RB $n$ |
| $d^{(m)}$ | UE demand factor |
| $I^{(n)}$ | indicator to show whether RB $n$ is restricted or not |
| $R^{(m)}$ | time average throughput achieved by UE $m$ |
| $\bar{R}$ | average throughput across all UEs |
| $\mathcal{G}_i^{(u)}$ | set of interfering stations in an interference cluster for UE $m$ in sector $i$ |

sector 1 of evolved NodeB 1 (eNB1) is likely to receive the most dominant interference from sector 2 or 3 of eNB1 (depending on the UE location), or from sector 2 or 3 of eNB2, or from sector 3 of eNB3, or from sector 2 of eNB7 due to their relative locations and antenna directivity.

As mentioned earlier, in addition to its higher path-loss, a cell-edge UE receives significant interference from the nearby sectors. As a consequence, these UEs are expected to see more poor-quality resource units having low SINRs. A resource unit is defined as the minimum granularity of time-frequency resource unit for scheduling [4]. An optimal or a sub-optimal allocation scheme with an objective of maximizing only network throughput will tend to overlook such disadvantaged UEs due to their poor contribution to the total throughput. Therefore, it is crucial to avoid interference on such UEs in order to guarantee their minimum required rates.

The list of symbols used in this chapter is given in Table 6.1.

Maximization of user rates is only meaningful when user traffic is insensitive to delay, i.e., elastic traffic [78]. Therefore, a utility measure as a function of rate and user achieved

throughput status is considered to make presented algorithm suitable for delay sensitive services as in earlier chapters. The algorithm can reside at any centralized or semi-centralized logical entity to run centrally or in a semi-distributed manner.

Two different coordination cluster sizes are considered. In the first, a UE forms a cluster with the two most dominant interferers (i.e., cluster size of 3), and in the second, it forms a cluster only with the most dominant interferer (i.e., cluster size of 2) among the first-tier interfering sectors. If $\psi_1$ and $\psi_2$ are the first and second dominant interfering sectors to UE $m$ in sector $i$, then the clusters of sizes 3 and 2 for UE $m$, respectively, are constructed with the indices of the following interfering sectors:

$$\mathcal{G}_i^{(u)} = \begin{cases} \{\psi_1, \psi_2\}; & \text{cluster size of 3 (including host sector } i) \\ \{\psi_1\}; & \text{cluster size of 2 (including host sector } i). \end{cases} \tag{6.1}$$

These clusters remain unchanged as long as the UE locations do not change. Once the clusters are determined, we calculate the conditional signal-to-interference plus noise ratios (SINRs) UEs experience for different interferer restriction possibilities, namely, in the case of cluster size of 3, when none, one, and two interferer(s) is(are) restricted. For a RB $n$, we express these SINRs as $\gamma_{i|\{\}}^{(m,n)}$, $\gamma_{i|\{\psi_1\}}^{(m,n)}$, $\gamma_{i|\{\psi_2\}}^{(m,n)}$, and $\gamma_{i|\{\psi_1,\psi_2\}}^{(m,n)}$ denoting no restriction, sector $\psi_1$ restricted, sector $\psi_2$ restricted, and sectors $\psi_1$ and $\psi_2$ restricted, respectively. Note that for the cluster size of 2 only two options exist: $\gamma_{i|\{\}}^{(m,n)}$ and $\gamma_{i|\{\psi_1\}}^{(m,n)}$. These conditional SINRs are calculated from the following expression:

$$\gamma_i^{(m,n)} = \frac{P_c \mathcal{H}_{i,i}^{(m,n)}}{P_c \sum\limits_{\substack{x \neq i \\ x \notin \mathcal{G}_i^{(m)}}} \mathcal{H}_{i,x}^{(m,n)} + P_c \sum\limits_{\psi \in \mathcal{G}_i^{(m)}} \mathcal{H}_{i,\psi}^{(m,n)} \cdot I_\psi^{(n)} + P_{TN}}, \tag{6.2}$$

where the channel gains for the desired link, in-cluster, and other interferer links are $\mathcal{H}_{i,i}^{(m,n)}$,

$\mathcal{H}_{i,\psi}^{(m,n)}$, and $\mathcal{H}_{i,x}^{(m,n)}$, respectively. The parameter $\mathcal{H}$ includes path-loss[1], fading, and antenna gain. The average thermal noise power experienced within the RB is denoted by $P_{TN}$. The parameter $I$ is a resource restriction indicator function which takes the value of 0 or 1 depending on whether a particular resource block is restricted in a sector or not. The allocated power per RB is expressed by $P_c$.

Here, $\gamma_{i|\{\psi_1\}}^{(m,n)} = \gamma_i^{(m,n)}|_{I_{\psi_1}^{(n)}=0}$; it implies that RB $n$ is restricted in sector $\psi_1$. The decision of which RB is to be restricted in which sector is determined by the solution of the optimization problem as described in the next section. The achievable rates for the corresponding conditional SINRs are obtained by adaptive modulation and coding (AMC) mapping for a desired bit-error rate (BER); i.e., $r_{i|\{\psi_1\}}^{(m,n)} \overset{BER,AMC}{\leftarrow} \gamma_{i|\{\psi_1\}}^{(m,n)}$. The detailed AMC model is discussed in Chapter 5.

We consider two different utility scenarios for different degrees of emphasis on throughput and fairness: 1) $u_i^{(m,n)} = r_i^{(m,n)} d_i^{(m)}$, and 2) $u_i^{(m,n)} = r_i^{(m,n)} \left[d_i^{(m)}\right]^2$. Here, we define UE demand factor $d_i^{(m)}$ as follows: $d_i^{(m)} = \bar{R}_i / R_i^{(m)}$, where $R_i^{(m)}$ is the average throughput of UE $m$ over a certain past time-window (a time duration of 10 RBs is considered in simulations), and $\bar{R}_i$ is the average throughput across all UEs and is given by $\bar{R}_i = \left(\sum_{m=1}^{M} R_i^{(m)}\right)/M$, where $M$ is the number of UEs per sector. The latter scenario implements greater emphasis on fairness in scheduling RBs. A UE near the cell-edge will likely have a higher $d_i^{(m)}$. Therefore, the utility incorporating $\left[d_i^{(m)}\right]^2$ provides advantages to rate deprived UEs to boost their performance. It should be noted that although a utility scenario proportional to $\left[d_i^{(m)}\right]^3$ could provide further enhancement to cell-edge throughput, it is not considered in this study due to the fact that it would over-penalize the cell throughput.

[1]distance dependent attenuation and shadowing.

## 6.3 Problem Formulation

We formulate the utility maximization problem as follows:

maximize

$$\sum_{i}\left[\sum_{\Pi}\sum_{m=1}^{M}\sum_{n=1}^{N}u_{i|\Pi}^{(m,n)}\rho_{i|\Pi}^{(m,n)}\right], \tag{6.3}$$

subject to

$$\rho_{i|\Pi}^{(m,n)} \in \{0,1\}; \forall m,\ \forall n, \tag{6.4}$$

$$I_i^{(n)} = \sum_{\Pi}\sum_{m=1}^{M}\rho_{i|\Pi}^{(m,n)} = \begin{cases} 0; & \text{RB } n \text{ is restricted in } i \\ 1; & \text{otherwise,} \end{cases} \tag{6.5}$$

where $\Pi = \{\{\}, \{\psi_1\}, \{\psi_2\}, \{\psi_1, \psi_2\}\}$ or $\Pi = \{\{\}, \{\psi_1\}\}$ denoting the set of transmission restriction possibilities of in-cluster dominant interfering sectors for cluster sizes of 3 and 2, respectively. The constraints in (6.4) indicate that the problem is of binary integer type and those in (6.5) imply that if RB $n$ is not restricted in $i$, it can be assigned to only one UE irrespective of what happens in the dominant interfering sectors.

For cluster size of 3, if the first and second dominant interferers to $i$ are $\psi_1$ and $\psi_2$, respectively, then the restriction possibilities are as follows: 1) $\psi_1$ and $\psi_2$ are not restricted from using RB $n$ (i.e., $I_{\psi_1}^{(n)} = 1$, $I_{\psi_2}^{(n)} = 1$) and user $m$ in sector $i$ achieves a rate of $r_{i|\{\}}^{(m,n)}$, 2) $\psi_1$ is restricted (i.e., $I_{\psi_1}^{(n)} = 0$, $I_{\psi_2}^{(n)} = 1$) and the rate of user $m$ in sector $i$ is $r_{i|\{\psi_1\}}^{(m,n)}$, 3) $\psi_2$ is restricted (i.e., $I_{\psi_1}^{(n)} = 1$, $I_{\psi_2}^{(n)} = 0$) and user rate in sector $i$ is $r_{i|\{\psi_2\}}^{(m,n)}$, and 4) both $\psi_1$ and $\psi_2$ are restricted (i.e., $I_{\psi_1}^{(n)} = 0$, $I_{\psi_2}^{(n)} = 0$) and the rate of user $m$ in sector $i$ is $r_{i|\{\psi_1,\psi_2\}}^{(m,n)}$. In calculating the conditional SINRs and rates, it is assumed that the sectors outside the cluster always use the RB; therefore, the conditional utilities in (6.3) become constant making the formulated optimization problem linear.

Clearly, sectors $\psi_1$ and $\psi_2$ impose restrictions to their own dominant interfering sectors, and this inter-relation would propagate in the network. These restrictions and concurrent

transmission possibilities for the cluster size of 3 scenario are modeled by the following set of constraints:

$$\begin{aligned}
\rho^{(m,n)}_{i|\{\psi_1\}} + I^{(n)}_{\psi_1} &= 0 \text{ or } 1, \\
\rho^{(m,n)}_{i|\{\psi_2\}} + I^{(n)}_{\psi_2} &= 0 \text{ or } 1, \\
\rho^{(m,n)}_{i|\{\psi_1,\psi_2\}} + I^{(n)}_{\psi_1} &= 0 \text{ or } 1, \\
\rho^{(m,n)}_{i|\{\psi_1,\psi_2\}} + I^{(n)}_{\psi_2} &= 0 \text{ or } 1.
\end{aligned} \tag{6.6}$$

For the cluster size of 2, the above set of constraints reduces to

$$\rho^{(m,n)}_{i|\{\psi_1\}} + I^{(n)}_{\psi_1} = 0 \text{ or } 1. \tag{6.7}$$

However, solving this problem network-wide as given by (6.3) through (6.6) or (6.7) with all available RBs at a time is computationally prohibitive due to the large number of variables and constraints. Therefore, the problem is broken down into a number of smaller sub-problems and each sub-problem is solved iteratively. Each sub-problem only takes a sub-set of available RBs (for instance, $\kappa \in \{1, 2, \cdots, N\}$; we assume $N = 10$ in simulations) and assigns them among UEs following (6.3) through (6.6) or (6.7).

It is recognized that scheduling has its own effect on cell-edge and sector throughput. In order to decouple the effect of scheduling, a consistent scheduling principle is used for all studied schemes. The following constraints model scheduling, where a UE is assigned a maximum of two RBs in each iteration:

$$\sum_{\Pi} \sum_{n} \rho^{(m,n)}_{i|\Pi} \leq 2; \quad \forall i, \ \forall m. \tag{6.8}$$

The pseudo code of the algorithm is given in Table 6.2, where each sub-problem is solved iteratively until all RBs are assigned in all sectors following (6.3) to (6.8).

Table 6.2: Pseudo Code of the Algorithm

Initialize the list of unassigned RBs $\mathcal{L} = \{1, 2, ...., N\}$
**while** $\mathcal{L} \neq \{\}$ **do**
  Take a set of RBs, $\kappa$, from unassigned set $\mathcal{L}$; $\kappa \in \mathcal{L}$.
  Solve optimization problem given by (6.3) to (6.8).
  Update $R$, $\bar{R}$, and $d$ for all UEs in all sectors.
  Remove $\kappa$ RBs from $\mathcal{L}$.
**end while**

## 6.4 System and Simulation Parameters

As this scheme is studied in the context of LTE system, system and simulation parameters are as described in Chapter 5 with a few exceptions. However for readability, Table 6.3 is provided, where system and simulation parameters are summarized. Here, 10 MHz of system bandwidth (i.e., 50 resource units) is used instead of 20 MHz. This assumption was taken to speed up simulation run-time. The channel model, large-scale path-loss, antenna pattern, AMC functions, etc. remain the same as in Chapter 5. MATLAB along with optimization solvers YALMIP [86] and TOMLAB/CPLEX [93] is used.

## 6.5 Simulation Results

For each utility scenario, we consider a corresponding reference scheme which also maximizes the same utility parameter with the difference that the reference scheme does not have the capability of interference coordination (namely, no ICIC). Therefore, the gain observed in the proposed scheme is entirely due to inter-cell interference coordination. The cell-edge throughput (measured as the $5^{\text{th}}$-percentile point of the CDF of time-averaged UE throughput), average sector throughput (averaged over central 3 sectors), the $95^{\text{th}}$-percentile UE throughput, and Jain's fairness index [29] have been used in order to compare the performance of the proposed schemes. Coordination cluster sizes of 2 and 3 representing different computational complexities are considered.

Table 6.3: System and Simulation Parameters

| | |
|---|---|
| Cellular layout | Hexagonal grid, 19 cell sites, 3 sectors per site |
| Inter-site distance | 500 m |
| Carrier frequency and bandwidth | 2.0 GHz and 10 MHz (50 RBs) |
| Path-loss exponent | 3.76 |
| Lognormal shadowing | Independent among links |
| Shadowing standard deviation | 8 dB |
| UE speeds | 30 km/hr |
| Penetration loss | 10 dB |
| Antenna configuration | Single-input single-output |
| BS antenna gain | 14 dBi |
| UE antenna gain | 0 dBi |
| UE noise figure | 7 dB |
| AMC modes | Attenuated Shannon bound for QPSK, 16- and 64-QAM with varying rates |
| Channel model | 6-tap SCME |
| Total sector TX power | 46 dBm |
| UE close-in distance | 35 m |
| Traffic model | Full buffer |

In each of the central 21 sectors, 10 UEs/sector are placed randomly for each simulation drop. Interferers are coordinated in these sectors only; the remaining sectors act as interference contributors only, where it is assumed that all RBs are always used in these sectors. Each drop is simulated for 50 RBs time duration and a total of 200 drops is considered for each utility scenario and for each studied scheme. Statistics are collected from the central 3 sectors belonging to Cell 1. User demand $d_i$ is calculated from the past throughput achieved over 10 RBs time duration.

The CDF of time averaged UE throughput is shown in Fig. 6.1. In the inset of the figure, the tail of the CDF is zoomed for the clarity to observe the $5^{\text{th}}$-percentile point (i.e., cell-edge throughput). The observed performance parameters from this figure is also summarized in Table 6.4. In all cases, $u = rd^2$ scenario with ICIC shows larger gain in terms of cell-edge throughput compared to $u = rd$ scenario. Also, in the ICIC schemes, the $u = rd^2$ scenario achieves less sector throughput and less $95^{\text{th}}$-percentile UE throughput

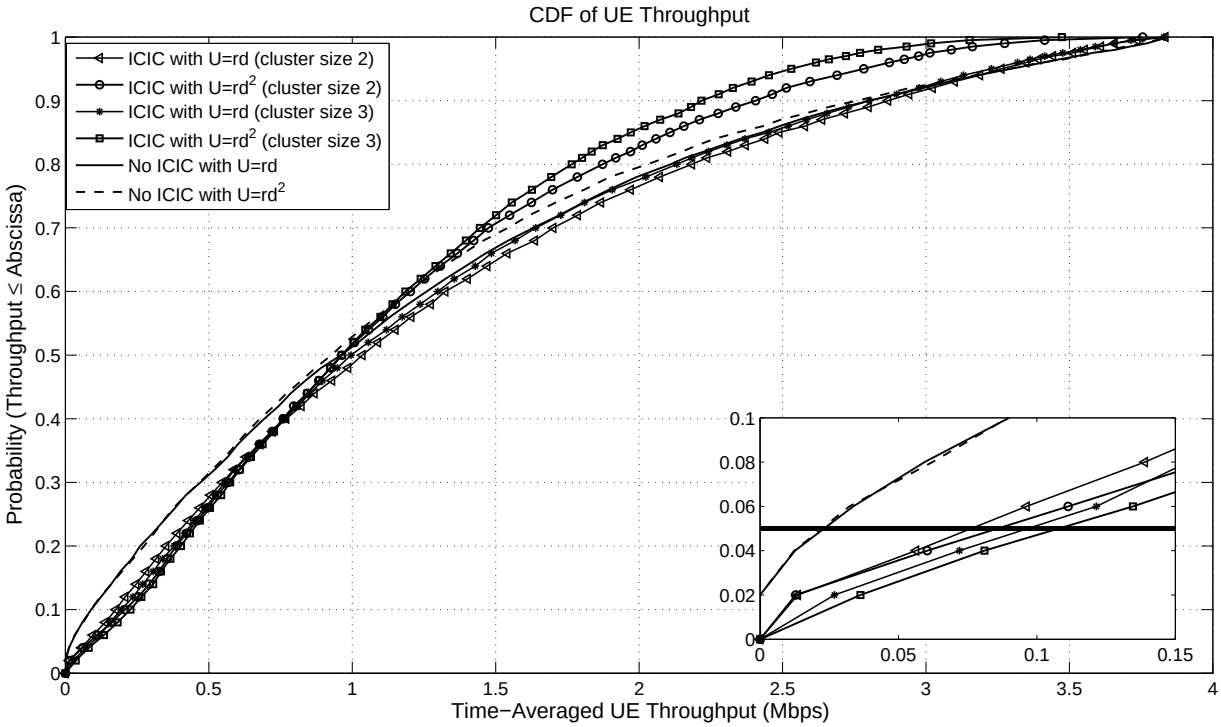


Figure 6.1: CDF of time-averaged user throughput.

Table 6.4: Comparison of Cell-Edge ($5^{\text{th}}$ Percentile), $95^{\text{th}}$ Percentile, and Total Sector Throughput

| Studied Scheme | $5^{\text{th}}$-Perc. (kbps) | $95^{\text{th}}$-Perc. (Mbps) | Total Sector Throughput (Mbps) |
|---|---|---|---|
| No ICIC with $u = rd$ | 23.2 | 3.30 | 12.11 |
| No ICIC with $u = rd^2$ | 20.9 | 3.29 | 11.79 |
| ICIC with $u = rd$ (cluster size 2) | 76.3 | 3.26 | 12.76 |
| ICIC with $u = rd^2$ (cluster size 2) | 82.5 | 2.78 | 11.42 |
| ICIC with $u = rd$ (cluster size 3) | 99.3 | 3.23 | 12.56 |
| ICIC with $u = rd^2$ (cluster size 3) | 109.0 | 2.53 | 11.01 |

showing a clear trade-off between cell-edge and sector throughput. The scheduling weight does not provide any noticeable gain in cell-edge throughput for the reference scheme.

While the cell-edge performance can be enhanced by a factor of 5 for the cluster size of 3 with $u = rd^2$ scenario, sector throughput is affected adversely. However, in the case of cluster size of 2, it is observed that the cell-edge throughput can be improved by a factor of 3 to 4, while the sector throughput is comparable or even better than those in the reference no ICIC case.

We compare achieved fairness index using Jain's fairness index in Fig. 6.2. It is observed that schemes with ICIC for all utility scenarios show better fairness compared to those where ICIC is not used. The $u = rd^2$ scenario with ICIC for the cluster size of 3 exhibits the

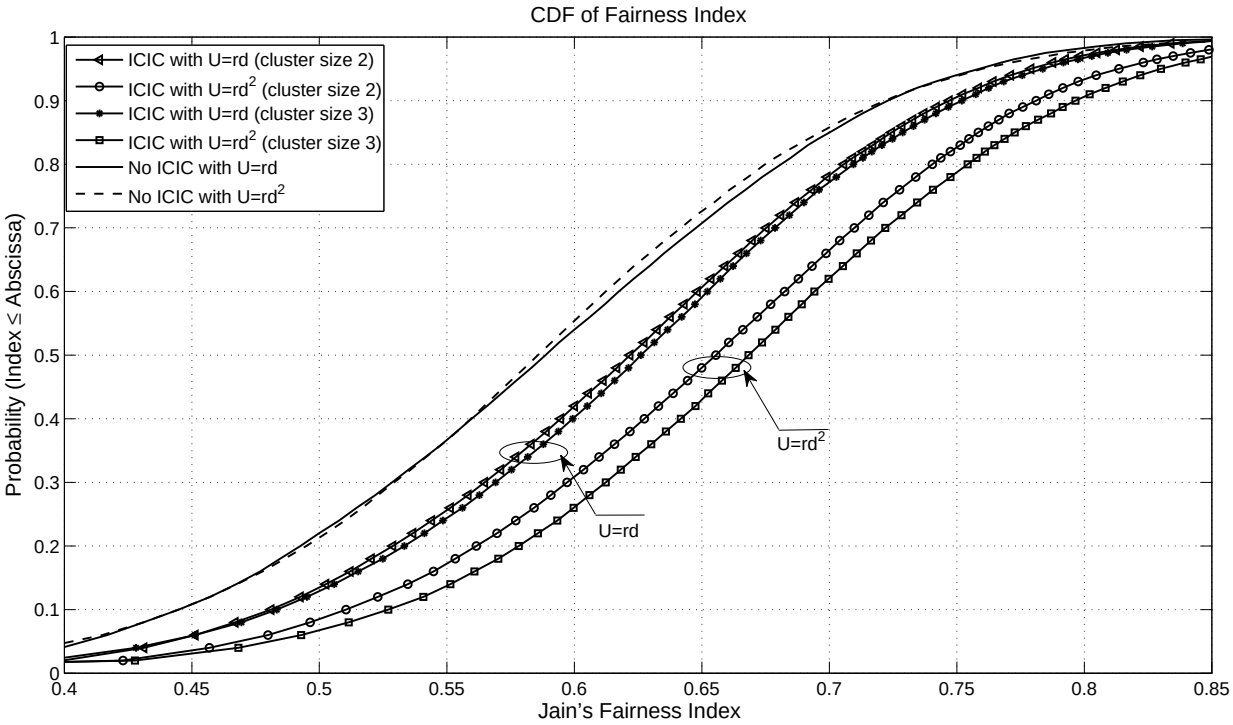


Figure 6.2: CDF of Jain's fairness index.

highest fairness index as expected. This result clearly demonstrates the trade-off between the enhanced cell-edge throughput and degraded sector throughput.

## 6.6 Simulation Time Comparison

The computational complexity of an ILP solver depends on the number of variables. A comparison of required simulation time for each allocation iteration among studied schemes is provided in Table 6.5. The stated number of variables are for all the 21 sectors having users in them for each iteration of the algorithm. We note that the number of binary variables of cluster size of 2 is twice as many of that in the scenario without coordination. And, the scenario with cluster size of 3 requires twice as many variables compared to those in cluster size of 2. The average computational time[2] taken by the CPLEX solver per iteration of the algorithm for the no ICIC case is 16 ms, while this for cluster sizes of 2 and 3 are 76 ms and 300 ms, respectively. The optimization constraint processing times required by YALMIP are 189 ms, 520 ms, and 1.38 sec for no ICIC, cluster size of 2, and size of 3, respectively.

[2]Computed in a personal computer with AMD Athlon X2 6400+ CPU, 4 GB main memory, and Windows XP 64-bit OS.

Table 6.5: Simulation Time Comparison

| Studied Scenario | No. of Variables | YALMIP Time (sec./iteration) | CPLEX Solver Time (sec./iteration) |
|---|---|---|---|
| No ICIC | 1155 | 0.189 | 0.016 |
| ICIC with cluster size 2 | 2310 | 0.520 | 0.076 |
| ICIC with cluster size 3 | 4620 | 1.378 | 0.300 |

## 6.7 Summary

In this Chapter, we have presented a dynamic inter-cell interference coordination (ICIC) scheme for downlink OFDMA system. Two different utility parameters have been defined to model different levels of user fairness. Furthermore, two different coordination cluster sizes representing different complexities have been considered. The problem is decomposed into a number of smaller sub-problems and solved iteratively.

It is observed that schemes employing ICIC outperform the corresponding reference schemes without coordination, with regard to cell-edge performance, sector throughput, and fairness. In particular, the utility scenario $u = rd^2$ with ICIC for the cluster size of 3 achieves 5 times cell-edge throughput, substantially better fairness, and slightly degraded sector throughput compared to those in the corresponding reference scheme without ICIC, at the expense of substantial computational complexity. However, it is observed that around 3-4 times cell-edge throughput and a better fairness level can be achieved with minimal impact to or even some gain in sector throughput compared to those in the reference scheme when the coordination cluster size is 2, requiring only a reasonable increase in computational complexity.

# Chapter 7

# Conclusions

In this thesis, a literature review on interference avoidance has been provided and then elaborate descriptions of the proposed schemes on dynamic inter-cell interference coordination are presented.

In Chapter 3, a general optimization framework that maximizes the sum-utility for the interference coordination problem is formulated. Besides channel quality, the utility takes users' achieved throughput status into account and provides advantage to the cell-edge user terminals. Three different approaches have been considered that reflect different coordination means, network architectures, and complexities, as outlined from Chapter 4 to Chapter 6. In all proposed approaches, performance has been compared to schemes where inter-cell interference coordination is either not used or used in a static manner. The reference schemes use the same scheduling criteria and work with the same utility function as those in the proposed schemes. Therefore, the observed performance gain solely represent the strength of interference coordination in the presented schemes. It is observed that proposed schemes always significantly outperform the reference schemes in terms of cell-edge throughput and fairness, and with a minimum impact on network throughput or gain in some cases.

A unique, two-level algorithm is investigated in Chapter 4, where user-centric resource restriction request is prepared by the sector-level algorithm. While the sector-level algorithm is based on heuristic, the central algorithm is formulated using an ILP that resolves any potential resource restriction conflicts in an optimal manner. Since only restriction conflicts are handled at this stage, the overall complexity of the scheme is much less than that in the original problem formulated in Chapter 3. Two different cases have been investigated; in one, the restricted resource units are not used and in the other, these are used but with lower transmit power. Reference schemes to which the proposed schemes are compared are Reuse 1, Reuse 3, and a PFR. Both full-buffer (i.e., BS always has data to send) and traffic model (with Poisson arrival) scenarios are considered. For the latter scenario, besides symmetric traffic where each BS has the same average arrival rate, we also consider the case where some sectors are in the hot-spot having higher traffic arrival rate. We use two different schedulers- iterative Hungarian and proportional fair. It is observed that Reuse 3 scheme achieves the highest cell-edge throughput, however, with significant degradation in cell throughput due to resource partitioning, and Reuse 1 achieves the highest cell throughput with the poorest performance with respect to cell-edge throughput. On the other hand, the cell-edge performance of different variations of the proposed schemes can reach close to the level of Reuse 3 while their cell throughput is comparable to that in Reuse 1.

A distributed algorithm with neighboring cell coordination is presented in Chapter 5. The algorithm does not require a central controller and resource coordination is performed using BS to BS communication using an interface such as the X2 interface of the LTE systems. The interference originated from transmitters within the same BS is coordinated using a novel method based on Hungarian algorithm in a multi-cellular (i.e., multi-sector) context. The inter-BS interference is handled similar to the previous scheme in Chapter 4, however, resource restriction conflicts are resolved by inter-BS communication over the X2 interface. A number of reference schemes have been considered such as Reuse 1, Reuse

3, a PFR, and SFR with different effective reuse factors. Similar to the previous study, two different cases are examined where the restricted resources are not used in one and used with lower power in the other. It is observed that the proposed schemes can attain cell throughput quite close to or slightly better than that in Reuse 1 while achieving a comparable or slightly better cell-edge throughput that is achieved in Reuse 3.

A cluster-based centralized scheme is studied in Chapter 6, where clustering approach significantly reduces the complexity of original problem formulated in Chapter 3. Although far-away interferers may not affect signal qualities, the inter-dependency of interference propagates throughput the whole network. Therefore, inter-cluster relationship is modeled using constraints. The solution is obtained using a fast ILP solver in order to quantify the performance gain achievable in a system. Different cluster sizes that represent different computational complexity, and different utility functions for varying levels of fairness have been studied. The presented schemes achieve significant gain in cell-edge throughput without noticeable impact on cell throughput. It is also observed that although higher cluster size incur exponentially high complexity, the differential performance gain does not scale accordingly and observed to be modest.

While both the two-level algorithm with partial central processing and the cluster-based centralized algorithm can be applied to systems in which central processing is feasible, the former requires less computational complexity. The distributed scheme representing the least computational complexity, on the other hand, does not require any central entity; however, a mechanism for BS-BS communication, such as in LTE, is needed. It should be noted that although the LTE specifications do not encourage centralized RRM schemes, some of the key features of the future LTE-A systems are based on centralized processing. Therefore, all three presented schemes can be applied to such future systems.

Research presented in this thesis can be extended for future research as follows.

1. **Utility functions**

   The focus of this thesis has been on quantifying performance gain of the ideas presented on dynamic interference coordination. Therefore, simple and intuitive utility functions have been incorporated given the fact that both the proposed and reference schemes use the same functions for fair comparison. However, other functions possibly with additional QoS parameters may be explored which may further enhance network performance.

2. **Power control in conjunction with resource restriction**

   We have assumed equal power allocation across all sub-carriers in most of our schemes with the exception that a variation of the proposed scheme uses the restricted resource units with much lower power than the unrestricted resources. Although it has been shown that power control does not exhibit significant gain in throughput for an OFDMA-based system that already achieves channel selectivity and multiuser diversity gain using AMC [63], power control will have significant impact on cell-edge performance. This research can be extended to include power control along with resource restrictions.

3. **Inclusion of Multiple-In Multiple-Out (MIMO) antenna configuration with different combining algorithms**

   Only SISO antenna configuration has been used in this thesis for simplicity. Future research may include MIMO antennas with different combining methods as well as with transmit and receive diversity techniques.

4. **Integration of ICIC with other interference mitigation techniques**

   The dynamic ICIC schemes presented in these these can be combined with other

interference mitigation techniques such as interference cancellation and averaging in order to assess total mitigation gain in the network.

5. **Combining with Physical (PHY)-layer Coordinated Multi-Point Transmission and Reception (CoMP)**

   As mentioned, the ideas presented in this thesis are quite similar to coordinated scheduling part of the emerging CoMP technology. These schemes can be combined with PHY-layer CoMP processing to assess overall interference avoidance gain of the system.

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# Appendix A

# List of Publications

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**Remarks on the Prefix of the List of Publications**

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|---|---|
| **M** | Master's work |
| **P** | PhD work included in the thesis |
| **PI** | Intended publication from PhD work |
| **PN** | PhD work not included in the thesis |